Optical properties of donor–acceptor phenylene-ethynylene systems containing the 6-methylpyran-2-one group as an acceptor†

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Donor–acceptor phenylene ethynylene systems containing the 6-methylpyran-2-one group, synthesized *via* classic or microwave-assisted Sonogashira cross-coupling, exhibit pronounced solvatochromism in fluorescence suggesting a highly polar excited state; 4-[4-(4-*N*,*N*-dihexylaminophenylethynyl)phenylethynyl]-6-methylpyran-2-one has a fluorescence quantum yield >0.9 in cyclohexane.

The 2-pyrone (2*H*-pyran-2-one) moiety, a six-membered cyclic unsaturated ester which shares chemical and physical properties reminiscent of alkene and aromatic compounds, is a fundamental building block found in nature, exerting a range of important biological effects that are integral to the biological systems of animals, bacteria, fungi, insects and plants.[1] The therapeutic potential of molecular systems based upon 4-substituted 6-methyl-2-pyrones incorporating alkyl, alkenyl, aryl and alkynyl substituents, has been of interest to one of us[2] (Fig. 1). Furthermore, transition metal complexes of 2-pyrones, which are η^4-diene[3] and η^1-C=O coordinated,[4] have been reported; both types of complex exhibit carbon monoxide releasing properties.[5]

In line with our interest in expanding upon the potential applications of 2-pyrones, we have explored the possibility that this ring system could be incorporated into novel conjugated molecules. A literature survey reveals that 4-phenyl-substituted 2-pyrones have been noted as highly fluorescent.[6] The absence of studies on the photophysics of 4-ethynyl-substituted 2-pyrone systems is, however, surprising, considering that they are closely related to coumarins which are well known laser dyes.[7]

For some time, we have been exploring the optical properties of donor–acceptor systems based on phenylene–ethynylene structures.[8] The 2-pyrone moiety, containing a conjugated ester functionality, is a strong electron-accepting group, and therefore, if combined with strong donors such as dialkylamino groups,

might provide a suitable chromophore for systems which exhibit interesting linear and non-linear optical properties.

Indeed, a simple model reveals the extent to which charge transfer is possible (Fig. 2). More revealing are the results of DFT calculations on optimised geometries (B3LYP functional, 6-31G* basis set)[9] which show that the HOMO of **2** is largely localised on the dimethylaniline group whereas the LUMO is predominantly localised on the pyrone moiety, and this is even more pronounced in **3** (Fig. 3). TD-DFT calculations confirm that the lowest energy transition is that in which an electron is promoted from the HOMO to the LUMO. In this paper we report the first photophysical study on donor-substituted, π-conjugated 4-alkynyl-6-methylpyran-2-ones.

The most efficient method to prepare 4-ethynylpyran-2-ones involves the palladium-catalysed Negishi or Sonogashira alkynylation reactions[10] of terminal alkynes with 4-bromo-6-methylpyran-2-one. A variety of substituted 4-ethynyl-6-methylpyran-2-ones have been prepared in such a way including 6-methyl-4-(phenylethynyl)pyran-2-one **1**.[11] Compound **2**, 4-[4′-(*N*,*N*-dimethyl-aminophenyl)ethynyl]-6-methyl-2-pyrone, was obtained in 77% yield† *via* Sonogashira cross-coupling of 4-ethynyl-*N*,*N*-dimethylaniline with 4-bromo-6-methylpyran-2-one in refluxing triethylamine (Scheme 1). However, coupling of the extended analogue 4-[4-(ethynylphenyl)ethynyl]-*N*,*N*-dimethylaniline to 4-bromo-6-methylpyran-2-one resulted in a poorly-soluble product which proved extremely difficult to purify by chromotography and recrystallisation. The more soluble di-*n*-hexyl derivative, 4-[4-(4-*N*,*N*-dihexyl-aminophenylethynyl)phenylethynyl]-6-methylpyran-2-one, **3**, was prepared by an analogous route, purified *via* column chromatography on alumina, and isolated in 45% yield.†

These compounds may also be accessed using microwave-assisted Sonogashira cross-coupling reactions. For example,
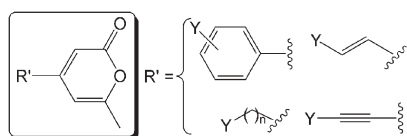
Fig. 1 4-Substituted 6-methyl-2-pyrones (Y = electron withdrawing group, electron donating group or alkyl chain of varying lengths).
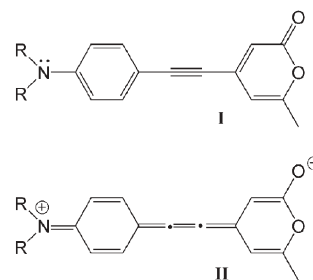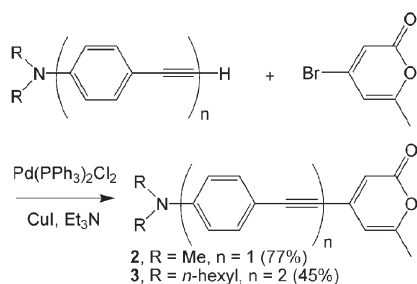
Fig. 2 A simple model illustrating the neutral and zwitterionic (quinoidal-cumulene) contributions to the bonding in conjugated 2-pyrones.
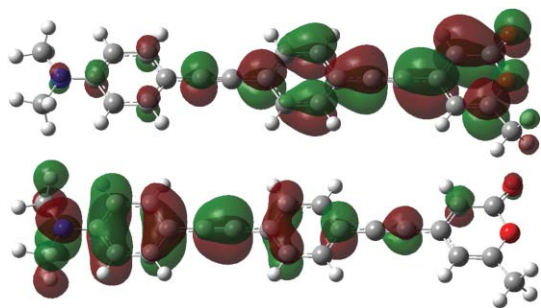
Fig. 3 HOMO (bottom) and LUMO (top) of compound **3** (Scheme 1) from DFT calculations.

Scheme 1 Synthesis of compounds **2** and **3**.

compound **2** was produced in 92% yield using 0.5 mol% $(PPh_3)_2PdCl_2$ and 0.5 mol% CuI in a CH_3CN–Et_3N solvent mixture (5 : 3) containing 1.05 equiv. of the terminal alkyne, using a standard CEM Discover microwave reactor (100 W, 10 min at 120 °C). It should be noted that the analogous reaction of 4-TsO-6-methyl-2-pyrone is less efficient than that of the bromo derivative under these reaction conditions and that the product is more difficult to purify (41% yield of pure **2**). Using conditions analogous to those for **2**, **3** was prepared in a Biotage-Personal Chemistry Emrys Optimizer automated microwave reactor in 38% isolated yield after column chromatography.

The structure of **2** has been obtained from single-crystal X-ray diffraction data,‡ and shows the molecule to be nearly planar (Fig. 4). The benzene ring, B, forms dihedral angles of 4.8° with the planar pyrone ring, A, and 3.5° with the plane of the sp^2 hybridised N atom, the bond angles at which sum to 359.0°. The bonding in ring A is substantially localised, as in unsubstituted α-pyrone,[12] but the O(1)–C(1), C(2)–C(3) and C(3)–C(4) bonds in **2** are appreciably longer than in the latter (1.384(3), 1.339(4) and 1.424(4) Å, respectively). The C(7)≡C(8) bond is longer and the adjacent single bonds shorter in **2** than in tolan (1.199(2) and
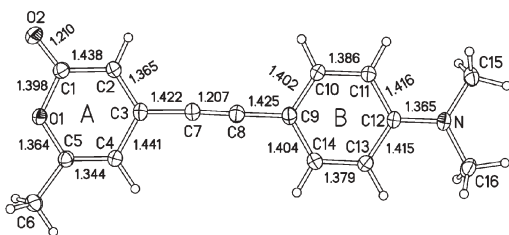
Fig. 4 Molecular structure of **2**, showing 50% thermal ellipsoids and selected bond lengths in Å (all e.s.d.'s are 0.001 Å).

Table 1 Photophysical properties of compounds **1–3**

Compound	Solvent	λ_{max}/ nm	ε/ cm^{-1} M^{-1}	λ_{em}/ nm	Stokes shift/cm^{-1}	Φ_f	τ^a/ns
1	C_6H_{12}	306	—	420	8900	0.002	—
1	CH_2Cl_2	310	—	422	8600	0.008	—
2	C_6H_{12}	370	—	395	1700	0.14	0.71
2	Toluene	388	—	460	4000	0.084	1.05
2	$CHCl_3$	395	—	535	6600	0.014	—
2	AcOEt	382	—	545	7800	0.008	—
2	CH_2Cl_2	395	29 800	580	8100	0.08	0.44
3	C_6H_{12}	388	—	432	2600	0.94	1.23
3	Toluene	395	—	485	4700	0.85	1.66
3	$CHCl_3$	402	—	592	8000	0.42	2.24
3	AcOEt	389	—	589	8730	0.23	1.18
3	CH_2Cl_2	400	32 000	634	9260	0.10	0.95

^{a} Fluorescence lifetime (time-correlated, single-photon counting method, λ_{ex} = 370 nm).

1.435(2) Å, respectively).[13] The bonding in ring B shows some quinoid character. The N–C(12) bond is shorter than in 33 *p*-alkyl derivatives of *N,N*-dimethylaniline present in the November 2004 issue of the Cambridge Structural Database[14] (average 1.387 Å).

The optical properties of these novel chromophores **2** and **3** have been investigated and are compared with those of the unsubstituted phenylethynyl pyrone **1** in Table 1. UV-visible spectra reveal an intense absorption in the UV region for **2** and **3**. As expected, the spectrum of chromophore **3** is red-shifted from that of compound **2**, revealing a smaller HOMO–LUMO gap. Compound **3** also has a larger oscillator strength than **2** as shown by a hyperchomic shift together with a larger peak width at half-height (6000 *vs.* 4400 cm^{-1} in C_6H_{12} and 5900 *vs.* 4500 cm^{-1} in CH_2Cl_2). We have also investigated their steady-state and time-resolved fluorescence properties. Whilst only a small degree of solvatochromism is observed in the absorption spectra, the two donor-substituted pyrones show very large bathochromic shifts in their emission spectra with increasing solvent polarity (185 nm from C_6H_{12} to CH_2Cl_2 for **2** and 202 nm for **3** (Fig. 5)); thus, the Stokes shift in both **2** and **3** increases drastically, as the emission spectra become featureless and the quantum yields decrease somewhat with increasing solvent polarity. These observations suggest that the excited state created upon UV irradiation is much more polar than the ground state, consistent with an intramo-lecular charge transfer (CT) process and the results of the DFT
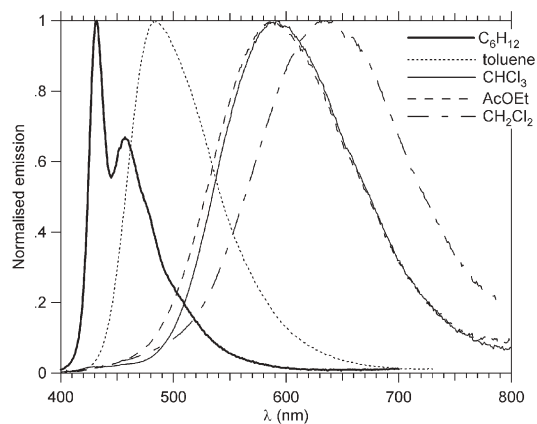
Fig. 5 Normalised emission spectra of **3** in a variety of solvents.

calculations, *vide supra*. If the CT state has a rather different electronic distribution than the ground state, this can result in a small overlap integral and hence weak oscillator strength and low emission intensity. However, in our systems, there is sufficient delocalisation of the HOMO and LUMO such that the overlap integrals are larger than might be found in other CT compounds.

Compound **3** also has a longer fluorescence lifetime and higher quantum yield than its shorter analogue, **2**. Moreover, the fluorescence quantum yield of **3** is very large in apolar media (>90% in C_6H_{12}), making it suitable for use as a dye for biological imaging in, for example, lipophilic membranes. Such properties could also be exploited to determine the mode of action of several human ovarian cancer cell line inhibitors based on 4-alkynyl-6-methylpyran-2-ones.[2] The functionalisation of the pyrone heterocycle has thus led to highly fluorescent derivatives **2** and especially **3** (Φ_f = 14% and 94% in C_6H_{12}, respectively) although for the short, unsubstituted parent compound **1**, $\Phi_f < 1$%.

The combination of a rigid-rod core and flexible alkyl chains in **3** prompted us to consider the potential for liquid crystal phase behaviour as related *para*-substituted bis(phenylethynyl)benzenes (BPEB) exhibit a variety of mesophases.[15] Thus, **3** was heated at 10 °C min^{-1} on a hot-stage and examined by transmitted, polarised light microscopy. The sample melted into the isotropic liquid phase at 160 °C and, on cooling at 10 °C min^{-1}, it crystallised at 88 °C showing a large hysteresis. No optical textures characteristic of liquid crystal phases were observed.

In summary, it has been shown that compounds **2** and **3** are accessible employing classic or microwave-assisted Sonogashira cross-coupling reactions. Both compounds are highly fluorescent. Compound **3** has a very large quantum yield in apolar solvents. Further studies on the synthesis and optical properties of analogous compounds based on 4-ethynylcoumarins[16] are in progress.

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Notes and references

‡ Crystallographic data for **2**: single crystals from toluene, $C_{16}H_{15}NO_2$ **2**, $M = 253.29$, $T = 120$ K, triclinic, space group $P\bar{1}$ (No. 2), $a = 7.307(1)$, $b = 8.038(1)$, $c = 12.305(1)$ Å, $\alpha = 96.35(1)$, $\beta = 101.85(1)$, $\gamma = 112.68(1)°$. $U = 638.04(13)$ Å^3, $Z = 2$, $\mu = 0.09$ mm^{-1}, Bruker SMART 6000 CCD area detector, Mo-Kα radiation, $\lambda = 0.71073$ Å, 9055 reflections collected with $2\theta \leqslant 60°$, 3708 unique, $R_{int} = 0.044$, $R = 0.047$ [2953 data with $F^2 \geqslant 2\sigma(F^2)$], w$R(F^2) = 0.149$ (all data). CCDC 264993. See http://www.rsc.org/suppdata/cc/b5/b502781k/ for crystallographic data in CIF or other electronic format.

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