A natural light induced regioselective 6π-electrocyclisation–oxidative aromatisation reaction: experimental and theoretical insights†

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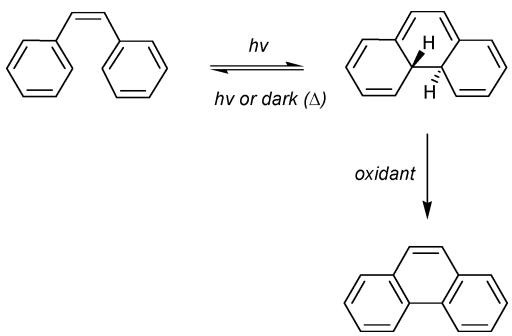
Stoichiometric intermolecular Pauson–Khand reactions of 4-(phenylethynyl)-6-methyl-2-pyrones with norbornene and dicobalt(0)octacarbonyl provide cyclopentenone products that undergo a facile 6π-electrocyclisation–oxidative aromatisation transformation in the presence of natural light and oxygen, affording functionalised benzo[*h*]indeno[1,2-*f*]isochromene type products. The results are rationalised by theoretical studies, which confirm that the electrocyclisation process is favoured at C3 in the 2-pyrone ring system. The identity and precise arrangement of the 'trienyl' substituents control whether the electrocyclisation occurs in natural light.

Introduction

Photochemically induced 6π-electrocyclisations of diarylethenes provide an important route into dihydrophenanthrenes (Scheme 1).[1] For certain types of aryl and heteroaryl moieties, the transformation has been used extensively to provide photochromic materials[2] and natural product targets.[3] The intermediate dihydrophenanthrenes usually undergo cycloreversion, but in certain cases can be isolated.[4] The presence of an oxidant, *e.g.* O_2 or I_2, allows thermodynamically favoured aromatic derivatives to be formed from the dihydrophenanthrene intermediates *via* the formal loss of H_2, *e.g.* trapped as H_2O. Whilst many of these photochemical processes require high energy UV irradiation, there are examples in the literature where natural light[5] can trigger certain 6π-electrocyclisations in highly conjugated triene systems. Those found at vital junctures in biomimetic processes yield fascinating structures of significant interest.[6]



Scheme 1 2-Pyrones and derivatives.

During the course of synthetic and biochemical studies on 2-pyrones,[7,8] specifically the 4-(phenylethynyl)-2-pyrone **1a**,[9] we became aware of a regioselective 6π-electrocyclisation–oxidative aromatisation reaction (**2a**→**4a**) taking place in natural light (Fig. 1). In this paper, we report the experimental results from this study. In addition, theoretical results are presented to support the experimental findings and offer an explanation for the regiochemical outcome observed during the electrocyclisation.[10]

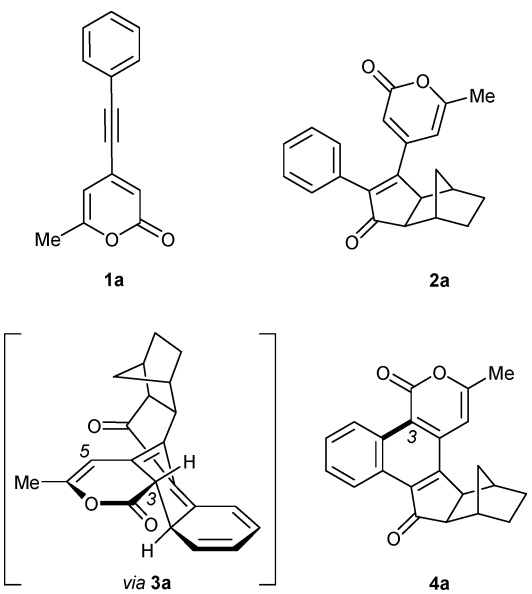


Fig. 1 Alkynylated 2-pyrone **1a** and cyclisation products.

Results and discussion

Our initial interest in this area derives from investigations on the stoichiometric intermolecular Pauson–Khand (PK) reaction[11] of

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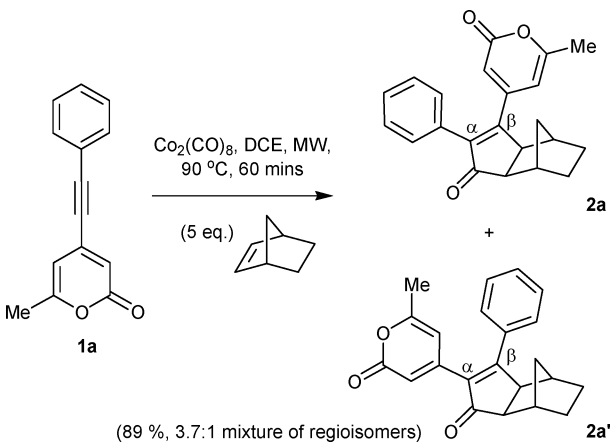
the internal alkyne **1a**,[12] norbornene and CO {from $Co_2(CO)_8$}. The reaction can, in principle, generate two regioisomeric products, **2a** and **2a′** (Scheme 2). Through consideration of the apparent polarisation effects across the alkyne bond in **1a**, and making the assumption that 2-pyrone and phenyl are sterically near equivalent, it was predicted[13] that the major regioisomeric product would possess the phenyl group at the α-position and the electron-deficient 2-pyrone at the β-position in the newly formed cyclopentenone ring. The reaction is very clean when conducted in a microwave,[14] producing both regioisomers in a 3.7:1 ratio and 89% overall yield (separable by chromatography on silica-gel). However, the structural assignments of the two isomeric products could not be definitively proven by simple ^1H and ^{13}C NMR spectroscopy. It is interesting to note that this specific example represents the first intermolecular PK reaction of any alkyne containing a 2-pyrone moiety.[15]



Scheme 2 Pauson–Khand reaction of **1a** with norbornene and $Co_2(CO)_8$.

It emerged that the major regioisomeric product from the PK reaction of **1a** with norbornene and $Co_2(CO)_8$ was being slowly converted to a new compound on standing in $CDCl_3$. At this stage, no special precaution was taken to protect the sample from O_2 or natural light. Using purified (dried and degassed) $CDCl_3$, or exposing the product to O_2 in the dark, resulted in no observable reaction. However, on exposure to both natural light and O_2 the reaction proceeded. This information, and the combined spectroscopic and spectrometric evidence, pointed to a photochemical 6π-electrocyclisation–oxidative aromatisation process taking place. The structure of the product was expected to be one of four regioisomers (Fig. 2); the 6π-electrocyclisation can in principle take place at C3 or C5 in the 2-pyrone ring system from either regioisomer **2a** (to give either **4a** or **4a′**) or **2a′** (to give either **4ab** or **4ab′**). Pleasingly, **4a** crystallised from a $CDCl_3$ solution of the major isomer from the PK reaction, allowing its structure to be determined by X-ray diffraction. This confirmed that a regioselective 6π-electrocyclisation–oxidative aromatisation reaction had occurred (Fig. 3). The structure determination also confirmed the major regioisomer formed in the PK reaction was **2a**. The minor regioisomer **2a′** does not undergo such a facile 6π-electrocyclisation–oxidative aromatisation reaction, being more stable in $CDCl_3$ solution in the presence of natural light and O_2.

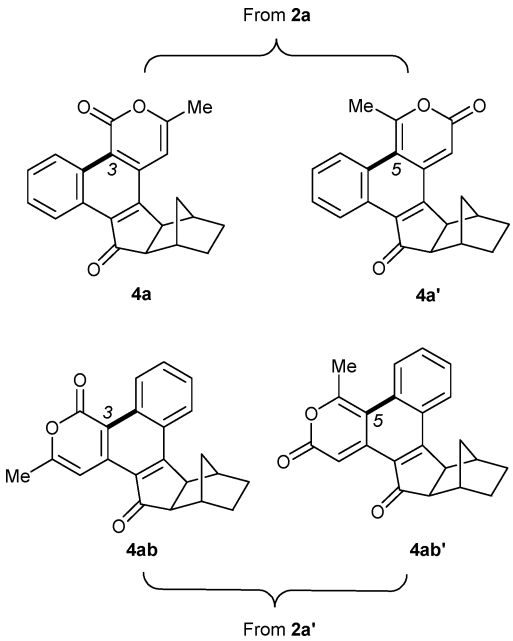


Fig. 2 Potential regioisomeric products (line in bold depicts the position of the new bond).

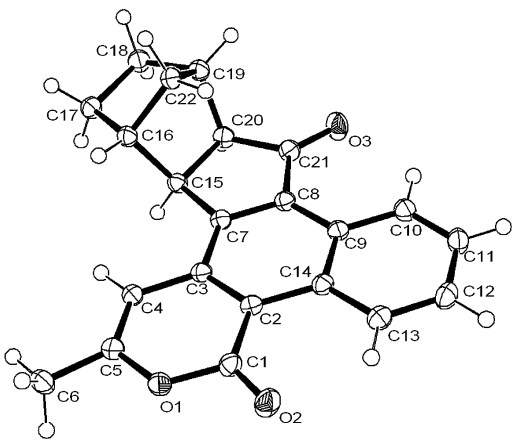
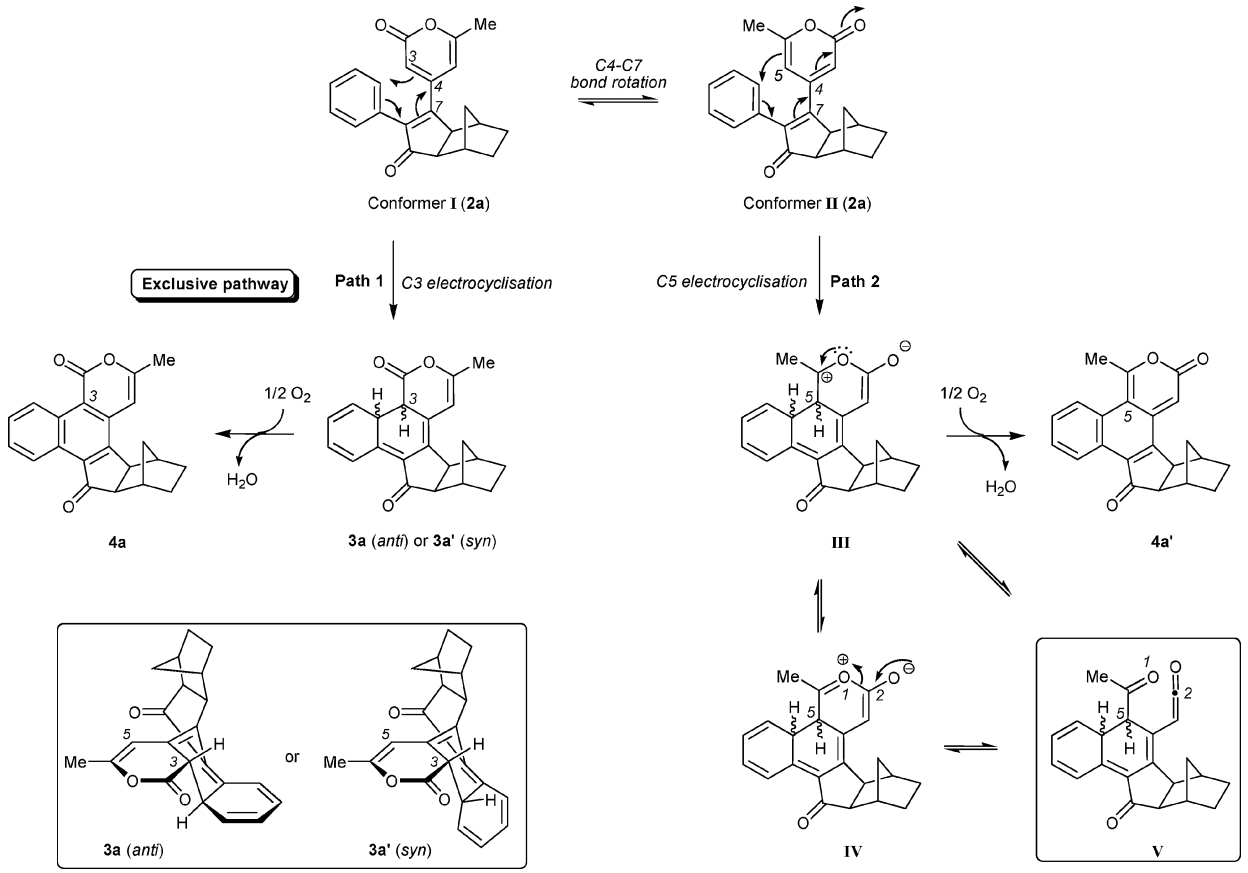


Fig. 3 X-Ray crystal structure of compound **4a** shown in ORTEP (arbitrary numbering used). Thermal ellipsoids are at 50% probability.

Thermal *versus* photochemical activation: origin of the regioselectivity in the 6π-electrocyclisation process

To validate that the reaction was activated by natural light and not by a thermal process, and wishing to establish the underpinning reason for C3 over C5 electrocyclisation, B3LYP density functional theory calculations were carried out. Geometry optimisation on **2a** gives two local minima, corresponding to conformers **I** and **II** (Scheme 3). The two structures are related by a simple rotation of the 6-methyl-2-pyrone group about the C4–C7 single bond and have similar stabilities. Conformer **I** is less stable by only 1.2 kcal/mol than **II**. Interestingly, attempts at the optimisation of structure **III** were not successful and resulted instead in the identification of γ-keto-ketene intermediate **V**. There are two pathways (**III**→**V** or **III**→**IV**→**V**, as indicated in Scheme 3). Structure **V** is 44.0 kcal/mol higher in energy than **2a**, and is therefore highly unstable and energetically inaccessible. The result is consistent with the experimental observation that the



Scheme 3 Mechanism to explain the selective formation of regioisomer **4a**. Note: arbitrary atom numbering used.

C5 electrocyclisation does not occur; **III** is not a species that corresponds to a stationary point on the potential energy surface.

For the C3 6π-electrocyclisation reaction, two intermediates, **3a** and **3a′**, can be obtained through conrotatory and disrotatory cyclisations, respectively. Due to the breaking of conjugation, the two intermediates are higher in energy by 21.5 and 32.7 kcal/mol, respectively, than reactant **2a** (Fig. 4). Furthermore, structure **3a′** is less stable than **3a** as it is more strained.

On the basis of the highest occupied molecular orbital (HOMO) of **2a** (Fig. 5), the cyclisation is relevant to a 6π-electron system and we expect that the disrotatory cyclisation is symmetry-allowed while the conrotatory cyclisation is symmetry-forbidden.[1] Indeed, we were able to locate the transition state $\mathbf{TS}_{\mathbf{I\text{-}3a'}}$ connecting **I** and **3a′**, which corresponds to the symmetry-allowed disrotatory cyclisation, and failed to locate the transition state $\mathbf{TS}_{\mathbf{I\text{-}3a}}$ connecting **I** and **3a**, which corresponds to the symmetry-forbidden conrotatory cyclisation. The calculations show that the symmetry-allowed disrotatory cyclisation has a barrier of 43.5 kcal/mol and gives the relatively less stable intermediate **3a′**. Therefore, in view of the inaccessibly high barrier and the very high instability of **3a′**, it is clear that the symmetry-allowed disrotatory cyclisation giving intermediate **3a′** is not responsible for the experimentally observed reaction that eventually leads to the formation of **4a**. Because of the symmetry-forbidden nature, and the fact that we failed to locate the corresponding transition state, a thermal conrotatory cyclisation giving intermediate **3a** can be ruled out.

Under the experimental conditions, it may be postulated that trace quantities of HCl (DCl) in the $CDCl_3$ solvent could have promoted the electrocyclisation through protonation of the carbonyl of the 2-pyrone fragment of **2a** (Scheme 4). However, the calculations do not support such a possibility. The calculated energies of $\mathbf{2a\_H^+}$, $\mathbf{3a'\_H^+}$ and $\mathbf{3a\_H^+}$ show that $\mathbf{3a'\_H^+}$ and $\mathbf{3a\_H^+}$ are higher in energy by 46.6 and 35.6 kcal/mol, respectively, than $\mathbf{2a\_H^+}$. The protonation increases the energy gaps between the intermediates and **2a**. Experimentally, the reaction proceeds in C_6H_6, as well as $CHCl_3$, ruling out trace acid as a reaction promoter.

In keeping with the Woodward–Hoffman rules,[16] for a 6π-electron system, a conrotatory cyclisation is brought about by light.[17] Given both the experimental observations and the theoretical insight, it is proposed that the visible light in the laboratory initiates the conrotatory cyclisation to give the relatively more stable intermediate **3a**, followed by hydrogen elimination in the presence of O_2 to give **4a** (and H_2O). Analogous ring-open systems convert to the corresponding ring-closed forms upon UV-visible irradiation.[18]

The first excited state of **2a** was calculated using the time-dependent density functional theory (TDDFT) method and can be accessed by absorption of light at 396 nm. The solvent ($CDCl_3$) effect was found to reduce the energy gap between the ground state and the first excited state, suggesting that **2a** can be excited by absorption of visible light. The small energy gap between the

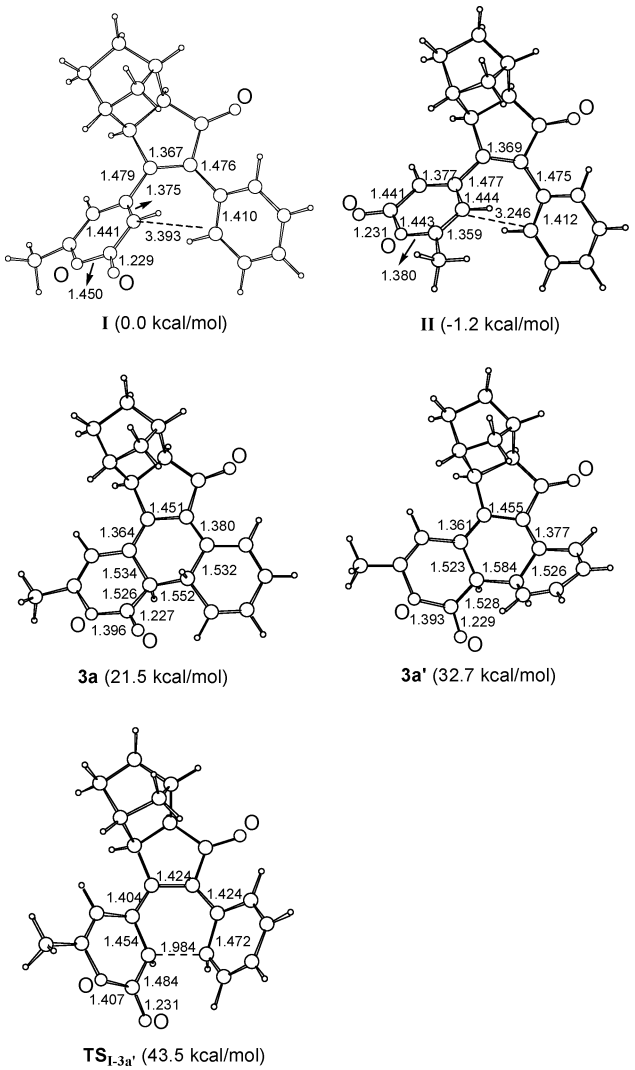


Fig. 4 B3LYP-optimised structures. The bond distances are given in angstroms.

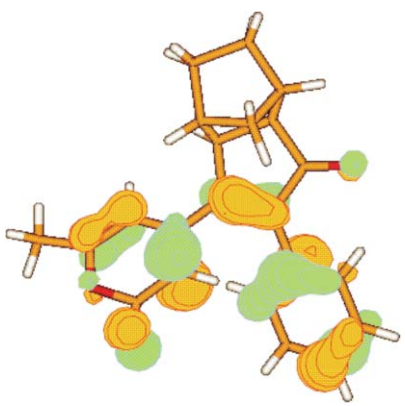
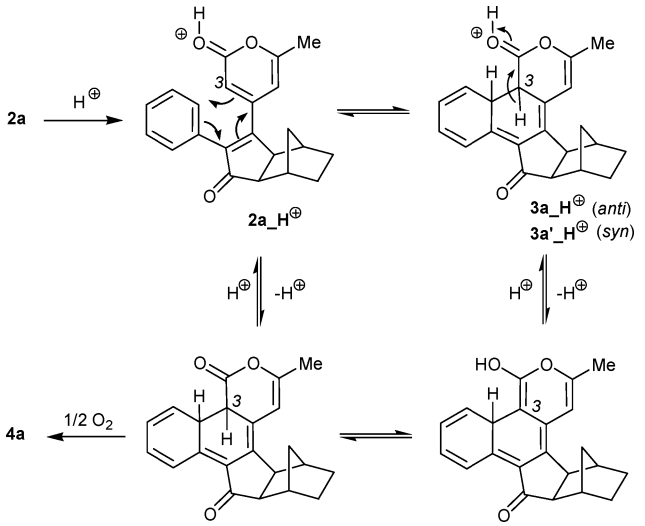


Fig. 5 The highest occupied molecular orbital (HOMO) of **2a** from conformer **I**.

ground state and the first excited state of **2a** is related to the extensive conjugation in **2a**.

More generally, dihydrophenanthrene irreversibly converts to phenanthrene in the presence of air, by hydrogen-elimination with



Scheme 4 Probing the potential role of trace acid.

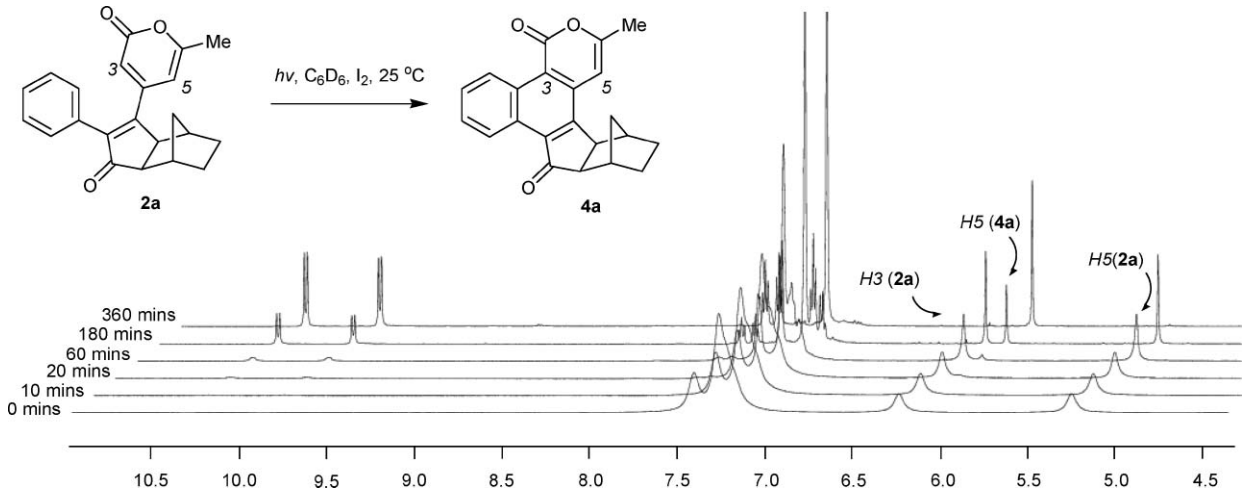
oxygen *vide supra.*[19,1] Therefore it is proposed that the oxidant rapidly reacts with intermediate **3a** to give **4a** exclusively (in natural light).

In order to accelerate the reaction, a solution of **2a** in $CDCl_3$ was photolysed using a standard UV lamp with a filter at 400 nm, in a reaction vessel open to air. After 6 h, the reaction was essentially complete (~quantitative conv.; >90% purity). A small quantity of an uncharacterised side-product was evident in the ^{1}H NMR spectra, which appears to be formed towards the latter stages of the reaction (and on prolonged exposure to light). The identical reaction in benzene gave a similar yield of **4a**, proceeding in 3 h. Iodine proved a superior oxidant in benzene, yielding a purer product, although the reaction time increased to 6 h. For this latter reaction, the evolution of **4a** was monitored over time by ^{1}H NMR spectroscopy (Scheme 5). The disappearance of the C3 and C5 protons of **2a** is evident (~ δ 5.2 and 6.2 ppm), as is the emergence of a new signal (~ δ 6.0) corresponding to the C5 proton of the new product. The appearance of highly deshielded aromatic protons at ~ δ 9.7 and 10.2 ppm confirms the formation of **4a**.

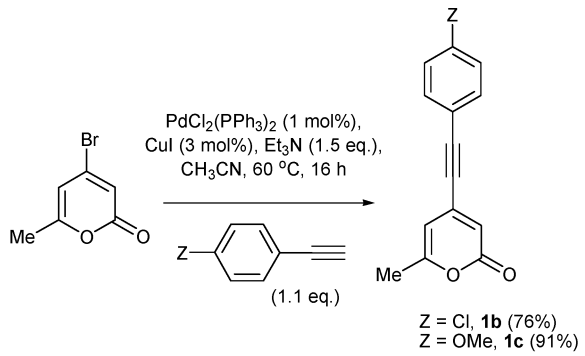
In an effort to detect intermediate **3a**, preliminary *in situ* photolysis experiments (325 nm He–Cd 27 mW continuous wave laser coupled directly to a 400 MHz NMR spectrometer) were carried out. Interestingly, at this higher energy, electrocyclisation–oxidative aromatisation occurs slowly in dry and degassed $CDCl_3$.[20] It should be noted that other uncharacterised products are formed in these reactions which do not derive from secondary reactions of **4a**. The identical reaction run in the presence of O_2 affords **4a** at a faster rate than the reaction run in its absence (for which uncharacterised side-products also result).

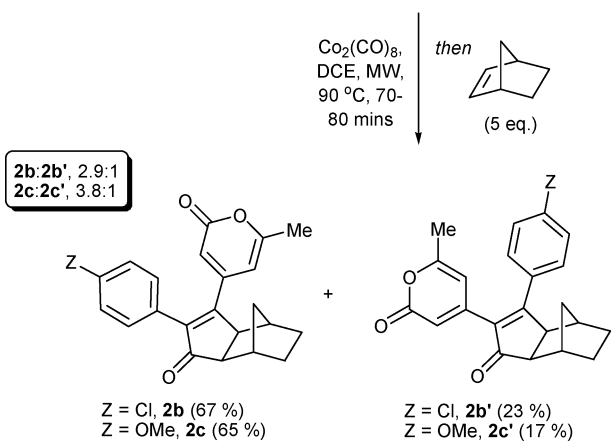
Substituent effects in the aryl ring system

We envisaged that substituents on the aryl ring system would significantly affect the rate of the 6π-electrocyclisation–oxidative aromatisation process. Two further PK reactions of alkynyl 2-pyrones **1b** and **1c** were explored. Both **1b** and **1c** were prepared by Sonogashira cross-coupling of 4-bromo-6-methyl-2-pyrone[8y] with the requisite terminal acetylene under standard conditions (Scheme 6). The PK reactions of both **1b** and **1c** with norbornene and $Co_2(CO)_8$ were then conducted using the previously developed



Scheme 5 6-π-electrocyclisation–oxidative aromatisation of **2a**→**4a**.[21] Note: arbitrary atom numbering used.

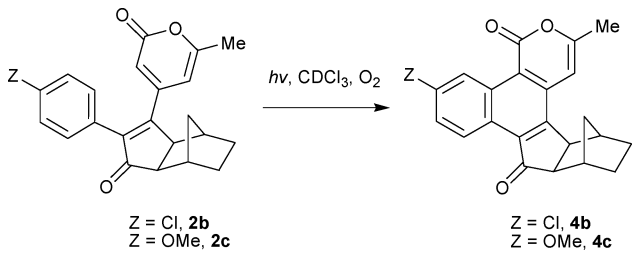




Scheme 6 Aryl-substituent effects in PK reactions.

microwave conditions. The presence of *p*-chloro or *p*-methoxy groups on the aryl ring does not significantly affect the overall regioselectivity. A comparison of the spectroscopic data for both regioisomers resulting from the PK reactions of **1b** and **1c** confirm that the major regioisomers are **2b** and **2c**, respectively.

To determine the relative rates of the electrocyclisation–aromatisation reactions for **2a–c**, $CDCl_3$ solutions of each compound were simultaneously exposed to sunlight for one hour (identical conditions), after which time the relative ratios of the starting compounds to products **4a–c** were determined by ^{1}H NMR spectroscopy (Table 1 and Scheme 7).



Scheme 7 6π-Electrocyclisation–oxidative aromatisation of **2b** and **2c**.

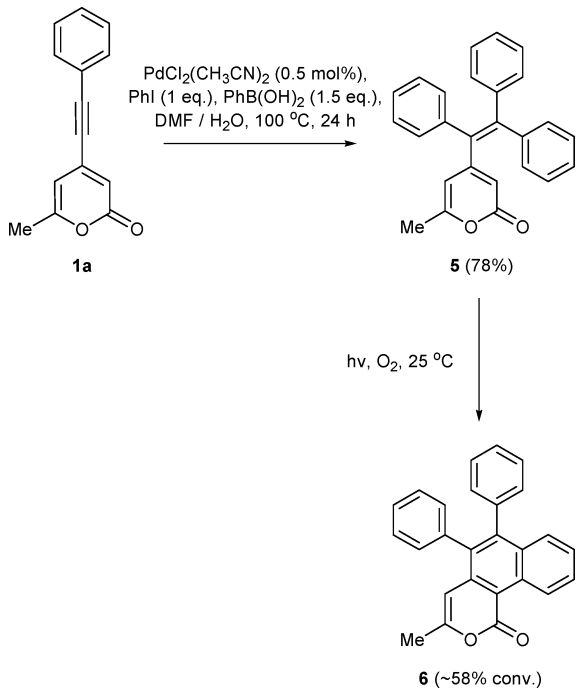
From the data collected in Table 1, it is clear that **2c** is undergoing a considerably faster electrocyclisation–oxidative aromatisation reaction than **2a** and **2b**. The slowest reaction is that involving **2b**, allowing a reactivity order to be established: *p*-OMe (**2c**) > H (**2a**) > *p*-Cl (**2b**). The increased reactivity of **2c** is attributed to the *meta*- or *ortho-meta*-effect (position of the substituents relative to the new C–C bond).[22] In this example, the electron-releasing methoxy group would be expected to stabilise the first excited state and accelerate the rate of the 6π-electrocyclisation process. The precise location of the substituents in **2a–c** appears to greatly assist the 6π-electrocyclisation–oxidative aromatisation process in natural light, as indicated by the fact that **2a′**, **2b′** and **2c′** do not participate in such a facile reaction.

Table 1 Comparison of the relative rates of electrocyclisation–aromatisation for **2a–c**[a]

Reaction	% Ratio[b] $t = 0$	% Ratio[b] $t = 60$ min	Relative % increase
2a → **4a**	96.9 : 3.1	93.1 : 6.9	3.8
2b → **4b**	97.0 : 3.0	95.9 : 4.1	1.1
2c → **4c**	95.4 : 4.6	80.0 : 20.0	15.4

[a] Concentration of reagents **2a–c** (75 mM in $CDCl_3$) exposed to sunlight for 1 h. [b] Percentage ratios given as starting material:product as determined by ^{1}H NMR spectroscopy (400 MHz).

It is also noted that compound **5**, formed by a double-arylation of **1a** by the reaction conditions reported by Larock and Zhou,[23] is stable in the presence of natural light and O_2 (Scheme 8). Irradiation (filter at 400 nm) of **5** in $CDCl_3$ in an NMR tube open to air at 25 °C resulted in a slow electrocyclisation–oxidative aromatisation reaction to give a product which based on ^{1}H NMR spectroscopic evidence (500 MHz, see ESI† for further discussion) is postulated to be **6** (58% relative conversion after 20 h).



Scheme 8 Synthesis of vinyl-2-pyrone **5** and electrocyclisation–aromatisation to give **6**.

Conclusions

The major PK regioisomeric products **2a–c** readily undergo a photochemically-induced 6π-electrocyclisation–oxidative aromatisation reaction to reveal functionalised benzo[*h*]indeno[1,2-*f*]isochromene type products **4a–c**, respectively. The precise arrangement of the substituents in **2a–c** appears to facilitate the photochemically-induced electrocyclisation process in natural light.

Experimental

Computational studies by DFT

Density functional theory (DFT) calculations at the B3LYP level[24] were performed to calculate the structures of the isomers and the transition states. Frequency calculations were also performed to confirm the characteristics of the calculated structures as minima or transition states. Calculations of intrinsic reaction coordinates (IRC)[25] were also performed on transition states to confirm that such structures are indeed connecting two minima. Time-dependent density functional theory was used to calculate the energy of the first excited state. The standard 6–31G basis set was used.[26] All calculations were carried out with the Gaussian 03 software package.[27]

General synthetic details

Solvents were dried where necessary using standard procedures prior to use and stored under an argon atmosphere. DCE refers to 1,2-dichloroethane. Nitrogen gas was oxygen-free and was dried immediately prior to use by passage through an 80 cm column containing sodium hydroxide pellets and silica. Argon gas was used directly *via* balloon transfer or on a Schlenk line. TLC analysis was performed routinely using Merck 5554 aluminum backed silica plates. Compounds were visualized using UV light (254 nm) and a basic aqueous solution of potassium permanganate. ^{1}H NMR spectra were recorded at either 400 MHz using a JEOL ECX 400 spectrometer, with ^{13}C NMR spectra recorded on the same instrument at 100 MHz (^{1}H decoupled); or at 500 MHz on a Bruker AV 500 spectrometer, with ^{13}C NMR spectra recorded on the same instrument at 125 MHz (^{1}H decoupled). Chemical shifts are reported in parts per million (δ) relative to $CHCl_3$ at δ 7.24 (^{1}H) or 77.0 (^{13}C). Coupling constants (*J* values) are reported in hertz (Hz), and spin multiplicities are indicated by the following symbols: s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet), br (broad). Photolysis was performed using a Philips HPK 125 W medium pressure mercury lamp. 4-Bromo-6-methyl-2-pyrone and 4-(phenylethynyl)-6-methyl-2-pyrone (**1a**) were prepared as previously reported.[8f,y]

In situ photolysis

Compound **2a** (5 mg, 0.015 mmol) was dissolved in dry and degassed $CDCl_3$ (0.5 mL) and added to a Youngs type NMR tube (prepared in a dry-box; O_2 <0.1 ppm). The sample was then photolysed and ^{1}H NMR spectra obtained approximately every 10 minutes. This was conducted using a modified NMR probe equipped for *in situ* photolysis, for which a general method has been described previously.[28] A Kimmon IK3202R-D 325 nm He–Cd 27 mW continuous wave (CW) laser was used as the light source.

General method for the preparation of 1b and 1c using Sonogashira cross-coupling

To a degassed Schlenk flask, 4-bromo-6-methyl-2-pyrone (1 eq.), arylacetylene (1.1 eq.), $PdCl_2(PPh_3)_2$ (1 mol%), CuI (3 mol%), dry acetonitrile (1.5 mL/mmol) and dry triethylamine (1.5 eq.) were added and the reaction heated at 60 °C for 16 h. The reaction mixture was cooled, washed with H_2O, extracted with CH_2Cl_2, dried over $MgSO_4$ and filtered. The solvent was removed *in vacuo* and the crude material subjected to chromatography on silica-gel using an EtOAc/hexane eluent (0/1 to 1/5, *v*/*v*) to give the products (characterisation data given below).

4-(4-Chlorophenylethynyl)-6-methyl-2-pyrone (1b)

Synthesised following the general Sonogashira procedure, with 4-bromo-6-methyl-2-pyrone (504 mg, 2.7 mmol) and 1-ethynyl-4-chlorobenzene (400 mg, 2.9 mmol), to afford the *title compound* as a yellow solid (495 mg, 76%); M.p. = 134–136 °C; δ_H (400 MHz, $CDCl_3$) 2.25 (3H, dd, J = 0.7, 0.9 Hz), 6.03 (1H, dq, J = 0.9,

1.4 Hz), 6.28 (1H, dq, J = 0.7, 1.4 Hz), 7.36 (2H, d, J = 8.7 Hz), 7.45 (2H, d, J = 8.7 Hz); δ_C (100.5 MHz, $CDCl_3$) 19.9 (CH_3), 86.2 (4°), 97.2 (4°), 105.2 (CH), 114.6 (CH), 119.7 (4°), 129.0 (CH), 133.3 (CH), 136.2 (4°), 138.5 (4°), 162.07 (4°), 162.10 (4°); ν_{max} (CH_2Cl_2, cm^{-1}) 2211, 1744, 1726, 1636, 1540, 1441, 1316, 1094, 1015; LR(ESI-MS): m/z 245/247 (Cl^{35}/Cl^{37} MH^+, 9%), 267/269 (Cl^{35}/Cl^{37} MNa^+, 100); HR(ESI-MS): m/z calcd for $C_{14}H_9ClNaO_2$ [M + Na]$^+$: 267.0183, found 267.0182 (0.6 ppm).

4-(4-Methoxyphenylethynyl)-6-methyl-2-pyrone (1c)

Synthesised following the general Sonogashira procedure, with 4-bromo-6-methyl-2-pyrone (325 mg, 1.7 mmol) and 1-ethynyl-4-methoxybenzene (250 mg, 1.9 mmol), to afford the *title compound* as a cream solid (376 mg, 91%); M.p. = 125–128 °C; δ_H (400 MHz, $CDCl_3$) 2.23–2.25 (3H, m), 3.84 (3H, s), 6.02–6.03 (1H, m), 6.24–6.25 (1H, m), 6.89 (2H, d, J = 8.9 Hz), 7.46 (2H, d, J = 8.9 Hz); δ_C (100.5 MHz, $CDCl_3$) 19.8 (CH_3), 55.4 (CH_3), 84.7 (4°), 99.4 (4°), 105.5 (CH), 113.2 (4°), 113.6 (CH), 114.3 (CH), 133.9 (CH), 139.3 (4°), 160.9 (4°), 161.7 (4°), 162.4 (4°); ν_{max} (CH_2Cl_2, cm^{-1}) 2204, 1725, 1637, 1605, 1539, 1509, 1444, 1317, 1295, 1212, 1174, 1139, 1110, 1030; LR(ESI-MS): m/z 241 (MH^+, 100%); HR(ESI-MS): m/z calcd for $C_{15}H_{13}O_3$ [M + H]$^+$: 241.0859, found 241.0863 (1.4 ppm).

General method for the Pauson–Khand reactions of 1a–c

(Based on **1a**.) To a microwave tube containing **1a** (105 mg, 0.5 mmol) was added $Co_2(CO)_8$ (171 mg, 0.5 mmol) and DCE (2 mL). The mixture was stirred at room temperature for 1 h. Norbornene (235 mg, 2.5 mmol) was added and the reaction heated in the microwave (100 W) at 90 °C for between 60 and 80 min (loss of the intermediate alkynyl–$Co_2(CO)_6$ complex was monitored by TLC analysis). On completion of the reaction, the solvent was removed *in vacuo* and the crude material subjected to column chromatography on silica-gel using an EtOAc/hexane eluent (1/99 to 1/5, v/v) to give the two regioisomeric products **2a** (117 mg, 70%) and **2a′** (33 mg, 19%) as white solids.

(3a*SR*,4*RS*,7*SR*,7a*RS*)-6-Methyl-4-(1-oxo-2-phenyl-3a,4,5,6,7,7a-hexahydro-1*H*-4,7-methanoinden-3-yl)-2*H*-pyran-2-one (2a)

M.p. = 117–120 °C (decomposes); δ_H (500 MHz, $CDCl_3$) 1.08 (1H, d, J = 10.8 Hz), 1.13 (1H, d, J = 10.8 Hz), 1.37–1.42 (2H, m), 1.63–1.74 (2H, m), 2.10 (3H, dd, J = 0.8, 0.8 Hz), 2.20 (1H, m), 2.49 (1H, d, J = 5.5 Hz), 2.60 (1H, m), 2.99 (1H, d, J = 5.5 Hz), 5.60 (1H, br s), 6.22 (1H, br s), 7.20–7.22 (2H, m), 7.34–7.36 (3H, m); δ_H (500 MHz, C_6D_6) 0.68–1.42 (6H, m), 1.61 (3H, br s), 1.84 (1H, br s), 2.09 (1H, br s), 2.34 (1H, br s), 2.56 (1H, br s), 5.18 (1H, br s), 6.17 (1H, br s), 7.01–7.52 (5H, m); δ_C (125 MHz, $CDCl_3$) 20.0 (CH_3), 28.5 (CH_2), 28.9 (CH_2), 31.6 (CH_2), 38.1 (CH), 39.6 (CH), 50.0 (CH), 53.9 (CH), 103.4 (CH), 111.4 (CH), 128.5 (CH), 128.9 (CH), 129.0 (CH), 130.3 (4°), 146.1 (4°), 151.3 (4°), 162.1 (4°), 162.5 (4°), 163.4 (4°), 207.6 (4°); ν_{max} (CH_2Cl_2, cm^{-1}) 2961, 1722, 1700, 1637, 1541, 1445, 1308; LR(ESI-MS): m/z 333 (MH^+, 100%), 355 (MNa^+, 13); HR(ESI-MS): m/z calcd for $C_{22}H_{21}O_3$ [M + H]$^+$: 333.1485, found 333.1496 (3.3 ppm).

(3a*SR*,4*RS*,7*SR*,7a*RS*)-6-Methyl-4-(1-oxo-3-phenyl-3a,4,5,6,7,7a-hexahydro-1*H*-4,7-methanoinden-2-yl)-2*H*-pyran-2-one (2a′)

M.p. = 149–152 °C; δ_H (500 MHz, $CDCl_3$) 1.03 (1H, d, J = 10.7 Hz), 1.11 (1H, d, J = 10.7 Hz), 1.38–1.42 (2H, m), 1.64–1.68 (2H, m), 2.09 (1H, m), 2.16 (3H, dd, J = 0.7, 0.9 Hz), 2.50 (1H, d, J = 5.5 Hz), 2.58 (1H, m), 3.20 (1H, d, J = 5.5 Hz), 5.75 (1H, dq, J = 0.9, 1.4 Hz), 6.08 (1H, dq, J = 0.7, 1.4 Hz), 7.34–7.44 (m, 5H; Ph); δ_C (100.5 MHz, $CDCl_3$) 20.0 (CH_3), 28.6 (CH_2), 28.9 (CH_2), 31.6 (CH_2), 38.4 (CH), 39.6 (CH), 51.4 (CH), 54.3 (CH), 104.7 (CH), 112.5 (CH), 128.3 (CH), 128.9 (CH), 130.7 (CH), 133.9 (4°), 138.3 (4°), 148.4 (4°), 161.8 (4°), 162.9 (4°), 174.2 (4°), 206.4 (4°); ν_{max} (CH_2Cl_2, cm^{-1}) 2964, 2877, 1720, 1698, 1639, 1607, 1548, 1445; LR(ESI-MS): m/z 291 ($MH_2 - CO_2^+$, 8%), 333 (MH^+, 100), 355 (MNa^+, 13); HR(ESI-MS): m/z calcd for $C_{22}H_{21}O_3$ [M + H]$^+$: 333.1485, found 333.1495 (3.0 ppm).

Other characterisation data (from reactions using 0.5 mmol of either **1b** or **1c**):

(3a*SR*,4*RS*,7*SR*,7a*RS*)-4-[2-(4-Chlorophenyl)-1-oxo-3a,4,5,6,7,7a-hexahydro-1*H*-4,7-methanoinden-3-yl]-6-methyl-2*H*-pyran-2-one (2b)

Cream solid (122 mg, 67%); M.p. = 194–199 °C (decomposes); δ_H (500 MHz, $CDCl_3$) 1.09 (2H, s), 1.36–1.41 (2H, m), 1.61–1.76 (2H, m), 2.15 (3H, s), 2.21 (1H, m), 2.48 (1H, d, J = 5.5 Hz), 2.59 (1H, m), 2.98 (1H, d, J = 5.5 Hz), 5.62 (1H, s), 6.20 (1H, s), 7.18 (2H, d, J = 8.5 Hz), 7.33 (2H, d, J = 8.5 Hz); δ_C (125 MHz, $CDCl_3$) 20.1 (CH_3), 28.5 (CH_2), 28.8 (CH_2), 31.6 (CH_2), 38.0 (CH), 39.6 (CH), 50.2 (CH), 53.9 (CH), 103.1 (CH), 111.4 (CH), 128.5 (4°), 128.8 (CH), 130.4 (CH), 135.1 (4°), 144.6 (4°), 151.1 (4°), 162.3 (4°), 162.6 (4°), 164.0 (4°), 207.3 (4°); ν_{max} (CH_2Cl_2, cm^{-1}) 2964, 2876, 1725, 1702, 1638, 1543, 1490, 1311, 1298, 1230, 1198, 1091, 1016; LR(ESI-MS): m/z 367 (MH^+, 100%); HR(ESI-MS): m/z calcd for $C_{22}H_{20}ClO_3$ [M + H]$^+$: 367.1095, found 367.1088 (1.9 ppm).

(3a*SR*,4*RS*,7*SR*,7a*RS*)-4-[3-(4-Chlorophenyl)-1-oxo-3a,4,5,6,7,7a-hexahydro-1*H*-4,7-methanoinden-2-yl]-6-methyl-2*H*-pyran-2-one (2b′)

White solid (42 mg, 23%); M.p. = 144–147 °C (decomposes); δ_H (500 MHz, $CDCl_3$) 1.07 (1H, d, J = 10.7 Hz), 1.09 (1H, d, J = 10.7 Hz), 1.37–1.42 (2H, m), 1.63–1.71 (2H, m), 2.08 (1H, m), 2.18 (3H, s), 2.50 (1H, d, J = 5.5 Hz), 2.59 (1H, m), 3.16 (1H, d, J = 5.5 Hz), 5.73 (1H, s), 6.07 (1H, s), 7.31 (2H, d, J = 8.5 Hz), 7.39 (2H, d, J = 8.5 Hz); δ_C (125 MHz, $CDCl_3$) 20.1 (CH_3), 28.6 (CH_2), 28.9 (CH_2), 31.7 (CH_2), 38.5 (CH), 39.7 (CH), 51.3 (CH), 54.3 (CH), 104.4 (CH), 112.6 (CH), 129.3 (CH), 129.6 (CH), 132.2 (4°), 137.0 (4°), 138.7 (4°), 148.0 (4°), 162.2 (4°), 162.6 (4°), 172.2 (4°), 206.0 (4°); ν_{max} (CH_2Cl_2, cm^{-1}) 2964, 2877, 1721, 1698, 1639, 1610, 1592, 1547, 1491, 1402, 1332, 1095; LR(ESI-MS): m/z 367 (MH^+, 100%); HR(ESI-MS): m/z calcd for $C_{22}H_{20}ClO_3$ [M + H]$^+$: 367.1095, found 367.1092 (0.8 ppm).

(3a*SR*,4*RS*,7*SR*,7a*RS*)-4-[2-(4-Methoxyphenyl)-1-oxo-3a,4,5,6,7,7a-hexahydro-1*H*-4,7-methanoinden-3-yl]-6-methyl-2*H*-pyran-2-one (2c)

Yellow solid (110 mg, 65%); M.p. = 97–101 °C (decomposes); δ_H (500 MHz, $CDCl_3$) 1.06 (1H, d, J = 10.7 Hz), 1.10 (1H, d, J = 10.7 Hz), 1.34–1.41 (2H, m), 1.61–1.74 (2H, m), 2.12 (3H, s), 2.20 (1H, m), 2.46 (1H, d, J = 5.5 Hz), 2.59 (1H, m), 2.95 (1H, d, J = 5.5 Hz), 3.81 (3H, s), 5.65 (1H, s), 6.23 (1H, s), 6.87 (2H, d, J = 1.9, 8.8 Hz), 7.18 (2H, dd, J = 1.9, 8.8 Hz); δ_C (125 MHz, $CDCl_3$) 20.0 (CH_3), 28.6 (CH_2), 28.9 (CH_2), 31.6 (CH_2), 38.1 (CH), 39.6 (CH), 49.9 (CH), 53.9 (CH), 55.3 (CH_3), 103.5 (CH), 111.3 (CH), 114.0 (CH), 122.4 (4°), 130.5 (CH), 145.3 (4°), 151.7 (4°), 160.1 (4°), 162.1 (4°), 162.1 (4°), 162.6 (4°), 208.0 (4°); ν_{max} (CH_2Cl_2, cm^{-1}) 2962, 2876, 2840, 1719, 1700, 1637, 1605, 1543, 1510, 1198, 1177, 1159, 1033; LR(ESI-MS): m/z 363 (MH^+, 100%); HR(ESI-MS): m/z calcd for $C_{23}H_{23}O_4$ $[M + H]^+$: 363.1591, found 363.1601 (2.7 ppm).

(3a*SR*,4*RS*,7*SR*,7a*RS*)-4-[3-(4-Methoxyphenyl)-1-oxo-3a,4,5,6,7,7a-hexahydro-1*H*-4,7-methanoinden-2-yl]-6-methyl-2*H*-pyran-2-one (2c′)

Yellow solid (31 mg, 17%); M.p. = 172–174 °C (decomposes); δ_H (500 MHz, $CDCl_3$) 1.01 (1H, d, J = 10.7 Hz), 1.09 (1H, d, J = 10.7 Hz), 1.37–1.44 (2H, m), 1.65–1.68 (2H, m), 2.12 (1H, m), 2.17 (3H, s), 2.48 (1H, d, J = 5.5 Hz), 2.57 (1H, m), 3.18 (1H, d, J = 5.5 Hz), 3.85 (3H, s), 5.76 (1H, br s), 6.13 (1H, br s), 6.91 (2H, dd, J = 1.9, 8.7 Hz), 7.37 (2H, dd, J = 1.9, 8.7 Hz); δ_C (125 MHz, $CDCl_3$) 20.0 (CH_3), 28.7 (CH_2), 29.0 (CH_2), 31.7 (CH_2), 38.9 (CH), 39.5 (CH), 50.9 (CH), 54.3 (CH), 55.4 (CH_3), 104.8 (CH), 112.5 (CH), 114.3 (CH), 125.9 (4°), 130.5 (CH), 136.7 (4°), 149.1 (4°), 161.8 (4°), 161.9 (4°), 162.9 (4°), 173.1 (4°), 206.1 (4°); ν_{max} (CH_2Cl_2, cm^{-1}) 2963, 2877, 1720, 1694, 1511, 1404, 1336, 1160, 1031; LR(ESI-MS): m/z 363 (MH^+, 100%); HR(ESI-MS): m/z calcd for $C_{23}H_{23}O_4$ $[M + H]^+$: 363.1591, found 363.1601 (2.7 ppm).

General procedure for electrocyclisation–oxidative aromatisation (NMR studies)

In a clean, dry NMR tube, **2a** (10 mg, 0.03 mmol) was dissolved in $CDCl_3$ (0.4 mL) under an atmosphere of air. Alternatively, the sample was dissolved in C_6D_6 (0.4 mL) and I_2 (1 eq.) was added. The tube was then placed in front of a 400 nm filter and the mixture photolysed, with ^1H NMR spectra recorded at 10, 20, 60 180 and 360 minute intervals, until the complete disappearance of **2a** was observed.

The comparison of the relative rates of electrocyclisation–aromatisation for **2a–c** were conducted in a similar manner to that detailed above except in sunlight for 1 h. Conversion to products **4a–c** was determined by ^1H NMR spectroscopy (samples protected from light after 1 h, prior to NMR spectroscopic analysis).

(9a*RS*,10*SR*,13*RS*,13a*SR*)-2-Methyl-4,9,9a,10,11,12,13,13a-octahydro-10,13-methanobenzo[*h*]indeno[1,2-*f*]isochromene-4,9-dione (4a)

M.p. = 225–229 °C; δ_H (500 MHz, $CDCl_3$) 0.88 (1H, d, J = 10.8 Hz), 1.01 (1H, d, J = 10.8 Hz), 1.45–1.64 (2H, m), 1.68–1.85 (2H, m), 2.46 (3H, s), 2.54 (1H, m), 2.65–2.75 (2H, m), 3.27 (1H, m), 6.64 (1H, s), 7.69–7.79 (2H, m), 9.30 (1H, d, J = 7.6 Hz), 9.70 (1H, d, J = 8.1 Hz); δ_H (500 MHz, C_6D_6) 0.57 (1H, d, J = 10.8 Hz), 0.65 (1H, d, J = 10.8 Hz), 1.06–1.16 (2H, m), 1.30–1.44 (2H, m), 1.75 (3H, s), 2.09 (1H, m), 2.32 (1H, d, J = 5.7 Hz), 2.58 (1H, d, J = 5.7 Hz), 2.62 (1H, m), 5.98 (1H, s), 7.43 (1H, m), 7.51 (1H, m), 9.71 (1H, d, J = 8.2 Hz), 10.15 (1H, d, J = 8.7 Hz); δ_C (100.5 MHz, $CDCl_3$) 20.0 (CH_3), 28.4 (CH_2), 29.4 (CH_2), 32.0 (CH_2), 39.8 (CH), 40.3 (CH), 46.2 (CH), 56.5 (CH), 100.5 (CH), 117.3 (4°), 124.2 (CH), 126.5 (CH), 127.7 (4°), 128.6 (CH), 129.3 (CH), 131.2 (4°), 137.2 (4°), 137.9 (4°), 153.7 (4°), 157.7 (4°), 161.6 (4°), 209.1 (4°); ν_{max} (CH_2Cl_2, cm^{-1}) 2963, 2876, 1724, 1701, 1655, 1612, 1592, 1560, 1509, 1443, 1385, 1351, 1229; LR(CI-MS): m/z 331 (MH^+, 100%); HR(CI-MS): m/z calcd for $C_{22}H_{19}O_3$ $[M + H]^+$: 331.13342, found 331.13254 (2.6 ppm).

(9a*RS*,10*SR*,13*RS*,13a*SR*)-6-Chloro-2-methyl-4,9,9a,10,11,12,13,13a-octahydro-10,13-methanobenzo[*h*]indeno[1,2-*f*]isochromene-4,9-dione (4b)

M.p. = 186–187 °C (decomposes); δ_H (400 MHz, $CDCl_3$) 0.84 (1H, d, J = 10.9 Hz), 1.03 (1H, d, J = 10.9 Hz), 1.49 (1H, m), 1.62 (1H, m), 1.74 (1H, m), 1.84 (1H, m), 2.47 (3H, d, J = 0.9 Hz), 2.55 (1H, m), 2.70–2.74 (2H, m), 3.28 (1H, d, J = 5.8 Hz), 6.65 (1H, m), 7.66 (1H, dd, J = 2.2, 9.0 Hz), 9.24 (1H, d, J = 9.0 Hz), 9.76 (1H, d, J = 2.2 Hz); δ_C (100.5 MHz, $CDCl_3$) 22.6 (CH_3), 28.4 (CH_2), 29.4 (CH_2), 32.1 (CH_2), 39.8 (CH), 40.4 (CH), 46.2 (CH), 56.5 (CH), 100.5 (CH), 116.4 (4°), 125.6 (CH), 125.8 (CH), 126.0 (4°), 129.2 (CH), 132.1 (4°), 136.0 (4°), 137.8 (4°), 138.1 (4°), 153.7 (4°), 158.5 (4°), 161.3 (4°), 208.8 (4°); ν_{max} (CH_2Cl_2, cm^{-1}) 2963, 2929, 2877, 1723, 1701, 1653, 1608, 1503, 1363, 1346, 1156, 1197; LR(ESI-MS): m/z 365 (MH^+, 100%), 387 (MNa^+, 10); HR(ESI-MS): m/z calcd for $C_{22}H_{18}O_3$ $[M + H]^+$: 365.0939, found 365.0938 (0.3 ppm).

(9a*RS*,10*SR*,13*RS*,13a*SR*)-6-Methoxy-2-methyl-4,9,9a,10,11,12,13,13a-octahydro-10,13-methanobenzo[*h*]indeno[1,2-*f*]isochromene-4,9-dione (4c)

M.p. = 173–177 °C (decomposes); δ_H (400 MHz, $CDCl_3$) 0.85 (1H, d, J = 10.8 Hz), 1.00 (1H, d, J = 10.8 Hz), 1.48 (1H, m), 1.59 (1H, m), 1.72 (1H, m), 1.82 (1H, m), 2.46 (3H, d, J = 0.9 Hz), 2.54 (1H, m), 2.68 (1H, d, J = 5.7 Hz), 2.71 (1H, m), 3.26 (1H, d, J = 5.7 Hz), 4.02 (3H, s), 6.63 (1H, q, J = 1.0 Hz), 7.35 (1H, dd, J = 2.7, 9.2), 9.20 (1H, d, J = 9.2 Hz), 9.21 (1H, d, J = 2.7 Hz); δ_C (100.5 MHz, $CDCl_3$) 20.0 (CH_3), 28.4 (CH_2), 29.3 (CH_2), 32.1 (CH_2), 39.8 (CH), 40.3 (CH), 46.0 (CH), 55.5 (CH_3), 56.6 (CH), 100.7 (CH), 106.3 (CH), 116.3 (4°), 120.0 (CH), 122.8 (4°), 125.5 (CH), 133.4 (4°), 137.7 (4°), 137.8 (4°), 150.6 (4°), 157.5 (4°), 160.4 (4°), 162.0 (4°), 209.3 (4°); ν_{max} (CH_2Cl_2, cm^{-1}) 2963, 2876, 1716, 1699, 1657, 1615, 1596, 1516, 1466, 1353, 1236, 1204, 1116, 1082, 1033, 1003; LR(ESI-MS): m/z 361 (MH^+, 100%), 383 (MNa^+, 15); HR(ESI-MS): m/z calcd for $C_{23}H_{21}O_4$ $[M + H]^+$: 361.1434, found 361.1438 (1.0 ppm).

6-Methyl-4-(1,2,2-triphenylvinyl)-2-pyrone (5)

1a (106 mg, 0.5 mmol), iodobenzene (0.112 mL, 1 mmol), phenylboronic acid (184 mg, 1.5 mmol), sodium hydrogen carbonate (84 mg, 1 mmol), DMF (15 mL) and H_2O (4 mL) were added to a degassed Schlenk flask and stirred at 100 °C for 10 min.

$PdCl_2(MeCN)_2$ (2 mg, 0.005 mmol) in DMF (1 mL) was then injected into the mixture and the reaction was stirred for a further 24 h at 100 °C. The reaction mixture was cooled, quenched with saturated NaCl solution (30 mL) and the aqueous layer was extracted CH_2Cl_2 (3 × 10 mL). The combined organic layers were dried over anhydrous $MgSO_4$, filtered and the solvent removed *in vacuo.* Isolation of the product by chromatography on a silica-gel column using pet. ether/EtOAc as eluent (95/5, *v*/*v*) gave the *title compound* (142 mg, 78%) as a yellow solid; M.p. = 235–238 °C; δ_H (400 MHz, $CDCl_3$) 2.05 (3H, dd, $J = 0.7$, 0.9 Hz), 5.59 (1H, dq, $J = 0.9$, 1.5 Hz), 5.83 (1H, dq, $J = 0.7$, 1.5 Hz), 6.93–6.96 (2H, m), 7.01–7.04 (2H, m), 7.07–7.17 (8H, m), 7.23–7.27 (3H, m); δ_C (400 MHz, $CDCl_3$) 19.8 (CH_3), 106.2 (CH), 113.9 (CH), 127.4 (CH), 127.7 (CH), 128.1 (CH), 128.2 (CH), 128.3 (CH), 130.5 (CH), 131.0 (CH), 131.1 (CH), 136.6 (4°), 140.5 (4°), 141.96 (4°), 141.98 (4°), 153.3 (4°), 159.4 (4°), 160.5 (4°), 163.4 (4°)—one CH signal not observed; ν_{max} (CH_2Cl_2, cm^{-1}) 1709, 1634, 1548, 1493, 1445, 1383, 1314, 1097, 1076, 1029; LR(ESI-MS): *m*/*z* 365 (MH^+, 100%); HR(ESI-MS): *m*/*z* calcd for $C_{26}H_{21}O_2$ $[M + H]^+$: 365.1536, found 365.1541 (1.0 ppm).

Electrocyclisation–oxidative aromatisation of 6-methyl-4-(1,2,2-triphenylvinyl)-2-pyrone (5)

In a clean, dry NMR tube, **5** (15 mg, 0.04 mmol) was dissolved in $CDCl_3$ (0.4 mL) under an atmosphere of air. The tube was then placed in front of a 400 nm filter and the mixture photolysed for 20 h. Selected ^1H NMR spectroscopic data, including discussion, is provided in the ESI.†

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