

## Sunlight-induced Regio- and Stereo-specific ( $2\pi + 2\pi$ ) Cycloaddition of Arylethenes to 2-Substituted-1,4-naphthoquinones†

Christopher Covell,<sup>a</sup> Andrew Gilbert<sup>\*a</sup> and Christoph Richter<sup>b</sup>

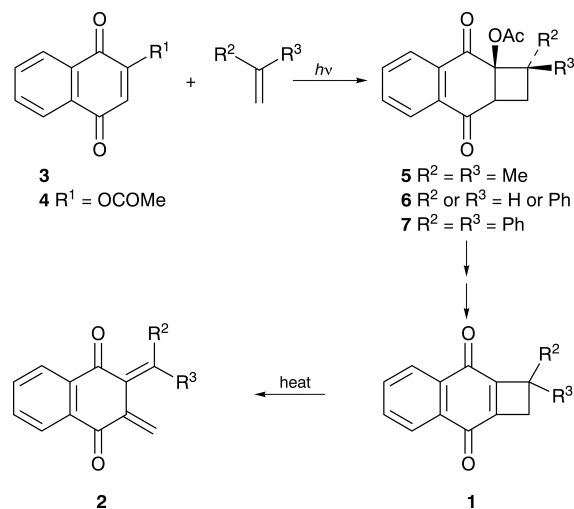
<sup>a</sup>Department of Chemistry, The University of Reading, Whiteknights, P.O. Box 224, Reading, Berkshire RG6 6AD, UK

<sup>b</sup>Plataforma Solar de Almería, 04200 Tabernas, Almería, Spain

2-Acetoxy-1,4-naphthoquinone undergoes photochemical regio- and stereo-specific ( $2\pi + 2\pi$ ) addition to styrene and 1,1-diphenylethene in high yield, whereas the stilbenes yield mainly spirooxetanes: the cyclobutane formation occurs essentially quantitatively in sunlight.

Our recent interest in the photochemistry of 1,4-naphthoquinone has been to elucidate the features which may control the site of addition of ethenes to give spirooxetanes and cyclobutane derivatives.<sup>1</sup> Although there is some indication for alkenes that the ease of electron transfer to the quinone is an important aspect, for other ethenes structural effects appear to control the site of reaction but not in a wholly predictable manner. The cyclobutane formation could, however, provide a versatile and convenient access to cyclobutene quinones **1**, the ring-opened isomer **2** of which has potential in anthracyclinone and pyranoquinone synthesis. 1,4-Naphthoquinones **3** with an electron-donor substituent at the 2-position appeared to be suitable for this purpose as formation of the cyclobutane adduct would be favoured over the spirooxetane process because of the increase in the energy of the quinone  $^3n\pi^*$  state<sup>2</sup> and, furthermore, conversion into the cyclobutene moiety may be facilitated. However, the 2-hydroxy-, 2-amino-, and 2-thio-1,4-naphthoquinones undergo ( $3 + 2$ ) photocycloaddition to ethenes thereby giving a useful entry to naphtho[2,3-*b*]furan,<sup>3</sup> benz[*f*]indole,<sup>4</sup> and naphtho[2,3-*b*]thiophene<sup>5</sup> derivatives respectively; and cyclobutane adducts from 2-methoxy-1,4-naphthoquinone yield hydroxyoxetanes from a secondary photochemical process.<sup>6</sup> Furthermore, 2-halogeno-1,4-naphthoquinones undergo non-selective addition with the ethenes of interest in the present study.<sup>7</sup> Our studies to develop a realistic route to cyclobutene quinones have thus focused on the photochemistry of protected 2-hydroxy- and 2-amino-quinones and the recent account by Suginome *et al.*<sup>8</sup> of the photoaddition of 2-acetoxy-1,4-naphthoquinone **4** to 2-methylpropene in benzene solution to give the head-to-head adduct **5** in 41% yield using a Pyrex-filtered high-pressure mercury arc lamp prompts us to report our findings with these systems. The projected application of the cyclobutene quinones from this study necessitated the use of arylenes as the photochemical addends to the quinones, and the facile high-yield access to the required cyclobutanes is illustrated here by the additions of styrene and of 1,1-diphenylethene to the 2-acetoxy derivative (Scheme 1).

The initial studies used Pyrex-filtered radiation from a (medium-pressure mercury arc) on methanol or acetonitrile solutions of the addends. Preliminary spectroscopic analysis of the crude material showed that only the head-to-head isomers **6** and **7** were formed from styrene and 1,1-diphenylethene respectively. Although the crude yields of these photoadducts were in excess of 80%, the need to remove minor impurities by flash chromatography reduced the



Scheme 1

isolated yields to approximately 50%. Detailed NMR spectral data of the adduct from **4** and styrene allowed the *exp* structure **6** (R<sup>2</sup> = H, R<sup>3</sup> = Ph) to be assigned. The head-to-head regiospecificity of the adducts is expected from formation of the most stable intermediate 1,4-diradical but the observed stereospecificity is not common for quinone additions. For example, both the *exo* and *endo* cyclobutane isomers are formed from styrene and 1,4-naphthoquinone.<sup>1</sup> In contrast to the reaction-mode specificity for cyclobutane formation with both styrene and 1,1-diphenylethene, both *cis* and *trans* stilbenes gave exclusively spirooxetanes with 2-acetoxy-1,4-naphthoquinone from attack at the 4-carbonyl group and in each case one stereoisomer predominated (>80%). Again, this contrasts with the parent quinone which yields both spirooxetanes and the cyclobutane isomers with the stilbenes.<sup>7</sup> Protection of 2-amino-1,4-naphthoquinone also promotes cyclobutane formation with ethenes in preference to the ( $3 + 2$ ) photoaddition reported for the parent derivative.<sup>4</sup>

The proposed route to cyclobutene quinones would only be acceptable as a realistic synthetic procedure if the photochemical step giving the cyclobutane adducts could be scaled-up and gave the product with purity suitable for the next step without the need for chromatography. In an attempt to achieve these aims and to ensure that the photochemistry would be environmentally acceptable as well as hazard-free, we investigated the sunlight-induced formation of the cyclobutanes from **4** and the arylenes at the Plataforma de Solar in Almería. The small-scale reactor at the facility allows cycling and cooling of the reactant solution (1 l) and comprises an exposed borosilicate glass tube (Duran, 1.0 m × 0.032 m o.d.) at the focal line of a

\*To receive any correspondence.

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compound parabolic collector aluminium mirror which has an optical concentration of 2. In this apparatus a greater than 96% conversion of **4** (10 g) into **6** ( $R^2 = H$ ,  $R^3 = Ph$ ) or **7** was achieved in 6 h exposure, and furthermore the adducts were obtained in a high state of purity directly by rotary evaporation of the solvent (recycled) from the reaction mixture: in particular, the minor by-products using artificial light were not evident in the high-resolution  $^1H$  NMR spectrum of the 'crude' material from solar radiation. The concentration of the quinone can be increased to 6% w/v without any adverse effects: this has the advantage of increasing the absorption cut-off of the quinone from ca. 370 to 430 nm (at absorbance 1.5) in the region of high increase in solar emission and so producing higher yields of the cyclobutane adducts from shorter exposure times. The photoaddition is also not influenced by temperature up to 60 °C so that water cooling of the solar-irradiated solutions is not essential.

The solar-induced process has thus given access to multi-gram quantities of the cyclobutane adducts in excellent yields and purities and with a minimum work-up procedure.

### Experimental

*Photochemical Methods.*—(a) *Artificial irradiation.* The photochemical source comprised a 125 W medium-pressure mercury arc inside a water-cooled Pyrex immersion well: this was placed in a Pyrex vessel containing an acetonitrile solution of the 2-substituted quinone (0.005 mol) and the aryethene (0.02 mol) under air. The reaction was monitored by HPLC (1000 × 4.6 mm, 5 μm ODS column; 20% aqueous acetonitrile eluent). The adducts were purified by flash chromatography using ICN silica 32-63 (Park Scientific Ltd.) with ethyl acetate-hexane (1:3) as eluent.

(b) *Sunlight irradiation.* The essential features of this apparatus are briefly described above. The reactions were monitored by HPLC and the adducts obtained in essentially quantitative yield and >99% purity by rotary evaporation: the adducts can be recrystallised from methanol.

*Compound 6* ( $R^2 = H$ ,  $R^3 = Ph$ ). mp 134–136 °C;  $\delta_H$  (400 MHz,  $CDCl_3$ ) 8.27 (1 H, dd,  $J$  7.32,  $J$  0.73), 8.20 (1 H, dd,  $J$  7.32, 0.73), 7.83 (2 H, dd), 7.37 (2 H, m, aryl H), 7.29 (3 H, m, aryl H), 3.97 (1 H, br overlapping dd,  $J$  9.16, 1.1), 3.62 (1 H, ddd,  $J$  12.46, 5.87, 1.1), 3.12 (1 H, ddd,  $J$  13.55, 12.46, 9.16), 2.60 (1 H, ddd,  $J$  13.55, 9.16, 5.87 Hz), 2.00 (3 H, s,  $CH_3$ );  $\delta_C$  (100 MHz,  $CDCl_3$ ) 195.77

(C=O), 191.84 (C=O), 170.37 (ester C=O), 135–135 (12 aryl C), 81.00, 49.54, 45.43, 28.02, (cyclobutane C), 20.46 ( $CH_3$ );  $\tilde{\nu}_{max}$  (Nujol)/ $cm^{-1}$  1726s, 1687s, 1683s (Found: C, 74.92; H, 5.17. Calc. for  $C_{20}H_{16}O_4$ : C, 75.04; H, 5.04%);  $m/z$  321.1129,  $[M + H]^+$  (Calc. for  $C_{20}H_{17}O_4$ : 321.1127).

*Compound 7.* mp 191–192 °C;  $\delta_H$  (400 MHz,  $CDCl_3$ ) 7.93 (1 H, dd,  $J$  7.70, 0.73), 7.80 (1 H, dd,  $J$  7.33, 1.1), 7.58 (2 H, m,  $J$  7.70, 7.32, 1.09, 0.73), 7.49 (2 H, m), 7.35 (3 H, m), 7.222 (2 H, d,  $J$  7.32), 6.98 (3 H, overlapping dd), 3.57 (1 H, dd,  $J$  10.62, 4.40), 3.51 (1 H, dd,  $J$  12.20, 4.40), 3.43 (1 H, dd,  $J$  12.20, 10.62), 2.12 (3 H, s,  $CH_3$ );  $\delta_C$  (100 MHz,  $CDCl_3$ ) 195.65, 192.34, 170.76, 134.66–126.41 (18 lines), 81.10, 58.55, 48.87, 33.79, 20.78;  $\tilde{\nu}_{max}$  (Nujol)/ $cm^{-1}$  1741s, 1695s (Found: C, 78.20; H, 5.20. Calc. for  $C_{26}H_{20}O_4$ : C, 78.79; H, 5.09%);  $m/z$  397.1447,  $[M + H]^+$  (Calc. for  $C_{26}H_{21}O_4$ : 397.1444).

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