Pergamon

Tetrahedron, Vol. 53, No. 43, pp. 14729-14736, 1997

0040-4020/97 $17.00 + 0.00

PII: S0040-4020(97)00942-3

Photocyclization of 2-Cinnamylphenols *via* Excited State Proton Transfer (ESPT) Involving the Lowest-lying Styrenic Singlet

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Abstract: The attachment of substituents to the styrenic ring of *trans*-2-cinnamylphenol produces a decrease in the singlet energy of the styrenic moiety. As a consequence, the resulting chromophore becomes responsible for the photophysical and photochemical properties of this type of bichromophoric compounds. Both fluorescence emission and photocyclization occur predominantly from the lowest-lying styrenic singlet. The result is a marked regioselectivity towards 6-membered ring products, *via* an excited state proton transfer. © 1997 Elsevier Science Ltd.

INTRODUCTION

The photochemistry of *o*-allylphenol and its derivatives has been investigated in some detail, due to the intriguing mechanistic aspects of the involved reactions.[1-8] In general, photocyclization to dihydrobenzofurans and dihydrobenzopyrans has been explained by intramolecular excited state proton transfer (ESPT);[6-8] however, alternative pathways involving excited state electron transfer (ESET) have also been suggested.[9]

We have previously dealt with *trans*-2-cinnamylphenol and some of its analogues substituted at the phenolic ring.[10,11] In the parent compound, proton transfer was again found to be the main process leading to photocyclization. On the other hand, it was assumed that the phenolic singlet is responsible for the formation of the dihydrobenzofuran, while the dihydrobenzopyran arises from the styrenic singlet.[10]

In the present work, we have undertaken a systematic investigation on the photochemical behaviour of *trans*-2-cinnamylphenols bearing substituents at the styrenic ring. As such substitution should be associated with a decreased energy of this chromophore, we expected to disclose in this way whether an enhanced

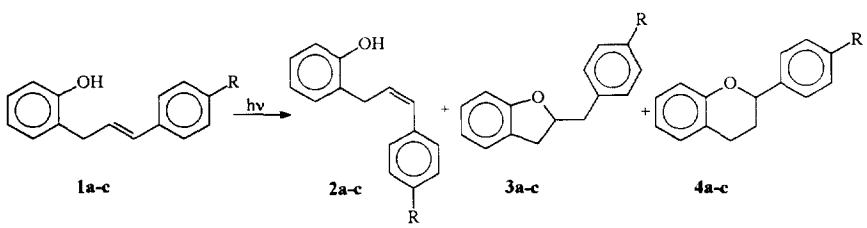
regioselectivity towards the six-membered ring compounds results from control of the photoreactivity by the lowest-lying styrenic singlet.

RESULTS AND DISCUSSION

The cinnamylphenols **1b,c** were prepared as described in the literature.[12,13] Cinnamylphenol **1a** was synthesized by reduction of the corresponding *o*-hydroxychalcone with $LiAlH_4/AlCl_3$ in tetrahydrofuran. The absorption spectra of these compounds showed their maxima below 300 nm, but irradiation using quartz-filtered light led to a high degree of polymerization. Hence, the irraditions were carried out through Pyrex. All the samples were exhaustively deoxygenated before irradiation and the solvents used were benzene (direct irradiations), acetone (triplet photosensitized irradiations) and benzene/dioxane (to check the involvement of a proton transfer mechanism). The results are summarized in Table 1.

Product studies

The photoproducts obtained were the *cis* isomers **2a-c** together with the cyclic ethers **3a-c** and **4a-c**.



1a-c **2a-c** **3a-c** **4a-c**

a: R = Ph
b: R = CH_3
c: R = OCH_3

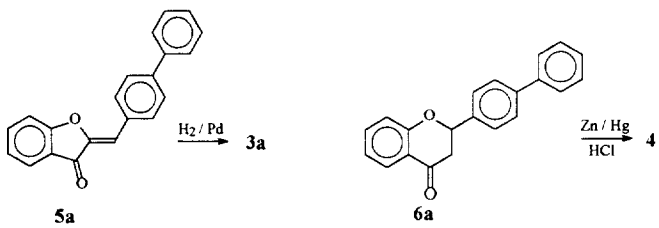
Direct irradiation of **1a** (Table 1, entry 1) yielded dihydrobenzopyran **4a** as the major product, accompanied by small amounts of the *cis* isomer **2a** and the five membered ring compound **3a**. When dioxane was added (Table 1, entry 2), the amounts of the cyclic ethers **3a** and **4a** were markedly lower. We have previously reported that in the case of the *trans*-cinnamylphenol with a methyl or a methoxy substituent (**1b, c**), the irradiation in benzene gives similar results.[13] The data are also included in Table 1 for discussion (entries 4 and 7). In the case of **1b**, addition of dioxane produced a decrease in the cyclic ethers **3b** and **4b** and a parallel increase in the yield of **2b** (Table 1, entry 5). This effect was even more significant for **1c** (Table 1, entry 8). In all cases, irradiations using acetone as solvent gave rise to the *cis* isomers as single products (Table 1, entries 3, 6 and 9).

Table 1. Photolysis of *trans*-2-Cinnamylphenols **1a-c**

Entry	Substrate	Conditions*	Conversion	Product distribution (%)		
				2	**3**	**4**
1	**1a**	A	58	13	21	64
2	**1a**	B	56	34	16	50
3	**1a**	C	45	100	-	-
4	**1b**	A	71	40	20	40
5	**1b**	B	70	69	12	19
6	**1b**	C	70	100	-	-
7	**1c**	A	51	19	22	59
8	**1c**	B	61	66	5	29
9	**1c**	C	52	100	-	-

*A: Benzene, B: Benzene/Dioxane, C: Acetone

Compounds **3b,c** and **4b,c** were known.[13] The structures of dihydrobenzofuran **3a** and dihydrobenzopyran **4a** were confirmed by alternative synthesis from known precursors: hydrogenation of the aurone **5a** or Clemmensen reduction of the chromanone **6a** respectively.



Photocyclization via the ESPT mechanism

Interchromophoric association in the ground state. It is known that *o*-allylphenols exhibit an intramolecular interaction between the phenolic OH group and the olefinic side-chain.[14-16] This has been experimentally evidenced by means of IR spectral measurements in dilute solutions and confirmed by quantum mechanical (PCILO) studies, which point tho the generality of this phenomenon and to the role of charge transfer $\pi \rightarrow XH^*$ excitation.[17] Moreover, such ground state interaction has been claimed to determine the photochemical reactivity, anticipating the stable conformation of twisted zwitterionic singlet excited states and the geometry of photoproducts.[17]In this context, GC-FTIR measurements can be specially suitable for the study of this problem, as they are performed in the gas phase and clearly exclude the possibility of intermolecular OH association. As a matter of fact, the GC-FTIR spectra of compounds **1a-c** show two bands in the OH stretching zone (Figure 1). The free OH appears at higher wavenumber, while the intramolecularly associated OH gives rise to a band at lower wavenumber values.

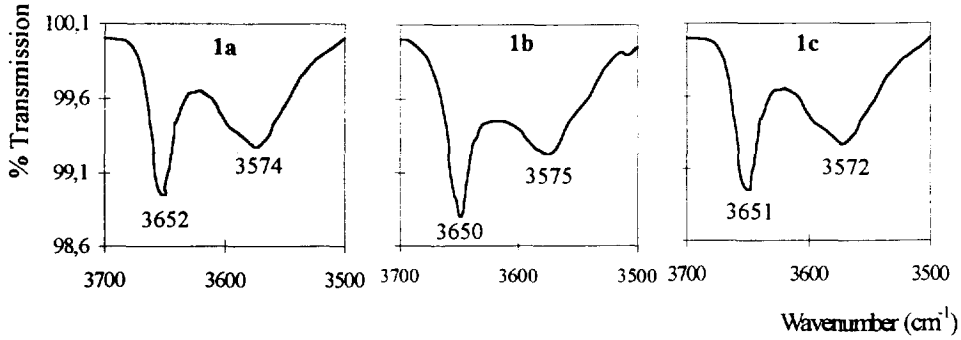


Figure 1.GC-FTIR spectra (3700-3500 cm^{-1} zone) of the *trans*-2-cinnamylphenols **1a-c**

Nature of the involved excited states. In order to obtain information about the nature of the involved singlet excited states of compounds **1a-c**, their fluorescence spectra were recorded. The results obtained at room temperature in a non polar solvent (cyclohexane) are summarized in Table 2.

Table 2. Photophysical Data of Compounds **1a-c** at Room Temperature in Cyclohexane

Compound	λ_{exc} (nm)	$\lambda_{max\ emission}$ (nm)	E_S (kcal/mol)	ϕ_F
1a	270	324-335	92	0.075
1b	260	318	97	0.026
1c	270	326	93	0.064

Taking into account the reported data on the emission maxima of 4-phenyl-, 4-methyl- and 4-methoxystyrene and phenol (333, 310, 320 and 300 nm, respectively),[18-20] the values obtained for *trans*-2-cinnamylphenols **1a-c** strongly suggest that the major contribution in the fluorescence spectra of these compounds is due to the styrenic chromophore, while participation of the phenolic chromophore is not significant. Another proof in favour of the styrenic nature of the S_1 in these compounds is provided by the fluorescence spectra of the hydrogenated derivatives (not shown), whose maxima appear close to 300 nm, a value similar to that obtained for phenol.

Interchromophoric interaction in the excited states. The fact that the only significant emission observed at room temperature was that of the styrenic chomophore, independent from the excitation wavelengths, indicates that an intramolecular energy transfer deactivates most of the phenolic singlets. On the other hand, the fluorescence quantum yields of **1a-c** (see Table 2) are much lower than that of styrene or their substituted derivatives (typically 0.4).[20] This could be attributed to intramolecular quenching of the styrenic singlet by proton transfer, which ultimately leads to photocyclization.

When the fluorescence spectra were carried out in a solid matrix of methylcyclohexane (77 K), a dramatic change in the shape and position of the bands was observed upon excitation at different wavelengths. This is illustrated for compound **1c** in Figure 2. Thus, while excitation at 260 nm results in emission from the styrenic singlet, the use of shorter excitation wavelengths (240-250 nm) produces emission spectra similar to those obtained for the parent phenol in low temperature methylcyclohexane matrix.

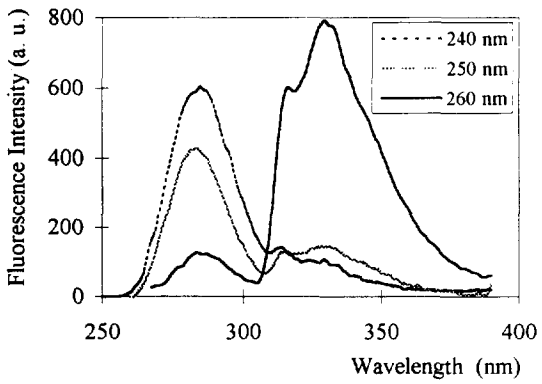


Figure 2. Fluorescence spectra of **1c** in methylcyclohexane at 77 K, using different excitation wavelengths

Quenching of photocyclization by disruption of the intramolecular OH association. The photocyclization results can be explained by intramolecular proton transfer in the excited singlet state. This agrees with the above mentioned interaction in the ground state between the phenolic OH and the styrenic double bond and with the fact that irradiation in the presence of dioxane (Table 1, entries 2, 5 and 8) produces a dramatic decrease in the yield of **3** and **4**. To ensure this point, a series of irradiations with increasing amounts of dioxane were performed in the case of compound **1c**, which showed the most efficient quenching in the preliminary experiments with this additive. The effects on the formation of photocyclization products is graphically represented in Figure 3.

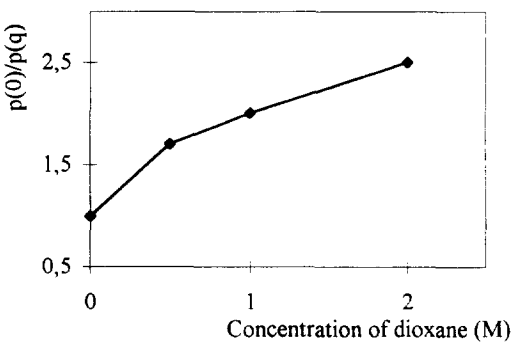


Figure 3. Influence of dioxane on the photocyclization of **1c**. The parameter p(0)/p(q) is the ratio between the percentage yields (**3c** + **4c**) in absence and presence of quencher

CONCLUSIONS

The attachment of substituents to the styrenic ring of *trans*-2-cinnamylphenol produces a decrease in the singlet energy of the styrenic moiety. As a consequence, the resulting chromophore becomes responsible for the photophysical and photochemical properties of this type of bichromophoric compounds. Both fluorescence emission an photocyclization occur predomintly from the lowest-lying styrenic singlets. The result is a marked regioselectivity towards 6-membered ring products, *via* an excited state proton transfer.

ACKNOWLEDGEMENTS

Financial support by the DGICYT (PB 94-0539) to M. A. M. and predoctoral fellowship to M. C. J. are gratefully acknowledged. We also wish to thank to Prof. J. C. Scaiano (University of Ottawa, Ottawa, Canada) for the facilities in the fluorescence measurements.

EXPERIMENTAL SECTION

General

UV spectra were recorded in cyclohexane in a Shimadzu UV-160A; λ_{max} (nm) and log ε values (in brackets) are given for each absorption band. IR spectra were obtained with a GC-FTIR Hewlett-Packard 5965; ν_{max} (cm^{-1}) is given for all the absorption bands. ^{1}H-NMR spectra were measured in $CDCl_3$ with a 300-MHz Varian Gemini-300, chemical shifts are reported in δ (ppm) values, using TMS as internal standard. Mass spectra were obtained under electron impact using a Hewlett-Packard 5988 A spectrometer; the ratios m/z and the relative intensities (%) are indicated for the significant peaks. Fluorescence spectra were recorded with a Perkin -Elmer LS50 instrument. High-resolution mass spectra were conducted on a VG Autospec instrument. Isolation and purification were done by conventional column chromatography on silica gel Merck 60 (0.063-0.200 mm) using dichloromethane as eluent, or by means of isocratic HPLC equipment provided with a semipreparative Microporasil column, using hexane/ethyl acetate as eluent.

General irradiation procedure. Solutions of 0.02 g of the substrate in 20 ml of benzene, benzene/dioxane 2M or acetone were placed into Pyrex tubes surrounding a centrally positioned quartz cooling jacket containing a 125 W medium-pressure Hg lamp and irradiated under argon for 1h. The reaction mixtures were analyzed by GC-MS and ^{1}H-NMR.

Synthesis of the substrates and the new compounds

Preparation of the substrates 1a-c. Compounds **1b,c** were prepared as described in the literature.[12,13] Compound **1a** was prepared in a similar way, by reduction of *trans*-3-(4-biphenyl)-1-(2-hydroxyphenyl)-2-propen-1-one[21] with $LiAlH_4/AlCl_3$ in tetrahydrofuran.

Alternative synthesis of compound 3a. The aurone **5a** (1 mmol) in ethyl acetate (25 ml) was hydrogenated in the presence of palladium/charcoal (11%) until consumption of 75 ml of hydrogen. The solution was filtered and on evaporation afforded the pure dihydrobenzofuran **3a** in quantitative yield.

Alternative synthesis of compound 4a. 1.3 g of zinc were added to a solution of mercuric chloride (0.2 g) in 4 ml of HCl (0.6 M). After the liquid layer was separated, 4 ml of HCl (8 M), 0.1 mmol of the chromanone **6**[21] and 2 ml of toluene were consecutively added to the remaining solid. The reaction mixture was refluxed for 3h, and then 4 ml of water were added. Extraction with ether, followed by evaporation of the solvent, gave a residue wich was purified by column chromatography. The yield was 86 %.

Synthesis of aurone 5a. 0.067 g (5 mmol) of 3-coumaranone were condensed with 0.91 g (25 mmol) of 4-phenylbenzaldehyde in acetic acid (5 ml) containing hydrochloric acid (0.4 ml). The reaction mixture was stirred for 5 h, poured into water, and filtered. Final purification was done by column chromatography. The yield was 62%.

Spectral data of the new compounds

trans-2-[3-(4-Biphenyl)-2-propenyl]phenol (1a). UV: 265 (4.4), 218 (4.2); FTIR: 3652 (OH), 3574 (OH), 3071, 3032, 1591, 1488, 1321, 1207, 1094, 1008, 966, 839, 749; ^{1}H-NMR: 3.58 (d, J = 6 Hz, 2H, CH_2), 4.98 (s, 1H, OH), 6.44 (dt, J_1 = 16 Hz, J_2 = 6 Hz, 1H, $CH_2C\underline{H}$=CH), 6.52 (d, J = 16 Hz, 1H, CH_2CH=C$\underline{H}$), 6.81 (d, 1H, 6-ArH), 6.91 (t, J = 8 Hz, 1H, 4-ArH), 7.10-7.60 (m, 11H, ArH); MS: 286, (M^+, 42), 192 (13), 191 (13), 180 (100), 167 (67), 165 (33), 152 (24), 131 (24), 107 (23), 91 (31), 77 (39); HRMS Calcd. for $C_{21}H_{18}O$: 286.1357. Found: 286.1348.

cis-2-[3-(4-Biphenyl)-2-propenyl]phenol (2a). UV: 272 (4.3), 216 (4.1); FTIR: 3650 (OH), 3594 (OH), 3070, 3029, 1593, 1487, 1322, 1255, 1206, 1008, 846, 748; ^{1}H-NMR: 3.73 (dd, J_1 = 7 Hz , J_2 = 1 Hz 2H, CH_2), 4.87 (s, 1H, OH), 5.89 (dt, J_1 = 11 Hz, J_2 = 7 Hz, 1H, $CH_2C\underline{H}$=CH), 6.69 (d, J = 12 Hz, 1H, CH_2CH=C$\underline{H}$), 6.81 (dd, 1H, J_1 = 7 Hz, 4-ArH), 6.92 (dt, 1H, , J_1 = 7 Hz , J_2 = 1 Hz, 6-ArH), 7.12-7.27 (m, 2H, 3,5-ArH); 7.36-7.64 (m+AA'BB', 9H, 2'3'5'6'-ArH+C_6H_5) MS: 286 (M^+, 45), 180(100), 179 (21), 178 (22), 167 (57), 165 (29), 131 (18), 119 (24), 91 (20), 77 (20); HRMS Calcd. for $C_{21}H_{18}O_2$: 286.1358. Found: 286.1359.

2-(4-Biphenylmethyl)-2,3-dihydrobenzofuran (3a). FTIR:3070, 3035, 1598, 1481, 1230, 983, 746; ^{1}H-NMR: 2.92 (m, 2H, CH_2), 3.19 (m, 2H, CH_2), 4.98 (m, 1H, CH), 6.72 -7.52 (m, 13H, ArH); MS: 286 (M^+, 36), 169 (10), 168 (66), 167 (28), 165 (16), 152 (10), 119 (100), 91 (43), 77 (3); HRMS Calcd. for $C_{21}H_{18}O$: 286.1358. Found: 286.1358.

2-(4-Biphenyl)-3,4-dihydro-2H-benzopyran (4a). FTIR: 3071, 3034, 2942, 2863, 1583, 1488, 1458, 1341, 1300, 1234, 1111, 1071, 1001, 927, 750; ^{1}H-NMR: 2.12 (m, 2H, $CH_2C\underline{H_2}CH$), 2.88 (m, 2H, $C\underline{H_2}CH_2CH$), 5.08 (dd, J_1 = 10 Hz, J_2 = 2 Hz, 1H, CH), 6.90 (m, 2H, 6,8-ArH), 7.10 (m , 2H, 5,7-ArH), 7.32-

7.61 (m, 9H, ArH); MS: 286 (M^+, 40), 180 (100), 178 (29), 167 (36), 165 (23), 119 (20), 91 (19), 78 (15), 77 (18); Anal.: Calcd. for $C_{21}H_{18}O$: C: 88.04 %, H: 6.34%. Found: C: 88.06 %, H: 6.29 %.

2-[(4-Biphenyl)metylen]-3(2H)benzofuranone ***(5a).*** FTIR: 3071, 3037, 2934, 1726 (C=O), 1657, 1603, 1467, 1296, 1207, 1183, 1124, 1102, 1009, 887, 755, 696. ^{1}H-NMR: 6.94 (s, 1H, =CH), 7.21 (t, J= 8 Hz, 1H, 5-ArH), 7.34 (d, J= 8 Hz, 1H, 7-ArH), 7.45-8.00 (m , 8H, ArH); MS: 298 (M^+, 85), 297 (100), 221 (53), 178 (25), 165 (15), 115 (14), 92 (5), 77 (4), 76 (12); HRMS Calcd. for $C_{21}H_{18}O$: 286.1358. Found: 286.1363.

REFERENCES

1. Horspool, W. M.; Pauson, P. L. *J. Chem. Soc., Chem. Commun* **1967**, 195-196.
2. Fráter, G.; Schmid, H. *Helv. Chim. Acta* **1967**, *50*, 255-262.
3. Kropp, P. J.; Krauss, H. J. *J. Am. Chem. Soc.* **1969**, *91*, 7466-7474.
4. Shani, A.; Mechoulam, R. *Tetrahedron* **1971**, *27*, 601-606.
5. Houri, S.; Geresh, S.; Shani, A. *Isr. J. Chem.* **1973**, *11*, 805-818.
6. Geresh, S.; Levy, O.; Markovits, Y.; Shani, A. *Tetrahedron* **1975**, *31*, 2803-2807.
7. Kitamura, T.; Imagawa, T.; Kawanisi, M. *Tetrahedron* **1978**, *34*, 3451-3457.
8. Chow, Y. L.; Zhou, X.-M.; Gaitan, T. J.; Wu, Z.-Z. *J. Am. Chem. Soc.* 1989, 111, 3813-3818.
9. Morrison, H. *Org. Photochem.* **1979**, *4*, 143-188.
10. Jiménez, M. C.; Márquez, F.; Miranda, M. A., Tormos, R. *J. Org. Chem.* **1994**, *59*, 197-202.
11. Jiménez, M. C.; Leal, P.; Miranda, M. A.; Tormos, R. *J. Org. Chem.* **1995**, *60*, 3243-3245.
12. Bokadia, M. M.; Brown, B. R.; Cobern, D.; Roberts, A.; Somerfield, G. A. *J. Chem. Soc.* **1962**, 1658-1666.
13. Delgado, J.; Espinós, A.; Jiménez, M. C.; Miranda, M. A.; Tormos,. R. *Tetrahedron* **1997**, 53, 681-688.
14. Baker, A. W.; Shulgin, A. T. *J. Chem. Soc.* **1958**, 5358-5363.
15. Oki, M.; Iwamura, H. *Bull. Chem. Soc. Jpn.* **1959**, 950-955.
16. Oki, M.; Iwamura, H. *Bull. Chem. Soc. Jpn.* **1960**, 681-685.
17. Trinquier, G.; Malrieu, J.-P. *J. Mol. Struct.* **1978**, *49*, 155-170.
18. Brede, O.; David, F.; Steenken, S. *J. Photochem. Photobiol. A: Chem.* **1996**, *97*, 127.
19. Berlman, I. B. *J. Phys. Chem.* **1970**, *52*, 5616.
20. Murov, S. L. *Handbook of Photochemistry*; Marcel Dekker, Inc.: New York, 1973.
21. Hoshino, Y.; Oohinata, T.; Takeno, N. *Bull. Chem. Soc. Jpn.* **1986**, *59*, 2351- 2352.

(*Received in UK* 17 *July* 1997; *accepted* 14 *August* 1997)