Excited-State Intramolecular Proton Transfer in *o*-Hydroxybiaryls: A New Route to Dihydroaromatic Compounds

Matthew Lukeman and Peter Wan*

Department of Chemistry, Box 3065, University of Victoria, Victoria, British Columbia, Canada V8W 3V6

Received November 17, 2002 ; E-mail: pwan@uvic.ca

Many organic molecules possess both acidic and basic functionalities that experience enhanced acidity and basicity, respectively, when the molecule undergoes electronic excitation. This simultaneous change in proton donating and accepting power is significant enough on many occasions to promote the transfer of a proton from the acidic group to the basic group, via the process known as excited-state intramolecular proton transfer (ESIPT).[1] Nearly all examples of ESIPT involve an OH or NH acid, and a heteroatomic basic group, such as an aromatic heterocyclic nitrogen or a carbonyl oxygen atom. In such cases, the proton transfer is usually facilitated by ground-state hydrogen bonding interactions between the proton donor and acceptor. Such proton transfers are reversible, with the reverse reaction often being very fast. Consequently, such systems have found extensive use as photostabilizers, and there is interest in exploiting their inherent photochromic properties for use as laser dyes and in other applications.[2]

The first examples of ESIPT to a carbon atom were reported by Yates and co-workers[3] for *o*-hydroxystyrene and *o*-hydroxyacetylene. They showed that on photolysis in water, these substrates underwent ESIPT from the phenol to the β-carbon atom to give the corresponding tautomer (an *o*-quinone methide), which was then trapped by water to give the photohydration product. More recently, we reported[4] the first examples of ESIPT from phenol to a carbon atom that is part of an aromatic ring as shown for 2-phenylphenol (**1**) in eq 1. ESIPT of **1**-*OD* led to formation of *o*-quinone methide **2**-*2′D*, which underwent reverse proton transfer to regenerate starting material with deuterium introduced at the 2′-position of the less-substituted ring to give **1**-*2′D*. This new type of ESIPT was observed in a variety of solvents, as well as in the solid state. After a preliminary investigation[4b] into the geometric requirements for this new type of ESIPT, it was concluded that only *o*-hydroxybiaryls that are twisted in the ground state are able to undergo this reaction. The twisted geometry allows overlap between the s-orbital of the acidic proton on the phenol with the accepting π-system, forming a weak ground-state hydrogen bond, which is a prerequisite for the proton transfer.
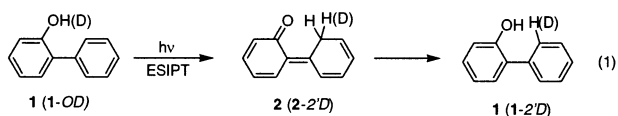
To explore whether the above ESIPT is available for other *o*-hydroxybiaryls, we considered derivatives for which a naphthyl group is the proton accepting ring. The steric bulk imposed by the naphthyl ring would ensure a highly twisted ground-state geometry, a feature apparently required for ESIPT. We prepared **3**, the simplest *o*-hydroxybiaryl containing a 1-naphthyl proton accepting ring, as well as binaphthyl derivative **4**, which is structurally similar to the extensively used chiral discriminating agent 1,1′-BINOL. We present results that demonstrate that not only does efficient ESIPT

to the 2′-carbon atom of the naphthyl ring occur for derivatives **3** and **4**, leading to deuterium exchange at this position, but ESIPT with similar efficiency also occurs to the 7′-carbon atom of the accepting naphthyl ring, bringing about a novel net ring-closing reaction, to form dihydrobenzoxanthene derivatives in high yield.

A simple H−D exchange reaction stemming from ESIPT (as observed for **1**) would not change the chromophore, and hence no changes to the absorption spectrum would be observed with photolysis. However, to our surprise, photolysis of **3** ($\sim 10^{-5}$ M, deoxygenated[5] 9:1 (v/v) CH_3CN-H_2O, $\lambda_{ex} = 300$ nm) led to dramatic changes in the absorption spectrum, indicating the formation of a product with a different chromophore (Figure 1). The absorption bands with maxima at 222 and 283 nm characteristic of **3** were converted to new bands with maxima at 215, 270, and 307 nm on photolysis. A preparatory scale photolysis[6] ($\sim 10^{-3}$ M, 9:1 (v/v) CH_3CN-H_2O, 20 min) was carried out, and the primary photoproduct[7] was chromatographically isolated (10% ether in hexane, silica gel). This product was air stable and was analyzed by NMR and MS. All data are consistent with the assignment of the photoproduct to structure **5** (yield ≈ 80%), which was readily oxidized to 1,9-benzoxanthene (**6**), by refluxing in toluene containing catalytic amounts of Pd/C (eq 2). This reaction represents a new synthetic route to benzoxanthene derivatives.
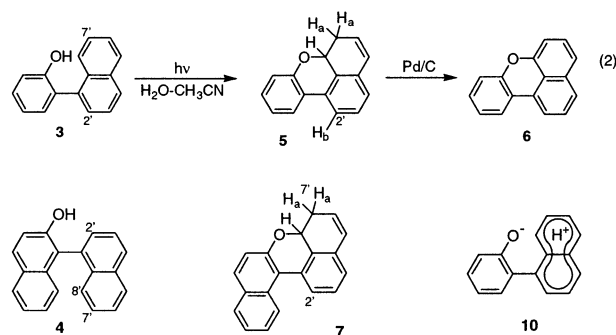
To monitor whether a deuterium exchange reaction analogous to that reported for **1** was also occurring for **3**, preparatory scale photolyses were run in which the aqueous cosolvent was replaced with D_2O, and the products were analyzed by 500 MHz ^{1}H NMR. Recovered starting material showed deuterium exchange primarily at the 2′-position of the naphthalene ring ($\Phi = 0.14 \pm 0.02$),[8] indicating that an analogous ESIPT reaction does occur. Also formed was **5**-*7′D* ($\Phi = 0.20 \pm 0.02$),[8] with one of the methylene protons (H_a) replaced with deuterium. The presence of deuterium in **5**-*7′D* strongly indicates that the cyclization reaction also proceeded from an initial ESIPT from the phenol to the naphthalene ring.

Analogue **4** behaved similarly on photolysis. UV−vis, NMR, and MS data are wholly consistent with formation of **7**. Photolysis in D_2O resulted in deuterium exchange analogous to that observed
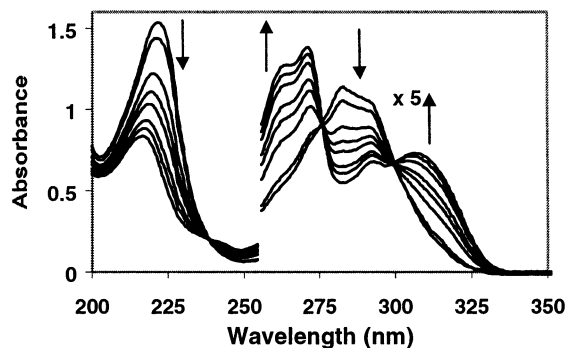
Figure 1. UV−visible spectra showing the conversion of **3** to **5** with photolysis time. Traces were recorded after 0, 0.25, 0.5, 1, 2, 3, 5, and 7 min of photolysis time in a Rayonet photoreactor fitted with 300 nm lamps (9:1 CH$_3$CN−H$_2$O, deaerated).
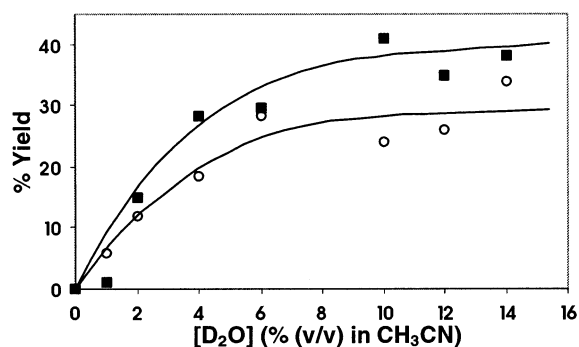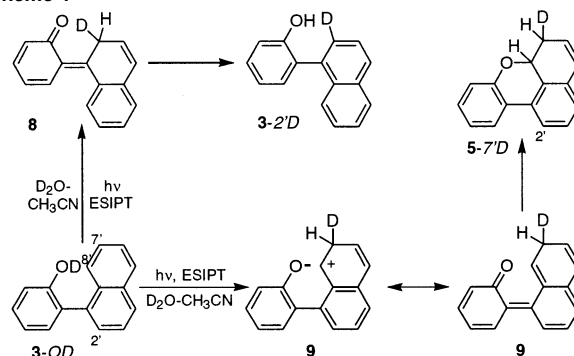

Figure 2. Plot of yield of **5**-7′D (■) and **3**-2′D (○) vs D$_2$O content (in CH$_3$CN). Samples (∼10^{-3} M in 50 mL of solvent) were irradiated in a Rayonet reactor with 16 lamps (300 nm) for 20 min. Estimated errors are ±10%.

for **3**. Recovered was starting material with deuterium incorporation at the 2′-position of the naphthalene ring ($\Phi = 0.11 \pm 0.02$)[8] and photoproduct **7** ($\Phi = 0.11 \pm 0.02$)[8] with 50% deuterium incorporation at the 7′-position (H$_a$).

In the ESIPT reaction reported for **1**, it was observed that deuterium exchange efficiency (at the 2′-position) reached a maximum at less than 1% D$_2$O content. It was concluded that the proton transfer was not mediated by water. Studying the effect of water content on reactivity of **3** (and **4**) should provide additional information on the mechanisms of cyclization versus deuterium exchange. Therefore, preparatory photolyses of **3** in varying concentrations of D$_2$O (in CH$_3$CN) were carried out. The efficiency for formation of **3**-2′D and **5**-7′D showed a similar strong dependence on water content (Figure 2). With no reaction observed in neat CH$_3$CN, the efficiency rose to a maximum at ≥10% water. The formation of **3**-2′D and **5**-7′D required much higher water content to reach maximum efficiency than **1**, suggesting that the photoproducts do not arise via an explicit ESIPT as proposed for **1**, but instead from a water-mediated ESIPT. We propose provisional mechanisms for the deuterium incorporation and the cyclization reactions observed for **3** and **4** (Scheme 1). A water-mediated ESIPT in **3**-*OD* from the phenol to the 2′-carbon atom on the appended naphthyl ring gives rise to the quinone methide intermediate **8**. Reverse proton transfer in **8** furnishes **3**-2′D. If formation of **5**-7′D were to proceed via electrocyclic ring closure of **8** (after isomerization about the exocyclic alkene), followed by a [1,7]-hydrogen shift, the 2′-position of **5**-7′D produced from **3**-*OD* should show a minimum of 50% deuterium exchange, regardless of the extent of conversion. Isolation of **5**-7′D generated in a low conversion run showed 50% deuterium exchange of the methylene protons (H$_a$), but with only residual exchange (5%) at the 2′-

position. This finding rules out **8** as being a common intermediate to both **3**-2′D and **5**-7′D. A preferred mechanism involves water-mediated ESIPT to the 7′-carbon atom, forming quinone methide **9** (Scheme 1). Ring closure gives **5**-7′D directly. This mechanism is consistent with exclusive isolation (from D$_2$O runs) of **5**-7′D in which the 7′-position is exactly 50% exchanged with deuterium.

While it is apparent from the deuterium labeling experiments that **3**-2′D and **5**-7′D do not result from the same quinone methide intermediate, the similarity in their water dependence does suggest a common intermediate prior to quinone methide formation. One such possible intermediate could result from initial water-mediated ESIPT from the phenol to the naphthyl π-system, forming the zwitterionic "protonated π-complex" **10**. Once formed, intramolecular rearrangement can lead to formation of the two possible quinone methides. While further study is required to address such mechanistic details, it is apparent from this work that the photocyclization of o-(1-naphthyl)phenols is a new reaction pathway initiated by ESIPT. It is a clean, efficient, and high-yielding route to benzoxanthenes and dihydrobenzoxanthenes, which are not readily accessible by thermal methods. Moreover, the proliferation of Pd-based aryl−aryl coupling reactions enables the synthesis of an abundant number of starting phenols and hence the ability to make a wide variety of benzoxanthene derivatives.

References

(1) (a) Ormson, S. M.; Brown, R. G. *Prog. React. Kinet.* **1994**, *19*, 45. (b) LeGourrierec, D.; Ormson, S. M.; Brown, R. G. *Prog. React. Kinet.* **1994**, *19*, 211. (c) Formosinho, S. J.; Arnaut, L. G. *J. Photochem. Photobiol., A* **1993**, *75*, 21. (d) Chou, P.-T.; Liao, J.-H.; Wei, C.-Y.; Yang, C.-Y.; Yu, W.-S.; Chou, Y.-H. *J. Am. Chem. Soc.* **2000**, *122*, 986. (e) Fischer, M.; Wan, P. *J. Am. Chem. Soc.* **1999**, *121*, 4555. (f) Chou, P.-T.; Chen, Y.-C.; Yu, W.-S.; Chou, Y.-H.; Wei, C.-Y.; Cheng, Y.-M. *J. Phys. Chem. A* **2001**, *105*, 1731.
(2) (a) Chou, P.-T.; McMorrow, D.; Aartsma, T. J.; Kasha, M. *J. Phys. Chem.* **1984**, *88*, 4596. (b) Kasha, M.; McMorrow, D.; Parthenopoulos, D. A. *J. Phys. Chem.* **1991**, *95*, 2668. (c) Kasha, M. *J. Chem. Soc., Faraday Trans. 2* **1986**, *82*, 2379. (d) Kasha, M. *Acta Phys. Pol.* **1987**, *71A*, 717.
(3) (a) Isaks, M.; Yates, K.; Kalanderopoulos, P. *J. Am. Chem. Soc.* **1984**, *106*, 2728. (b) Kalanderopoulos, P.; Yates, K. *J. Am. Chem. Soc.* **1986**, *108*, 6290.
(4) (a) Lukeman, M.; Wan, P. *J. Chem. Soc., Chem. Commun.* **2001**, 1004. (b) Lukeman, M.; Wan, P. *J. Am. Chem. Soc.* **2002**, *124*, 9458.
(5) Oxygen was removed to eliminate possible residual photooxidation.
(6) The corresponding methyl ether derivative of **3** was not reactive under similar conditions, indicating that the phenol group is required for reaction.
(7) A small amount (less than 5% of product yield) of other as yet unidentified products were formed in addition to the primary photoproduct under these conditions.
(8) Reaction quantum yields were estimated by using the deuterium exchange reaction of 2-phenylphenol (ref 4b) as a secondary reference standard. The reported values are the average of three runs.

JA029376Y