

Electrochemical and Homogeneous Proton-Coupled Electron Transfers: Concerted Pathways in the One-Electron Oxidation of a Phenol Coupled with an Intramolecular Amine-Driven Proton Transfer

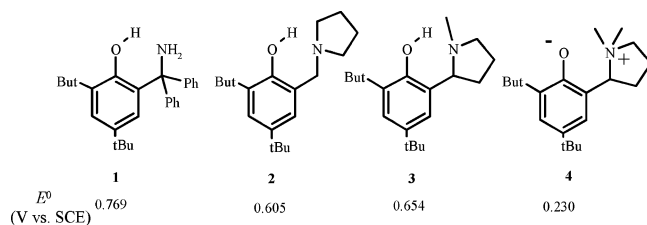
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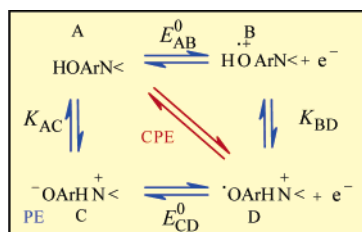
Proton-coupled electron transfers (CPET) currently attract considerable attention in view of their likely involvement in many natural processes.¹ In this connection, ortho-substituted 4,6-di(*tert*-butyl)phenols in which the phenolic hydrogen atom is H-bonded to the nitrogen atom of a nearby amine are particularly interesting mimics, such as the molecules shown in Scheme 1 and other similar compounds.²

Scheme 1



Evidence has been presented that the oxidation of **1** by a series of triarylamine cation radicals follows a concerted proton electron transfer (CPE) pathway (Scheme 2).^{2d} One would expect that

Scheme 2



electrochemical oxidation of these compounds would equally follow the same mechanism. Although reversible cyclic voltammetry (CV) has been reported in several cases,² only one mechanistic study has appeared, concluding to the occurrence of a square scheme mechanism that would involve both the EP and PE branches shown in Scheme 2.^{2c} Although this proposal has been considered as unlikely,³ no definite mechanistic conclusion has been drawn so far.

We have found that a careful analysis of the CV responses obtained with **2** and of its OD derivative allows, after estimation of the various thermodynamic parameters, a definite answer to the question. The next step was to apply the same approach to the homogeneous oxidation of **1** and check the validity of the CPE mechanism. Finally, the values of the reorganization energy and preexponential factor were compared to the theoretical estimations, leading to the proposal that the CPE reactivity is boosted by an electric field effect in the electrochemical and homogeneous reactions.

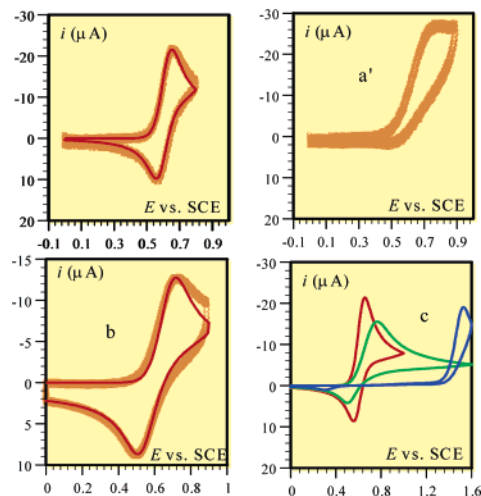


Figure 1. CV of **2** in acetonitrile + 0.1 M *n*-NBu₄PF₆. Temp: 20 °C. Scan rate: 0.2 (a, a', c), 5 V/s (b). a': after addition of 0.5 M pyridine. Red lines in a, b, and c: simulation of the CPE pathway (see text). Blue and green lines in c: simulation of the square scheme mechanism (see text), with, respectively: $\lambda = 0.7$ eV, $E_{AB}^0 = 1.59, 1.39, E_{CD}^0 = 0.23, 0.43$ V vs SCE, $K_{AC} = 3.5 \times 10^{-7}, 9.8 \times 10^{-4}, K_{BD} = 9 \times 10^{16}, 3.2 \times 10^{13}$.

At low scan rates, the CV of **2** in acetonitrile (Figure 1) shows a wave that is not completely chemically reversible, indicating that the reaction product, $\text{OArHN}^{\bullet+}$, is not completely stable within the time-scale of the experiment (Figure 1a). That this instability results from deprotonation of the cation radical is confirmed by the fact that the addition of a base such as pyridine renders the wave completely irreversible (Figure 1a'). At 0.2 V/s, the HOArN< wave corresponds to a fast electron transfer, with a standard potential $E_{AD}^0 = 0.605$ V vs SCE, followed by a slow deprotonation reaction (rate constant: 0.25 s^{-1}). At higher scan rate, chemical reversibility is restored, and the kinetics of electron transfer starts to interfere (Figure 1b). Repeating the experiment shown in Figure 1b in the presence of 2% methanol and 2% CD₃OD indicated the existence of a small but definite kinetic isotope effect ($Z_{\text{H}}/Z_{\text{D}} = 1.8$).⁴ Based on these data and on simulation of the CV response in Figure 1c, using the previously established relationships characterizing electrochemical CPE reactions,⁵ the preexponential factor, Z , and the reorganization energy, λ , are estimated to be $1300 \text{ cm}^2 \text{ s}^{-1}$ and 0.8 eV, respectively.⁴

Although the observed kinetic isotope effect is a good clue to the occurrence of a CPE reaction, it is interesting to see whether the CV data could be concurrently interpreted in terms of the square scheme mechanism involving the EP and or PE pathways shown in Scheme 2. In this purpose we need to estimate the standard potentials and equilibrium constants defined in Scheme 2, which obeys the following relationships:

$$E_{AD}^0 = E_{AB}^0 - (RT/F) \ln K_{BD} = E_{CD}^0 - (RT/F) \ln K_{AC} \quad (1)$$

As a first approximation, E_{CD}^0 can be equated with the standard potential of **4**. Comparison of this standard potential to that of the tri-*tert*-butylphenate⁶ points to a strong through-space electrostatic stabilization of the zwitterionic form. It follows from eq 1 that $K_{AC} = 3.5 \times 10^{-7}$. Similarly, E_{AB}^0 can be equated with the standard potential of tri-*tert*-butylphenol (1.59 V vs SCE).⁷ Thus, from eq 1: $K_{BD} = 9 \times 10^{16}$. Simulation⁸ of the voltammogram expected at 0.2 V/s, taking for the rate constant of intramolecular proton exchange the maximizing value of 10^{13} s^{-1} in the downhill direction⁹ (blue line in Figure 1c), is clearly incompatible with the experimental data. These estimates of the E^0 's and K 's assumed that the electrostatic and H-bonding stabilization of C is equal to the electrostatic stabilization of **4** and that H-bonding stabilization of A and B are approximately the same. Such approximations may lead to an underestimation of the contributions of the PE and EP pathways. Adding 0.2 eV, which is an average value of H-bond energy,¹⁰ to the preceding value of E_{CD}^0 and subtracting the same quantity from E_{AB}^0 provide an upper (and very optimistic) limit to the contributions of the PE and EP pathways. As seen in Figure 1c, even with these very favorable values, simulation (green line in Figure 1c) is clearly incompatible with the experimental data.

We may use the same estimated values to examine the occurrence of the PE and EP pathways in the homogeneous oxidation of **1** by a series of triarylamine cation radicals^{2d} taking into account the difference in the value of E_{AD}^0 , 0.769 V vs SCE instead of 0.605, since we have passed from compounds **2** to **1**.⁴ The results shown in Figure 2 (P and Q designate the triarylamines and their cation radicals, respectively) clearly point to the incompatibility of the PE and EP pathways with the experimental data, in agreement with the mechanism suggested in ref 2d.

Having established that the reaction mechanism involves a CPE transfer in the electrochemical and homogeneous cases, we may now examine whether the magnitudes of the observed preexponential factor, reorganization energy, and isotope kinetic effect are compatible with current models. In the electrochemical case, it appears that λ is close to what is expected, whereas Z is abnormally large. λ may be compared to the λ (0.7 eV) characterizing the outer-sphere electron transfer to a similar molecule, namely tri-*tert*-butylphenol,⁷ which undergoes the same charge variation and a similar intramolecular reorganization upon electron transfer. Addition of an extra solvent reorganization term related to proton transfer, of the order of 0.1 eV,⁴ falls in line with the value used to fit experimental data.

The value of the preexponential factor essentially reflects the conditions under which the proton tunnels (Figure 3). It can be predicted from the model of electrochemical CPET reactions⁵ and from the attending quantum chemical estimations as equal to 120 cm s^{-1} .⁴ This value is 1 order of magnitude smaller than the experimental value.

In the homogeneous case, the simulation of the experimental data shown in Figure 2 was performed with $\lambda = 1.15 \text{ eV}$ and $Z = 10^{10} \text{ M}^{-1} \text{ s}^{-1}$. The preexponential value is only 1 order of magnitude lower than the maximum value for an homogeneous bimolecular reaction ($10^{11} \text{ M}^{-1} \text{ s}^{-1}$). It thus seems too high for a CPE reaction as it is in the electrochemical case. These observations may be explained as follows.

The electrochemical reaction takes place in a strong electric field, thus leading to the stabilization of the zwitterionic form and decreasing the proton tunneling barrier (Figure 3). Calculations of the electrochemical preexponential factor taking this effect into account⁴ leads to a value of 1176 cm s^{-1} , compatible with the

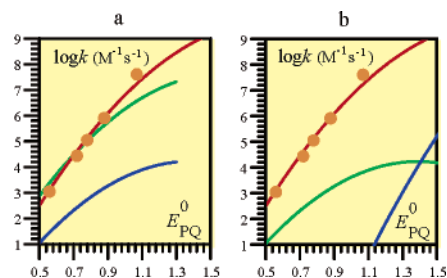


Figure 2. Oxidation of **1** by triarylamine cation radicals. Red dots: experimental data.^{2d} Red line: simulation of the CPE pathway. a, b simulation ($\lambda = 1 \text{ eV}$) of the PE [$E_{CD}^0 = 0.54$, $K_{AC} = 5.4 \times 10^{-8}$ (blue), $E_{CD}^0 = 0.34$, $K_{AC} = 1.5 \times 10^{-4}$ (green)] and EP [$E_{AB}^0 = 1.7$, $K_{BD} = 5 \times 10^{15}$ (blue), $E_{AB}^0 = 1.5$, $K_{BD} = 2 \times 10^{12}$ (green)] pathways.

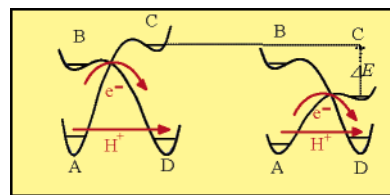


Figure 3. Potential energy profiles for proton transfer in the electrochemical CPET to **2** in the absence (left) and presence (right) of an electric field. A, B, C, D are the corresponding species at the transition state.

experimental value. A similar effect is expected in the homogeneous case since an electric field is exerted by the positive charge borne by the electron acceptor. Calculation of the deuterium kinetic effect also leads to a value compatible with the experimental data.⁴

Investigation of other examples of electrochemical intramolecular CPE reactions is in progress, aiming in particular at further assessing the electric field effect that we have observed.

Supporting Information Available: Experimental and simulation procedures; estimation of the various theoretical parameters. This material is available free of charge via the Internet at <http://pubs.acs.org>.

References

- (1) (a) Stubbe, J.; van der Donk, W. A. *Chem. Rev.* **1998**, *98*, 705. (b) Stubbe, J.; Nocera, D. G.; Yee, C. S.; Chang, M. C. Y. *Chem. Rev.* **2003**, *103*, 2167. (c) Chang, C. J.; Chang, M. C. Y.; Damrauer, N. H.; Nocera, D. G. *Biochim. Biophys. Acta* **2004**, *1655*, 13. (d) Mayer, J. M.; Rhile, I. J. *Biochim. Biophys. Acta* **2004**, *1655*, 51. (e) Renger, G. *Biochim. Biophys. Acta* **2004**, *1655*, 195.
- (2) (a) Maki, T.; Araki, Y.; Ishida, Y.; Onomura, O.; Matsumura, Y. *J. Am. Chem. Soc.* **2001**, *123*, 3371. (b) Benisvy, L.; Blake, A. J.; Collison, D.; Davies, E. S.; Garner, C. D.; McInnes, E. J. L.; McMaster, J.; Whittaker, G.; Wilson, C. J. *Chem. Soc., Dalton Trans.* **2003**, 1975. (c) Thomas, F.; Jarjayes, O.; Jamet, H.; Hamman, S.; Saint-Aman, E.; Duboc, C.; Pierre, J.-L. *Angew. Chem., Int. Ed.* **2004**, *43*, 594. (d) Mayer, J. M.; Rhile, I. J. *J. Am. Chem. Soc.* **2004**, *126*, 12718. (e) Lachaud, F.; Quaranta, A.; Pellegrin, Y.; Dorlet, P.; Charlot, M.-F.; Un, S.; Leibl, W.; Aukauloo, A. *Angew. Chem., Int. Ed.* **2005**, *44*, 1536.
- (3) Rhile, I. J.; Mayer, J. M. *Angew. Chem., Int. Ed.* **2005**, *44*, 598.
- (4) See Supporting Information.
- (5) (a) Costentin, C.; Evans, D. H.; Robert, M.; Savéant, J.-M.; Singh, P. S. *J. Am. Chem. Soc.* **2005**, *127*, 12490. (b) Costentin, C.; Robert, M.; Savéant, J.-M. *J. Electroanal. Chem.* **2006**, *588*, 197.
- (6) Richards, J. F.; Whitson, P. E.; Evans, D. H. *J. Electroanal. Chem.* **1975**, *63*, 311.
- (7) (a) From the cyclic voltammetric peak width and peak potential location,⁶ 1.59 V vs SCE. $\lambda = 0.7 \text{ eV}$.^{7b} The double-layer effect is also expected not to be very different. (b) Savéant, J.-M. *J. Phys. Chem. B* **2003**, *543*, 9387.
- (8) (a) Using the DigiElch software; see: Rudolph, M. *J. Electroanal. Chem.* **2003**, *543*, 23. (b) With a reorganization energy $\lambda = 0.7 \text{ eV}$ and a double-layer effect amounting to an apparent standard rate constant lower than the true rate constant by a factor of 10.
- (9) Smaller rate constants, e.g., 10^{11} s^{-1} , give the same results insofar as they are large enough for the electron-transfer steps to be rate-determining.
- (10) Atkins, P. W. *Physical Chemistry*, 6th ed.; Oxford University Press: Oxford, 1998; p 666.

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