J. Am. Chem. Soc. 1984, 106, 1957–1962

6627-78-7; 1-bromo-2-methylnaphthalene, 2586-62-1; 2-bromonaphthalene, 580-13-2; 1-(chloromethyl)naphthalene, 86-52-2; 2-(bromomethyl)naphthalene, 939-26-4; 1-chloronaphthalene, 90-13-1; 2-chloronaphthalene, 91-58-7; 9-bromoanthracene, 1564-64-3; 9,10-dibromoanthracene, 523-27-3; 2-iodoanthracene, 22362-94-3; 9-iodoanthracene, 22362-86-3; 1-(bromomethyl)naphthalene, 3163-27-7; 2-(chloromethyl)naphthalene, 2506-41-4; 1-(chloromethyl)-2-methylnaphthalene, 6626-23-9.

Preceding Chemical Reaction Mechanisms in Homogeneous Electron Transfer Reactions. Mediated Electrochemical Reduction of Highly Reactive Benzylic Halides

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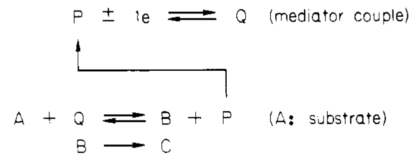
Abstract: The reduction of 9-chloro-9-[α-(9-fluorenylidene)benzyl]fluorene and 9-chloro-9-mesitylfluorene in acetonitrile can be homogeneously catalyzed by ferrocenes and organic reversible couples at potentials up to 2 V ahead of the direct electrochemical process leading to the corresponding persistent radicals, whereas the carbanions are obtained in the uncatalyzed reduction. In this very positive potential range, the catalytic efficiency does not depend upon the concentration and standard potential of the catalyst, suggesting the occurrence of a predissociation mechanism in which the primary step is the uphill formation of the carbocations which are then rapidly reduced into the radicals by the catalyst. The validity of this mechanism was proved by a detailed analysis of the kinetics as a function of the substrate and chloride ion concentration and the standard potential of the catalyst. This also led to the determination of the rate constants of the various steps. The occurrence of such a mechanism underscores the possible importance of predissociation steps in the reduction of aliphatic halides similar to S_N1 processes in nucleophilic substitution reactions.

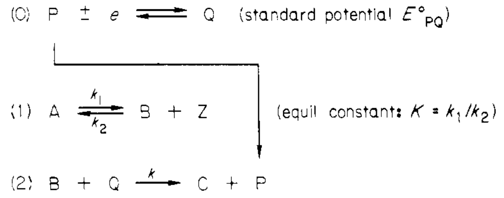
Kinetic studies of homogeneous electron transfer reactions generally involve one redox couple, both members of which are chemically stable, and a second reactant which may give rise to a chemically stable or unstable species on reduction or oxidation. The electrochemical analogues of these reaction schemes are simple electrode electron transfer reactions in the first case and "EC" (electrochemical–chemical) mechanisms in the second. One way of investigating homogeneous electron transfer reactions or reactions triggered by a prior electron transfer step is to use electrochemical techniques indirectly. The electron transfer reagent (mediator) is generated at the electrode surface under controlled potential conditions. It then transfers (or abstracts) one electron to (or from) the substrate, the reduction (or oxidation) product of which being either chemically stable or able to undergo a further chemical reaction. It is then observed that the current corresponding to the generation of the electron transfer reagent is increased by the addition of the substrate according to the reaction sequence in Scheme I.

The catalytic enhancement of the reduction (or oxidation) current of P is a function of the overall kinetics of the homogeneous reactions.[2] Means are thus provided for determining the rate constants of these reactions and/or the standard potential of the substrate couple A/B. Experimental investigation of several reactions have demonstrated the practical applicability of this approach. Illustrative examples have concerned the reductive cleavage of aryl halides,[3] of aryl sulfides,[4] and triarylhalogermane[5] as well as electron transfer induced conformational changes of bianthrone.[6] When the homogeneous electron transfer step is an outer-sphere reaction giving rise to "redox catalysis" as opposed to "chemical catalysis",[2] the essential reason why reduction (or oxidation) occurs in a potential region where the direct electrochemical process would be inefficient pertains to the three-dimensional distribution of the electron exchanging particles as opposed to the surface character of the electrochemical process.

Scheme I



Scheme II



In direct electrochemistry, reaction schemes involving dissociation of the substrate prior to electron transfer

$$A \rightleftarrows B + Z$$

$$B \pm 1e \rightleftarrows C$$

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(1) (a) Universite de Paris 7. (b) Universität Regensburg.

(2) (a) Andrieux, C. P.; Dumas-Bouchiat, J. M.; Savēant, J. M. *J. Electroanal. Chem.* **1978**, *87*, 39. (b) *Ibid.* **1978**, *87*, 55. (c) *Ibid.* **1978**, *88*, 43. (d) *Ibid.* **1980**, *113*, 1. (e) *Ibid.* **1980**, *113*, 19.

(3) (a) Andrieux, C. P.; Blocman, C.; Dumas-Bouchiat, J. M.; Savēant, J. M. *J. Am. Chem. Soc.* **1979**, *101*, 3431. (b) Andrieux, C. P.; Blocman, C.; Dumas-Bouchiat, J. M.; M'Halla, F.; Savēant, J. M. *J. Am. Chem. Soc.* **1980**, *102*, 3806.

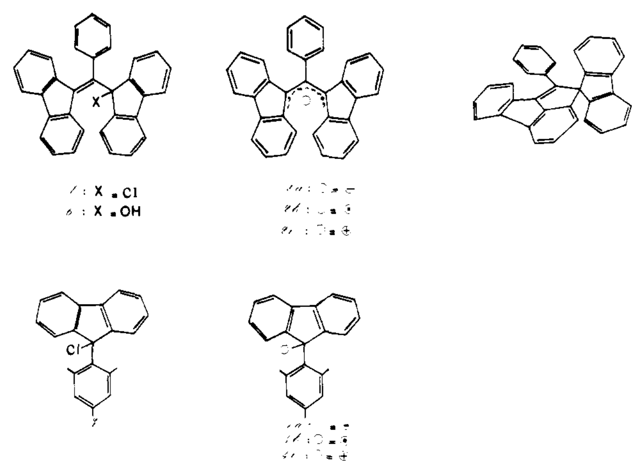
(4) Griggio, L. *J. Electroanal. Chem.* **1982**, *140*, 155.

(5) Dabosi, G.; Martineau, M.; Simonet, J. *J. Electroanal. Chem.* **1982**, *139*, 211.

(6) (a) Evans, D. H.; Xie, N. *J. Electroanal. Chem.* **1982**, *133*, 367. (b) Evans, D. H.; Xie, N. *J. Am. Chem. Soc.* **1983**, *105*, 315.

0002-7863/84/1506-1957$01.50/0

Chart I



with B being easier to reduce (or oxidize) then A, are well-documented reactions.[7–9] They are usually termed "CE" (for "chemical–electrochemical") mechanisms. The reduction (or oxidation) of A may occur in a potential region where it is not itself reducible (or oxidizable) through prior dissociation into B. The kinetics of the overall oxido–reduction process are then functions of the thermodynamics and kinetics of the preceding chemical step: the easier, from a thermodynamic and kinetic viewpoint, the chemical step, the faster the overall redox process. Experimental examples of such reaction mechanisms have involved as preceding reaction dehydration of aldehyde hydrates,[7,9] protonation of various organic molecules,[8] and ligand exchange of coordination complexes. Concerning the latter example, CE mechanisms appear as a very common pathway in the electrochemistry of transition metal complexes. A good illustration of this point is provided by the electrochemistry of vitamin B12 derivatives where exchange of axial ligands at the central cobalt atom plays a major role both for the Co(III)/Co(II) and the Co(II)/Co(I) redox reactions.[10]

Homogeneous redox catalytic "CE" processes would involve reaction Scheme II. The catalytic enhancement of the reduction (or oxidation) current of P is anticipated to be a function of the rate constants k_1, k_2, and k. The investigation of its dependency on the various experimental parameters should therefore offer a route to the values of these rate constants. It is expected that a CE catalytic current could be observed under conditions where a direct CE current cannot be detected due to insufficient and/or insufficiently fast pre-activation. This is again related to the three-dimensional distribution of the electron exchanging particles as opposed to the surface character of the electrochemical process.

There has been so far no example of a homogeneously mediated CE reaction. We describe hereafter such a process involving the reduction of two highly reactive chlorides, 9-chloro-9-[α-(9-fluorenylidene)]benzylfluorene, **1**, and 9-chloro-9-mesitylfluorene, **3** (Chart I). The electrochemistry of **1** has been previously described in some detail.[11] **1** and **3** have the particular advantage that their corresponding carbanions 2a,[12] 4a,[13] and free radicals 2b,[14] 4b[15] are stable species under the conditions of the electrochemical experiments. They can thus serve as model systems for certain mechanistic aspects of the electrochemical reduction of the carbon halogen bond.[11] Additionaly, in the context of the present investigation, it is of utmost importance that **1** and **3** are tertiary halides of the triarylmethane type which are well-known for their high reactivity in SN1 displacement of the halide ion via the carbenium ions. Thus, **1** and **3** appear particularly well-suited for the study of a possible CE mechanism.

Experimental Section

Chemicals. 9-Chloro-9-[α-(9-fluorenylidene)]benzylfluorene, **1**,[14] and 9-chloro-9-mesitylfluorene, **3**,[15] and their corresponding free radicals, **2b**[14] and **4b**[15] were prepared according to the literature procedures. We with to note that high yields of the halides can be obtained when benzene solutions of the carbinol precursors are stirred with 12 N hydrochloric acid containing solid calcium chloride. It was not possible to obtain **1** free from traces of the radical **2b**.

The carbinol 6 was converted into the spiro-hydrocarbon **5**, mp 193 °C (lit. 194–96),[16] by the action of perchloric acid in glacial acetic acid.

The highly strained spiro structure of **5** was confirmed by its ^{13}C NMR spectrum. The expected number of absorptions was found in the proton decoupled spectrum for a structure with C_{2v} symmetry; the expected number of absorptions remained uncoupled in the off-resonance spectrum, including the spiro carbon at 78.336 ppm vs. Me_4Si. High resolution MS; Calcd for $C_{33}H_{20}$: 416.15650; Found: 416.15649; UV/Vis in ethanol: λ = 356 nm (ϵ = 18 000), 310 (14 400), 298 (12 300). The deep red cation **2c**, in acetonitrile/0.1 M TBAP was generated from **6** in a UV spectrometer cell by rapid addition of a 150-fold excess of 70% perchloric acid, and the decay of the extinction at 800 nm was followed spectrophotometrically. The observed first-order rate constant for the conversion into **5** was determined as 0.011 +/−0.005 at 25 °C. After 30 min the spectrum of pure **5** was obtained.

Ferrocene and 1,1′-dimethylferrocene were commercial products. 1-Methyl, 1-ethyl, and 1-isopropylferrocene were prepared as described in the literature.[17] The ferrocinium cations were prepared as tetrafluoroborates by oxidation of the ferrocenes with *p*-benzoquinone in acetic acid containing HBF_4, 1-ethyl-, and 1-isopropylferrocene were isolated as tetraphenylborates since the tetrafluoroborates are liquids at room temperature. All samples had satisfactory elemental analyses and gave clean Nernstian voltammetric signals under our experimental conditions.[18]

Electrochemical Techniques. All experiments were performed under dry nitrogen or in vacuo, under the vapor pressure of the solvent at ambient temperature (22 °C).

Tetra-*n*-butylammonium perchlorate, TBAP (Fluka) was twice recrystallized from 65% aqueous ethanol and dried in vacuo. Tetra-*n*-butylammonium chloride (Fluka, technical grade) was freed from residual water by azeotropic distillation with benzene and three times recrystallized from benzene/ethyl acetate; after drying for three days at 80 °C in vacuo, a stock solution in acetonitrile was prepared at the vacuum line. Acetonitrile (Fluka puriss p.A) was vacuum distilled twice from P_4O_{10} and once from CaH_2. It was either distilled directly into the electrochemical cell (vacuum line technique) or stored over 3 Å molecular sieves and transferred under nitrogen by syringe techniques.

The electrochemical instrumentation was a Princeton Applied Research Model 170 Electrochemical System together with an *XY* recorder or storage oscilloscope. All measurements were performed in three electrode cells with the working electrode (Pt disk) compartment separated from the reference and counter electrode compartments by fine porosity glass frits. With vacuum line cells the reference electrode was a silver wire and the potential was calibrated after finishing the experiment by a suitable redox couple of known potential vs. the SCE. Otherwise, an SCE was used with a salt bridge (0.1 M Et_4NClO_4 in acetonitrile).

In the vacuum line experiments, the concentration of the ferrocinium mediators was obtained from the peak heights of the cyclic voltammograms with previously determined current functions. Preweighed solid **1** or **3** was introduced from a side arm of the vacuum cell. Otherwise, solutions of the mediator were prepared volumetrically and the halide was added as a solid or as a concentrated benzene solution.

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[7] Bard, A. J.; Faulkner, L. R. "Electrochemical Methods"; Wiley: New York, 1980; Chapter 11.

[8] Strehlow, H. "Electrochemical Methods for the Investigation of Fast Chemical Reactions in Methods for the Investigation of Fast Chemical Reactions, Part II", Hammer, G. G., Ed.; Wiley-Interscience: New York, 1974; Chapter VIII.

[9] Heyrovsky, J.; Kuta, J. "Principles of Polarography"; Academic Press: New York, 1966; Chapter VII.

[10] Lexa, D.; Savéant, J. M. *Acc. Chem. Res.* **1983**, *16*, 235.

[11] The reversibility of the $R^+/R\cdot$ and $R\cdot/R^-$ couples produced upon reduction of **1** has been demonstrated in a preliminary account of the direct electrochemistry of **1**: Merz, A.; Tomahogh, R. *Angew. Chem. Int. Ed. Engl.* **1979**, *18*, 938.

[12] Kuhn, R.; Fischer, H.; Neugebauer, F. A. *Liebigs Ann. Chem.* **1972**, *654*, 64.

[13] Itaya, K.; Kawai, M.; Toshima, S. *Chem. Phys. Lett.* **1976**, *42*, 179.

[14] Koelsch, C. F. *J. Am. Chem. Soc.* **1957**, *79*, 4431.

[15] (a) Theilacker, W.; Schulz, H.; Baumgarte, U.; Droessler, H. G.; Rohde, W.; Thater, F.; Uffmann, H. *Angew. Chem.* **1957**, *63*, 322. (b) Chaudron, E. A.; Shelley, C. R. *J. Am. Chem. Soc.* **1968**, *90*, 4345.

[16] Koelsch, C. F. *J. Am. Chem. Soc.* **1932**, *54*, 4744.

[17] (a) Schloegl, K.; Fried, M. *Monatsh. Chem.* **1964**, *95*, 558. (b) Schloegl, K.; Moher, A.; Peterlik, M. *Ibid.* **1961**, *92*, 921.

[18] As to the stability for ferricinium cations in dipolar aprotic solvent, see: Sato, M.; Yamada, T.; Nishikama, A. *Chem. Lett.* **1980**, 925.

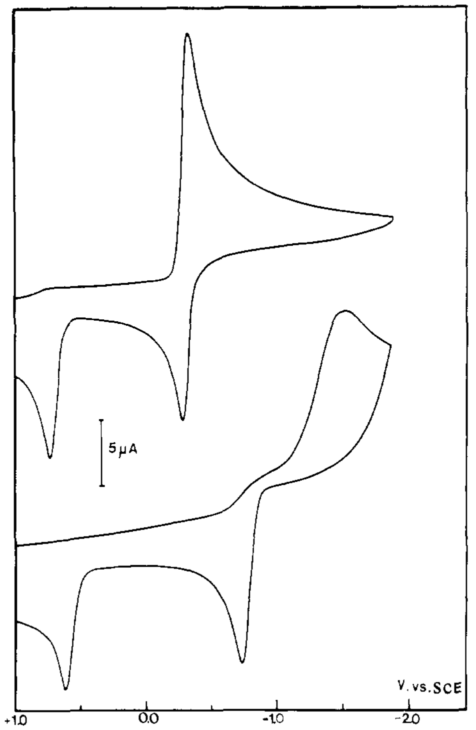

Figure 1. Cyclic voltammetry of 1 mM **1** (upper) and **3** (lower) at a platinum disk electrode in dry acetonitrile with 0.1 M NBu_4ClO_4 as supporting electrolyte. Scan rate: 0.2 V s^{-1}.

Table I. Characteristic Potentials for the Electrochemical Reduction of Compounds 1 and 3 and the Resulting $R\cdot/R^-$ and $R^+/R\cdot$ Couples in Dry Acetonitrile[a]

compd	$E_{p,c}$	$E°_{R^+/R\cdot}$[d]	$E°_{R\cdot/R^-}$[d]
1	-1.5[b]	0.79	-0.34
3	-1.35[c]	0.75	-0.69

[a] All potentials are expressed in V vs. the aqueous saturated calomel electrode. [b] Cathodic peak potential at 10 V s^{-1} for the reduction $RCl + 2e \rightarrow R^- + Cl^-$. [c] Cathodic peak potential at 0.2 V s^{-1} for the reduction $RCl + 2e \rightarrow R^- + Cl^-$. [d] Standard potentials taken from cyclic voltammograms of the free radicals **2b** and **4b**.

Results and Discussion

Direct Electrochemistry of 1 and 3. Although early studies in the field of the electrochemical reduction of the carbon halogen bond have attempted to relate the mechanism to the classical SN reactions,[19] modern views are principally based on $RX^{-}\cdot$ radical anions produced by direct one electron transfer to organic halides RX. The very existence of these radical anions has found ample evidence from electrochemical[20] and pulse radiolysis studies,[21] their lifetime ranging from quasi indefinite to less than nanoseconds with regard to the bond cleavage $RX^{-}\cdot \rightarrow R\cdot + X^-$, depending on the structure of R and the nature of X (X = F, Cl, Br, I). In the case of aliphatic halides, the lifetimes of $RX^{-}\cdot$ are particularly short, so that the electron transfer and the bond cleavage may be discussed as a concerted process.[21,22] This has two consequences: (i) the electrochemical reduction potential will be dominated by the activation energy of the carbon halogen bond cleavage and may be far negative from the thermodynamic value; (ii) R will be produced in the immediate vicinity of the electrode surface and, with the prevailing negative potential, be immediately reduced to the carbanion R^- which will then be the intermediate in follow-up chemical reactions.

This behavior has been demonstrated for **1**[11] and is also true for **3**. Some features relevant to the subsequent discussion are given hereafter. The cyclic voltammograms of **1** and **3** are shown in Figure 1. The carbanions **2a** or **4a** are formed in an irreversible two-electron wave. A one electron reversible wave (corresponding to the formation of a possible transient $RX^{-}\cdot$) could not be found with the highest sweep rates accessible to us (500 V s^{-1}). Instead, a strong negative shift and broadening of the reduction wave is observed. Indeed, the relatively positive reduction potential of **1**, almost coinciding with the **2b**/**2a** redox couple, is caused by an autocatalytic effect involving carbanion **2a**; at scan rates ≥ 1 V s^{-1}, the appearance of the cyclic voltammogram of **1** approaches the behavior of **3**. The appearance of the foreward cathodic trace is dependent on the electrode material and its condition in both cases.[23] On the backward anodic scan, two well-separated peaks appear, corresponding to the oxidation to the free radicals and further to the carbenium ions. The first oxidation peak is reversible while the second is fast but irreversible due to rapid recombination of the carbenium ions with the chloride ions present from the first reduction step. This interpretation is easily demonstrated by the electrochemistry of the isolated free radicals **2b** (Koelsch' radical[14]) or **4b**, i.e., in chloride-free solution: only the two purely Nernstian redox couples are found. When **2b** is oxidized on a coulometric time scale, the cation **2c** is converted into the spirocyclic hydrocarbon **5** by an intramolecular Friedel–Crafts reaction with a first-order rate constant of 0.011 s^{-1} which does not interfere on the c.v. time-scale.

The redox potentials of **1** and **3** and their follow-up products are given in Table I. In summary, the direct electrochemistry of **1** and **3** is a clear demonstration of direct electron transfer to RX. No kinetic wave in the potential region of R^+/R indicative of some possible CE participation is discernible within experimental accuracy. Despite these findings, we were able to demonstate the CE mechanism in the mediator catalyzed reduction of the same compounds as described in the following section.

Mediated Electrochemical Reduction. During an attempt to calibrate the reduction potential of **1** vs. the standard potential of the ferricinium/ferrocene (FC^+/FC) couple, it was noticed that **1** was instantaneously reduced to the radical **2b**. The ferricinium/ferrocene couple thus appeared as an efficient mediator for the indirect electrochemical reduction of **1** which can thus be carried out at an electrode potential of +0.4 V instead of −1.5 V for the direct electrochemical reduction. Unlike the direct electrochemical reduction while leads to the carbanions through a two-electron process, the FC mediated reduction proceeds to the radicals only as expected from the relative locations of the standard potentials of the FC^+/FC and $R\cdot/R^-$ couples (Tables I and II).

It was observed, starting from a solution of ferricinium cations, that its cyclic voltammetric wave progressively loses its reversibility upon addition of **1**, while the height of the cathodic peak increases. A convenient measure of the efficiency of the homogeneous redox catalysis is given by the ratio $i_p/\gamma i_p°$, where i_p is the peak height of the catalytic current, $i_p°$ the peak height of the reversible wave of the mediator in the absence of substrate and $\gamma = C_A°/C_P°$ the excess factor, i.e., the ratio of the bulk concentration of substrate, $C_A°$, and catalyst, $C_P°$. Table III gives typical results obtained for the FC mediated reduction. It is seen that the values of the catalytic efficiency are rather modest. Still, however, it is very unusual for redox catalysis to occur with a potential difference between mediator and substrate of about 1.9 V in the context of the classical EC mechanism[2]

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(19) This question is discussed in Fry, A. J. "Synthetic Organic Electrochemistry"; Harper and Row: New York, 1972; p 173.

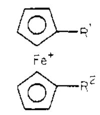
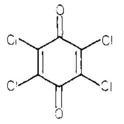
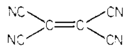
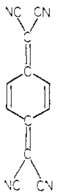
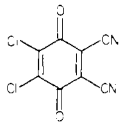
(20) Andrieux, C. P.; Savéant, J. M.; Zann, D. *Nouv. J. Chim.* in press, and references cited therein.

(21) (a) Steelhammer, J. C.; Wentworth, W. E. *J. Chem. Phys.* **1969**, *51*, 1802. (b) Neta, P.; Behar, D. *J. Am. Chem. Soc.* **1981**, *103*, 103. (c) Wentworth, W. E.; George, R.; Keith, H. *J. Chem. Phys.* **1969**, *51*, 1791.

(22) Canadell, E.; Karafiloglon, P.; Salem, L. *J. Am. Chem. Soc.* **1980**, *102*, 855.

(23) Bard, A. J.; Merz, A. *J. Am. Chem. Soc* **1979**, *101*, 2959, and references cited therein.

Table II. Standard Potentials of the Mediator Couples[a]

oxidized form of the mediator			code	E°_{PQ}
				
R^1	R^2	anion		
H	H	BF_4	FC	0.42
CH_3	H	BF_4	MFC	0.36
C_2H_5	H	BPh_4	EFC	0.37
i-C_3H_7	H	BPh_4	PFC	0.37
CH_3	CH_3	BF_4	DMFC	0.32
			CLA[b]	0.11
			TCNE[c]	0.26
			TCNQ[d]	0.40
			DDQ[e]	0.54

[a] In dry acetonitrile, in V vs. SCE. [b] Chloranil. [c] Tetracyanoethylene. [d] Tetracyanoquinodimethane. [e] Dichlorodicyanoquinone.

Table III. Homogeneous Redox Catalysis of the Reduction of 1 by Ferrocene and Substituted Ferrocenes[a]

mediator	FC	MFC	EFC	PFC	DMFC
mediator concn, mM	0.26	0.14	0.014	0.05	0.17
cat. efficiency, $i_p/\gamma i_p^\circ$	0.72	0.65	0.89	0.66	0.86

[a] Excess factor $\gamma = C_A^\circ/C_P^\circ = 5$; sweep rate: $v = 0.05$ V s^{-1}.

$$P + 1e \rightleftarrows Q$$

$$RCl + Q \rightleftarrows RCl^{-}\cdot + P$$

$$RCl^{-}\cdot \rightarrow R\cdot + Cl^{-}$$

Note that the rate-determining step would very probably be the forward homogeneous electron transfer step since the $RCl^{-}\cdot$ anion radical if it exists is likely to be extremely short-lived.

Generally speaking, the catalytic efficiency is a function of the excess factor, γ, and the time scale of the experiment, i.e., the scan rate, V, in cyclic voltammetry. In the particular case of an EC mechanism it is anticipated to be a function of the standard potential of the mediator couple: the more positive E^0_{PQ}, the less efficient the catalysis. In addition, when the forward electron transfer is the rds, the catalytic efficiency is expected to be an increasing function of the mediator concentration for a constant value of the excess factor. We therefore undertook a more detailed study of the mediated reduction of **1** using several other ferrocene derivatives to cover the potential range given in Table II. The data listed in Table III showed that at given values of v and γ, the catalytic efficiency is not very sensitive to variations of the mediator concentration and of the standard potential of the mediator couple.

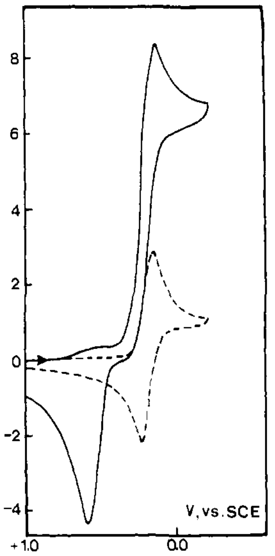


Figure 2. Mediated reduction of **3** by TCNQ. Cyclic voltammogram of TCNQ (1 mM, first reduction wave shown only) in the absence (---) and presence (—) of **3** (10 mM). Sweep rate: 0.1 s^{-1}. Experiment corresponding to first entry of TCNQ in Table V. The anodic peak is due to the oxidation of radical **4b**.

These results clearly rule out the occurrence of an EC catalytic mechanism. They are compatible with a redox catalytic process involving the pre-dissociation of the chloride giving rise to the carbocation which would receive an electron from the reduced form of the mediator

$$(0) \qquad P + 1e \rightleftarrows Q$$

$$(1) \qquad RCl \underset{k_2}{\overset{k_1}{\rightleftarrows}} R^+ + Cl^-$$

$$(2) \qquad R^+ + Q \xrightarrow{k} R\cdot + P$$

The latter reaction is expected to be fast and irreversible in view of the large standard potential difference between the $R^+/R\cdot$ and P/Q couples (Tables I and II). It is thus likely that the rate-determining step would be the pre-dissociation step (1). This fits with the observed lack of variation of the catalytic efficiency with the mediator standard potential and concentration.

In order to carry out a more quantitative analysis of the reaction mechanism, we changed mediators leaving the ferrocene derivatives for the series listed in Table II for two reasons. Because of the extreme sensitivity of the ferricinium cations toward traces of moisture and oxygen in nonaqueous solutions, experiments had to be carried out under vacuum line conditions which caused major difficulties in the reproduction of absolute and relative concentrations. Furthermore, we found that the ferricinium cations, acting as Lewis acids, catalyze the above-mentioned Friedel-Crafts reaction of **1** via **2c**. This led to a slow but significant decrease of the concentration of **1** during the measurements which is not observed in pure acetonitrile solutions. It turned out that the organic redox system of the second series of mediators (Table II) with potentials in the same range are as effective catalysts as the ferricinium salts being free, however, from disturbing side effects. Note that the mediating species is now the anion radical of the quinoid molecule. We also put emphasis on the reduction of **3** rather than of **1**. **3** is indeed easier to obtain as a pure form, freed of the radical R·, than **1**. An illustrative example of the mediated reduction of **3** by $TCNQ^{-}\cdot$ is given in Figure 2.

The results obtained for the mediated reduction of **1** and **3** by the quinoid catalysts are listed in Tables IV and V, respectively. They have been treated under the assumption that the rate-determining step of the catalytic process is the forward pre-dissociation reaction using the appropriate working curves that relate the catalytic efficiency to the governing factor $\gamma_1 = (RT/F)$

Table IV. Mediated Reduction of Compound **1** by Quinoid Catalysts

mediator	C_P°, mM[a]	$\gamma = C_A^\circ/C_P^\circ$	ν, V s^{-1} [b]	i_p/i_p° [c]	log λ_1 [d]	k_1, s^{-1} [e]
CLA	1.04	4.8	0.1	3.57	−0.09	3.31
	0.52	3.8	0.5	2.05	−0.88	2.63
		5.9	0.2	3.00	−0.46	2.74
					av	2.9
TCNE	1.11	4.0	0.5	2.30	−0.70	3.96
		8.3	0.5	3.15	−0.72	3.8
					av	3.9
TCNQ	1.14	4.4	0.5	2.41	−0.75	3.59
	0.49	10.6	1	2.44	−1.23	2.37
		5.19	1	1.80	−1.12	3.06
	0.21	10.4	1	2.36	−1.22	2.42
			0.1	5.03	−0.32	1.92
		20.5	1	3.30	−1.11	3.09
			0.1	7.70	−0.21	2.45
					av	2.7
		4.0	0.1	2.40	−0.70	0.79
		8.6	0.1	3.17	−0.74	0.73
					av	0.76

[a] Mediator concentration. [b] Scan rate. [c] Catalytic efficiency. [d] $\lambda_1 = (RT/F)(k_1/\nu)$. [e] Pre-dissociation rate constant.

Table V. Mediated Reduction of **3** by Quinoid Catalysts

mediator	C_P°, mM[a]	$\gamma = C_A^\circ/C_P^\circ$	ν, V s^{-1} [b]	$i_p/\gamma i_p^\circ$ [c]	log λ_1 [d]	k_1, s^{-1} [e]
CLA	1.08	4.7	0.1	0.436	−0.98	0.42
		9.4	0.1	0.234	−1.19	0.26
	0.50	5.0	0.05	0.490	−0.80	0.32
		10.0	0.02	0.326	−0.79	0.13
					av	0.28
TCNE	0.64	4.3	0.1	0.452	−1.03	0.37
		7.9	0.1	0.335	−1.00	0.40
					av	0.39
TCNQ	1.00	10	0.1	0.283	−0.90	0.50
	0.54	9.3	0.1	0.258	−0.97	0.43
					av	0.46
DDQ	1.00	10.2	0.03	0.149	−1.80	0.019
	0.48	4.9	0.02	0.289	−1.40	0.032
		10.3	0.02	0.145	−1.62	0.019
					av	0.023

[a] Mediator concentration. [b] Scan rate. [c] Catalytic efficiency. [d] $\lambda_1 = (RT/F)(k_1/\nu)$. [e] Pre-dissociation rate constant.

(k_1/v).[24] It is seen that for the three catalysts, CLA, TCNE, and TCNQ the values obtained for k_1 are approximately independent of the concentration and the standard potential of the mediator in agreement with the postulated mechanism. It is also observed that significantly lower values of k_1 are obtained with DDQ for the mediated reduction of both **1** and **3**. This again can be rationalized in the context of the pre-dissociation mechanism. As long as the potential difference between the $R^+/R\cdot$ and P/Q couple is large enough, k is itself large being close to the diffusion limit and consequently the overall kinetics is governed by the dissociation step. This is what happens with the three first catalysts. With DDQ these conditions as well be no longer fulfilled since the standard potential difference in only 250 mV for **1** and 210 mV for **3**. The overall kinetics would then be under the mixed control of reaction 1 and 2 leading to an apparent rate constant smaller than k_1. Note in this connection, that the apparent rate constant for DDQ is 17 times smaller than with the other three mediators in the case of **3** and only 4 times smaller in the case of **1**. This falls on line with the above interpretation since the potential difference is larger in the first case than in the second.

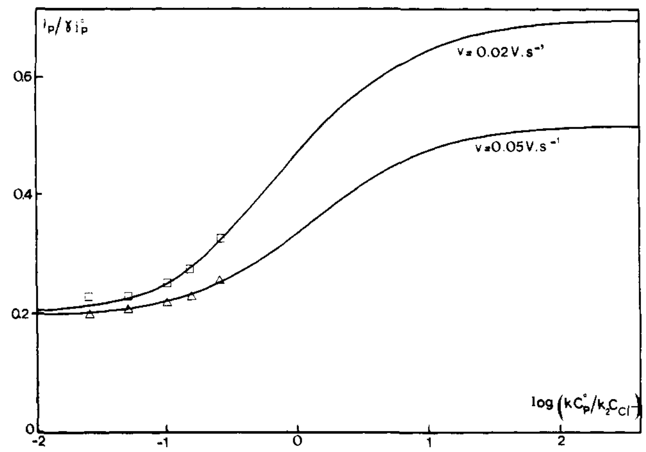


Figure 3. Mediated reduction of **3** by TCNQ in the presence of increasing amounts of chloride ions. Solid lines: simulated $i_p/\gamma i_p^\circ$ vs. log $(kC_P^\circ/k_2C_{Cl^-})$ curves for $\lambda_1 = 0.57$ (upper curve) and $\lambda_1 = 0.23$ (lower curve). Experimental points, $v = 0.02$ V s^{-1} (□), 0.05 (▲). From right to the left: C_{Cl^-}/C_P° = 500, 830, 1250, 2500, 5000; $\gamma = C_p^\circ/C_A^\circ = 5$.

A further confirmation of the pre-dissociation mechanism together with a quantitative kinetic characterization of its various steps was gained from a series of experiments where increasing amounts of chloride ions were introduced in the solution. These experiments were carried out with **3** as the substrate and TCNQ as the mediator. The results are shown in Figure 3. As expected in the context of the pre-dissociation mechanism, the catalytic efficiency decreases as the concentration of chloride ions increases. We start from a situation where the rate-determining step is forward reaction 1 and progressively pass to another situation where the rds is reaction 2 with reaction 1 acting as a pre-equilibrium. Under mixed control conditions, the overall kinetics as reflected by the catalytic efficiency depends upon two parameters. One, $\lambda_1 = (RT/F)(k_1/v)$, expresses the overall rate in the time scale of cyclic voltammetry. The second, $kC_P^\circ/k_2C_{Cl^-}$ measures the competition between reaction 2 and backward reaction 1. λ_1 can be derived, at each sweep rate, from the value of k_1 (0.47 s^{-1}) we determined in the above described experiments where no Cl^- was added to the solution under the assumption that kinetic control was then exclusively by forward reaction 1. Two values of the sweep rate were used, 0.02 and 0.05 s^{-1}, leading to $\lambda_1 = 0.57$ and 0.23, respectively. Two theoretical working curves relating the i_p/i_p° ratio to the competition parameter $k/k_2C_{Cl^-}$ were prepared[24] for these two values of λ_1 and $\gamma = 5$, the experimental value of the excess factor. It is seen in Figure 3 that there is a good fit between the experimental values of i_p/i_p° obtained at several Cl^- concentrations and the theoretical working curves. From this we derived the ratio $k/k_2 = 125$.[24]

It is now possible, knowing k_1 and k/k_2, to check back that the experiments carried out without addition of Cl^- (Table V) do correspond to a situation where the kinetic control is by forward reaction 1. This was found to be indeed the case by generation of the appropriate working curves.[24]

The occurrence of the pre-dissociation mechanism in the mediated reduction thus appears as well established on quantitative grounds. Taking $k = 2 \times 10^{10}$ M^{-1} s^{-1} for CLA, TCNE, and TCNQ, the following characteristics of the pre-dissociation reaction ensue: $k_1 = 0.4$ s^{-1}; $k_2 = 1.6 \times 10^8$ M^{-1} s^{-1}; $K = 2.5 \times 10^{-9}$.

On the basis of these figures, it is interesting to roughly estimate what should be the height of the kinetic prewave corresponding to a CE mechanism for the direct reduction of compound **3**. Using the theory previously derived for the CE reaction scheme in cyclic voltammetry, it is found that the kinetic prewave should be less than 3% of the total reduction wave which is in agreement with the experimental observations.

Let us return to the mediated reduction of **3** by DDQ. The less efficient catalysis which is observed with this mediator, as

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[24] (a) A detailed analysis of the kinetics of the pre-dissociation redox catalytic process is given elsewhere.[24b] (b) Andrieux, C. P.; Merz, A.; Savéant, J. M. *J. Electroanal. Chem.* submitted for publication.

compared to the other three, was attributed to a reversibility of reaction 2 owing to the proximity of the $E°$ of the $R^+/R\cdot$ couple.

Knowing the equilibrium constant of reaction 2 from the value of $E°_{R^+/R°} - E°_{DDQ}$ and the value of k_1, k_2, and k obtained previously, we introduce the backward reaction constant k' and we can generate the curves which give the catalytic efficiency. For example, if $E°_{R^+/R\cdot} - E°_{DDQ} = 210$ mV keeping $k = 2 \times 10^{10}$ M^{-1} s^{-1}, we must have $k' \simeq 7 \times 10^6$ M^{-2} s^{-1}. Simulation with these values for $\gamma = 4.9$ and $v = 0.02$ V/s give $i_p/\gamma i_p° = 0.30$ (experimental value 0.289). It is noted that with the three other catalysts the value of k' does not modify significantly, the determination of k_1.

Concluding Remarks

The above described study of the direct and mediated reduction of two highly reactive benzylic chlorides shows the possible importance of pre-activation pathways in electron transfer reactions. While in the present case this route appears as very inefficient in the direct electrochemical reduction, it gives rise to significant catalytic efficiencies in the mediated reaction. Homogeneous redox catalysis can thus be carried out at potentials that can be 2 V more positive than the potential where the direct electrochemical reduction occurs. Notably, the direct and mediated processes lead to different reaction products, the carbanions or free radical, respectively, in the present case. It has also been shown that the kinetic analysis of the system by means of cyclic voltammetry allows the determination of the equilibrium and rate constants of the preceding chemical step. The same procedures, here illustrated by the reduction of benzylic-type chlorides, can be applied to any other systems where a preceding reaction mechanism occurs.

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Registry No. 1, 72087-83-3; **3**, 20685-16-9; FC, 1282-37-7; MFC, 88946-23-0; EFC, 88946-24-1; PFC, 88946-25-2; DMFC, 52649-35-1; CLA, 118-75-2; TCNE, 670-54-2; TCNQ, 1518-16-7; DDQ, 84-58-2.

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(25) These figures are reasonable compared to some findings in the SN1 behavior of trityl chloride, a structure which is related to **3**. The forward rate constant is quite similar to the first-order solvolysis rate of trityl chloride in a solvent mixture of comparable polarity.[26a] Also, it has been observed that the dissociation constant of trityl chloride is extremely small in acetonitrile, but that SN1 reactions do rapidly occur when the chloride ion is removed from the equilibrium.[26b]

(26) (a) Swain, G.; Scott, C. B.; Lohmann, K. H. *J. Am. Chem. Soc.* **1953**, *75*, 136. (b) Baaz, M.; Gutmann, V.; Kunze, O. *Monatsh. Chem.* **1962**, *93*, 1142.

Spin Trapping in SDS Micelles

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Abstract: By the use of spin traps of differing solubility, radical reactions in the aqueous phase or the micellar interior of SDS micelles can be probed. Sodium 2-sulfonatophenyl *tert*-butyl nitrone (2-SSPBN) is useful for investigating the bulk aqueous phase, while 4-dodecyloxyphenyl *tert*-butyl nitrone (4-DoPBN) can be used to monitor the micellar interior. The effect of SDS on the line widths and hyperfine splitting constants of spin adducts of 2-SSPBN, 4-trimethylaminophenyl *tert*-butyl nitrone (4-M_3APBN), 4-DoPBN, and PBN have been investigated. ESR line shapes reveal a micelle/spin adduct charge association using 4-M_3APBN. Distinct asymmetry of the ESR spectra indicates premicellar aggregation.

Introduction

Perhaps the most exciting advance in spin trapping is the recent finding that in vivo detection of free radicals is possible by this method. Thus trichloromethyl radicals have been detected by phenyl *tert*-butyl nitrone (PBN) in the liver of rats exposed to carbon tetrachloride,[1] and a carbon-centered radical has been trapped by PBN in the lung of goats when subjected to small amounts of 3-methylindole.[2] A large amount of in vitro work preceded these experiments where the right conditions for spin trapping have been investigated and the assignments of various ESR spectra of spin adducts verified. In this connection it has been found that nitrones[3] are much more useful spin traps than nitroso compounds,[4] PBN and 5,5-dimethylpyrroline *N*-oxide (DMPO) receiving the most attention. Although DMPO is the trap of choice for the detection of hydroxyl radicals,[3,5] it has been

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(1) Lai, E. K.; McCay, P. B.; Noguchi, T.; Fong, K. L. *Biochem. Pharm.* **1979**, *28*, 2231. Poyer, J. L.; McCay, P. B.; Lai, E. K.; Janzen, E. G.; Davis, E. R. *Biochem. Biophys. Res. Commun.* **1980**, *94*, 1154. See also: Albano, E.; Lott, K. A. K.; Slater, T. F.; Stier, A.; Symons, M. C. R.; Tomasi, A. *Biochem. J.* **1982**, *204*, 593.

(2) Kubow, S.; Janzen, E. G.; Bray, T. M. *J. Biol. Chem.*, in press. Kubow, S.; DuBose, C. M.; Janzen, E. G.; Carlson, J. R.; Bray, T. M. *Biochem. Biophys. Res. Commun.* **1983**, *114*, 168.

(3) For reviews of spin trapping in biological systems see: Janzen, E. G. *Free Radicals Biol.* **1980**, *4*, 115. Kalyanaraman, B. *Rev. Biochem. Toxicol.* **1982**, *4*, 73. For reviews of spin trapping with nitrones see: Janzen, E. G. *Acc. Chem. Res.* **1971**, *4*, 31. Perkins, M. J. *Adv. Phys. Org. Chem.* **1980**, *17*, 1.

(4) Nitroso compounds should not be used as detectors of radicals in any system containing olefinic bonds because the "ene reaction" produces the hydroxylamine by a molecular reaction which gives detectable amounts of aminoxyls upon oxidation: Sullivan, A. B. *J. Org. Chem.* **1966**, *31*, 2811. Knight, G. T. *Chem. Commun.* **1970**, 1016. Floyd, R. A.; Soong, L. M.; Stuart, M. A.; Reigh, D. L. *Arch. Biochem. Biophys.* **1978**, *185*, 450. Sridhar, R.; Hampton, M. J.; Steward, J. E.; Floyd, R. A. *Appl. Spectrosc.* **1980**, *34*, 289. Sridhar, R.; Floyd, R. A. *Can. J. Chem.* **1982**, *60*, 1574. Floyd, R. A. *Ibid.* **1982**, *60*, 1577.

(5) Finkelstein, E.; Rosen, G. M.; Rauckman, E. J. *Arch. Biochem. Biophys.* **1980**, *200*, 1. Marriott, P. R.; Perkins, M. J.; Griller, D. *Can. J. Chem.* **1980**, *58*, 803.

0002-7863/84/1506-1962$01.50/0