

on two GLC columns (SP2100 Silicone and Carbowax 20M). Also, HPLC (silica A column, hexane) confirmed their presence by comparison of both retention times and UV spectra with those of authentic samples.

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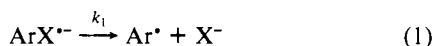
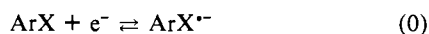
Electron Transfer Catalyzed Reactions. Electrochemical Induction of the Hydrogen Atom Transfer Oxidation of Alcohols and Other Substrates by Aromatic Halides

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Abstract: The reduction of aryl halides in the presence of primary or secondary alcohols in liquid ammonia or in pure alcohol leads to the formation of the corresponding carbonyl compounds along an electrocatalytic process consuming a vanishingly small amount of electricity. The aryl radical generated upon electrochemical reductive cleavage of the aryl halide first abstracts a H atom from the alcohol leading to a hydroxyalkyl radical which deprotonates into the ketyl anion radical, which is itself oxidized into the carbonyl compound. Side reactions are the reduction of the aryl radical and of the hydroxyalkyl radical. A detailed study of the feasibility and the mechanism of the reaction has been carried out by cyclic voltammetry and preparative scale electrolysis. The results underscore the fact that besides its acid-base properties, the H-atom donation ability of the solvent can play an important role in the course of electrochemical reactions. The electron stoichiometry, varying between 0 and 2, and the product distribution are functions of the redox and acid-base properties of the radical resulting from H-atom abstraction and of the redox and cleavage characteristic of the aryl halide anion radical. The reaction allows the oxidation of a large variety of substrates under electrochemically reducing conditions, those which lead to the formation of the aryl radical from the starting aryl halide.

The electrochemical reduction of aryl halides (ArX) has been the object of a large number of previous investigations (for recent reviews see ref 2). It has been shown that the anion radical ArX^{-•} resulting from the uptake of a first electron is unstable in most cases



and undergoes a cleavage reaction yielding the aryl radical, Ar[•], and the halide ion. The rate constant of the cleavage reaction, k_1 , has been determined in a number of cases either by direct electrochemical methods when it is not too large ($k_1 \leq 10^4 \text{ s}^{-1}$) or by redox catalysis methods when it is larger.^{3a} It was shown

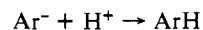
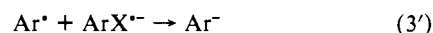
(1) (a) Université de Paris 7. (b) ESPCI.

(2) (a) Hawley, M. D. In *Encyclopedia of Electrochemistry of the Elements, Organic Section*; Bard, A. J.; Lund, H., Eds.; Dekker: New York, 1980; Vol. XIV. (b) Becker, J. Y. In *The Chemistry of Functional Groups, Supplement D*; Patai, S., Rappoport, Z., Eds.; Wiley: New York, 1983; Chapter 6, pp 203-285.

(3) (a) Andrieux, C. P.; Savéant, J. M.; Zann, D. *Nouv. J. Chim.* **1984**, 8, 107 and references cited therein. (b) The cleavage rate constant varies as a function of the halogen atom in the order I > Br > Cl. The variation with the nature of Ar makes a roughly linear correlation appear between the activation free energy of cleavage and the standard potential of the ArX/ArX^{-•} couple: the more negative the potential the faster the cleavage.^{3a,c} (c) Andrieux, C. P.; Savéant, J. M.; Su, K. B. *J. Phys. Chem.* **1986**, 90, 3815. (d) From the evidence gained so far, reactions 0 and 1 appear as sequential even for the fastest cleavage reactions.^{3a} It is, however, not excluded that with the fastest cleaving systems and with the low value of the electron transfer driving force, the two reactions could become concerted^{3c,f} as they have been shown to be in the case of aliphatic halides.^{3c,e} (e) Andrieux, C. P.; Gallardo, I.; Savéant, J. M.; Su, K. B. *J. Am. Chem. Soc.* **1986**, 108, 638. (f) Andrieux, C. P.; Savéant, J. M. *J. Electroanal. Chem.* **1986**, 205, 43.

that the lifetime of the anion radical, ArX^{-•}, varies considerably, from almost complete stability to nanoseconds, as a function of the nature of the aryl residue and of the halogen atom.³

The fate of the resulting aryl radical has also been the object of several investigations. Aryl radicals appear to be easily reducible species, much more than the usual aryl halides from which they derive.⁴ In solvents which are poor hydrogen atom donors, such as liquid ammonia, they thus undergo an immediate further electron transfer, at the potential where they are formed, yielding the corresponding aryl carbanion and eventually the hydrocarbon, ArH, upon proton transfer from acidic impurities or from the solvent itself:⁵



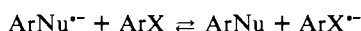
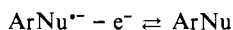
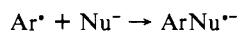
The second electron transfer reaction can occur concurrently at the electrode surface and in the solution from the ArX^{-•} anion radical, giving rise to a competition between an "ECE" (reactions 0 + 1 + 3) and a "DISP" (reactions 0 + 1 + 3') process.⁶ The

(4) (a) Although not determined with accuracy, the potential region where Ar[•] are reduced can be estimated to be around -0.3 V vs. SCE in organic solvents, at room temperature,^{4b} i.e., aryl radicals are more than 1 V easier to reduce than usual aryl halides. (b) Jaun, B.; Breslow, R. *J. Am. Chem. Soc.* **1980**, 102, 5741.

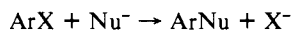
(5) Savéant, J. M.; Thiébault, A. *J. Electroanal. Chem.* **1978**, 89, 335.

competition between ECE and DISP pathways in the reduction of aryl halides in liquid ammonia has been investigated by direct cyclic voltammetry analysis of the reduction waves⁵ and also from the effects of the addition of a nucleophile to the solution, giving rise to an electrochemically induced SRN1 aromatic nucleophilic substitution⁷ (see below).

The very fact that the formation of aryl radicals from a dissociative one-electron-transfer reaction is a sequential rather than a concerted process^{3d} allows one to envisage that an aryl radical chemistry, and not only an aryl carbanion chemistry, could develop upon electrochemical reduction of aryl halides, although reactions 3 and 3' are anticipated to adversely affect this chemistry. A first example is the electrochemical⁷ induction⁸ of the SRN1 aromatic nucleophilic substitution.^{8b} The aryl radical formed upon dissociative one-electron transfer (reactions 0 + 1) is then trapped by a nucleophile, Nu⁻, added to the solution, leading to the ArNu⁻ anion radical which is eventually oxidized into the final substitution product, ArNu:

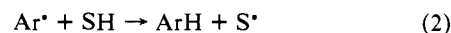


Such reactions are electrocatalytic (electron transfer catalyzed) in the sense that the overall reaction



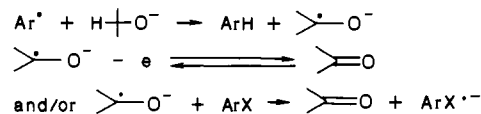
does not involve the net consumption of electrons. The latter serve only as catalysts. The way in which the substitution process is concurred by electron transfer to the aryl radical under an ECE or a DISP regime has been investigated in detail.⁷

Another example of aryl radical chemistry triggered by the electrochemical reduction of aryl halides involves the abstraction of a hydrogen atom from a substrate, SH

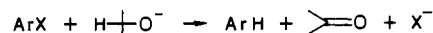


leading to the aromatic hydrocarbon and products deriving from further reactions of the S[•] radical. Thus far, two types of substrates giving rise to opposite behaviors have been investigated.

One type is exemplified by alcoholate ions which, not only are good H-atom donors but also have the particularity that S[•] is then a ketyl anion radical which is easily oxidized into the corresponding ketone



giving rise to electrocatalysis of the overall oxidation of alcoholates into ketones⁹



as in the case of SRN1 aromatic nucleophilic substitution.

Another example is provided by the electrochemical reduction of aryl halides in organic solvents such as dimethyl sulfoxide (Me₂SO) and acetonitrile. Reaction 2 still occurs, but the resulting S[•] radical is immediately further reduced into the corresponding carbanion at the electrode or in the solution, its reduction potential being positive to that of the starting aryl halide.¹⁰ In the presence of a small amount of water the solvent carbanion is further protonated, regenerating a solvent molecule.^{10c} Under these conditions, the overall process is not electrocatalytic: a two-electron per molecule stoichiometry is observed. A way of investigating the H-atom-transfer process is then provided by deuterium incorporation experiments.^{10b}

In the work described hereafter, we investigated the reaction of aryl radicals generated from the electrochemical reduction of aryl halides with alcohols as H-atom donors. The corresponding ketones are obtained along an electrocatalytic process which involves the deprotonation of the intermediary hydroxyalkyl radicals resulting from the H-atom-abstraction step. The resulting ketyl anion radical is then reoxidized, as in the case of alcoholates, at the electrode or in the solution which is the key step of the electrocatalytic process. On the other hand, the hydroalkyl radicals may concurrently be reduced, depending upon the basicity of the reaction medium, which is similar to what happens with Me₂SO and acetonitrile. Alcohols thus offer an example where the two types of behaviors described above are combined and compete one with the other. The aim of the present study is thus twofold: a better understanding of the role of the solvent in the electrochemical reduction of organic compounds emphasizing the concept that besides its general acid-base properties its H-atom-donor ability may be of major importance and the description of a type of reaction which allows the oxidation of organic substrates via H-atom transfer to aryl radicals produced under electrochemical reductive conditions.

The reaction was investigated both by cyclic voltammetry and at the preparative scale on the example of two alcohols, 2-propanol and benzhydrol, and several aryl halides.

Most of the experiments were carried out in liquid ammonia, with addition of increasing amounts of the H-atom donor, taking advantage of the fact that ammonia is itself a very poor H-atom donor.¹¹ A series of experiments was also carried out with pure 2-propanol as the solvent at room temperature. Brief indications will finally be given on the reactivity of other alcohols and other

(6) (a) The competition between the two pathways mainly depends upon the rate of cleavage: the faster the cleavage, the closer to the electrode Ar[•] is formed and thus the greater its propensity to be reduced at the electrode surface rather than by an incoming ArX^{•-} molecule. More generally, in the context of cyclic voltammetry, the competition is under the dependence of the dimensionless parameter $p = k_D[\text{ArX}](Fv/RT)^{1/2}k_1^{-3/2}$ (k_D = rate constant of reaction 2' vs. sweep rate). The DISP regime will prevail for large values of p and the ECE regime for small values. Since the Ar[•]/Ar^{•-} standard potential is much positive to that of the ArX/ArX^{•-} couple,⁴ k_D is likely to be close to the diffusion limit ($3 \times 10^{10} \text{ M}^{-1} \text{ s}^{-1}$ in liquid NH₃). Thus, at $v = 0.1 \text{ V s}^{-1}$ in liquid NH₃ at -40 °C, for a 1 mM ArX concentration, the reaction will follow equally the ECE and DISP pathways for $p = 7 \times 10^7 k_1^{-3/2}$. For a detailed analysis of the ECE-DISP problem see ref 6b and references cited herein. (b) Amatore, C.; Gareil, M.; Savéant, J. M. *J. Electroanal. Chem.* **1984**, *176*, 377.

(7) (a) Savéant, J. M. *Acc. Chem. Res.* **1980**, *13*, 323. (b) Amatore, C.; Pinson, J.; Savéant, J. M.; Thiébaud, A. *J. Am. Chem. Soc.* **1981**, *103*, 6930. (c) Lexa, D.; Savéant, J. M. *J. Am. Chem. Soc.* **1982**, *104*, 3503. (d) Amatore, C.; Pinson, J.; Savéant, J. M.; Thiébaud, A. *J. Am. Chem. Soc.* **1982**, *104*, 817. (e) Amatore, C.; Oturan, M. A.; Pinson, J.; Savéant, J. M.; Thiébaud, A. *J. Am. Chem. Soc.* **1984**, *106*, 6318. (f) Amatore, C.; Savéant, J. M.; Combéllas, C.; Robveille, S.; Thiébaud, A. *J. Electroanal. Chem.* **1985**, *184*, 25. (g) Amatore, C.; Oturan, M. A.; Pinson, J.; Savéant, J. M.; Thiébaud, A. *J. Am. Chem. Soc.* **1985**, *107*, 3451. (h) Amatore, C.; Combéllas, C.; Pinson, J.; Oturan, M. A.; Robveille, S.; Savéant, J. M.; Thiébaud, A. *J. Am. Chem. Soc.* **1985**, *107*, 4846. (i) Amatore, C.; Combéllas, C.; Robveille, S.; Savéant, J. M.; Thiébaud, A. *J. Am. Chem. Soc.* **1986**, *108*, 4754. (j) Amatore, C.; Gareil, M.; Oturan, M. A.; Pinson, J.; Savéant, J. M.; Thiébaud, A. *J. Org. Chem.*, in press.

(8) (a) Other modes of induction, photochemical, alkali metals dissolved in ammonia, and appropriate redox couples have also been shown to be operative.^{8b-m} (b) Bunnett, J. F. *Acc. Chem. Res.* **1978**, *11*, 413. (c) Galli, C.; Bunnett, J. F. *J. Am. Chem. Soc.* **1981**, *103*, 7140. (d) Wolfe, J. F.; Carver, D. R. *Org. Prep. Proced. Int.* **1978**, *10*, 225. (e) Carver, D. R.; Greenwood, T. D.; Hubbard, J. S.; Komin, A. P.; Sachdeva, Y. P.; Wolfe, J. F. *J. Org. Chem.* **1983**, *48*, 1180. (f) Rossi, R. A. *Acc. Chem. Res.* **1982**, *15*, 164. (g) Rossi, R. A.; Pinski, R. H. *Aromatic Nucleophilic Substitution by the SRN1 Mechanism*; The American Chemical Society: Washington, D.C., 1983; ACS Monograph 178. (h) Penenory, A. B.; Pierini, A. B.; Rossi, R. A. *J. Org. Chem.* **1984**, *49*, 3834. (i) Beugelmans, R. *Bull. Soc. Chim. Belg.* **1984**, *93*, 547. (j) Tolbert, L. M.; Martone, D. P. *J. Org. Chem.* **1983**, *48*, 1185. (k) Tolbert, L. M.; Siddiqui, S. *J. Org. Chem.* **1984**, *49*, 1744. (l) Swartz, J. E.; Stenzel, T. T. *J. Am. Chem. Soc.* **1984**, *106*, 2520. (m) Galli, C.; Bunnett, J. F. *J. Org. Chem.* **1984**, *49*, 3041.

(9) Amatore, C.; Badoz-Lambling, J.; Bonnell-Huyghes, C.; Pinson, J.; Savéant, J. M.; Thiébaud, A. *J. Am. Chem. Soc.* **1982**, *104*, 1979.

(10) (a) M'Halla, F.; Pinson, J.; Savéant, J. M. *J. Electroanal. Chem.* **1978**, *89*, 347. (b) M'Halla, F.; Pinson, J.; Savéant, J. M. *J. Am. Chem. Soc.* **1980**, *102*, 4120. (c) At low water concentrations, the formation of the solvent carbanion is attested by its reaction with the electrogenerated aryl radicals leading to SRN1 nucleophilic substitution products.^{10a}

(11) (a) Belloni, J. *Actions Chim. Biol. Radiat.* **1971**, *15*, 47. (b) Bunnett, J. F.; Gloor, B. F. *J. Org. Chem.* **1974**, *39*, 383. (c) Bunnett, J. F.; Scamehorn, R. G.; Traber, R. P. *J. Org. Chem.* **1976**, *41*, 3677.

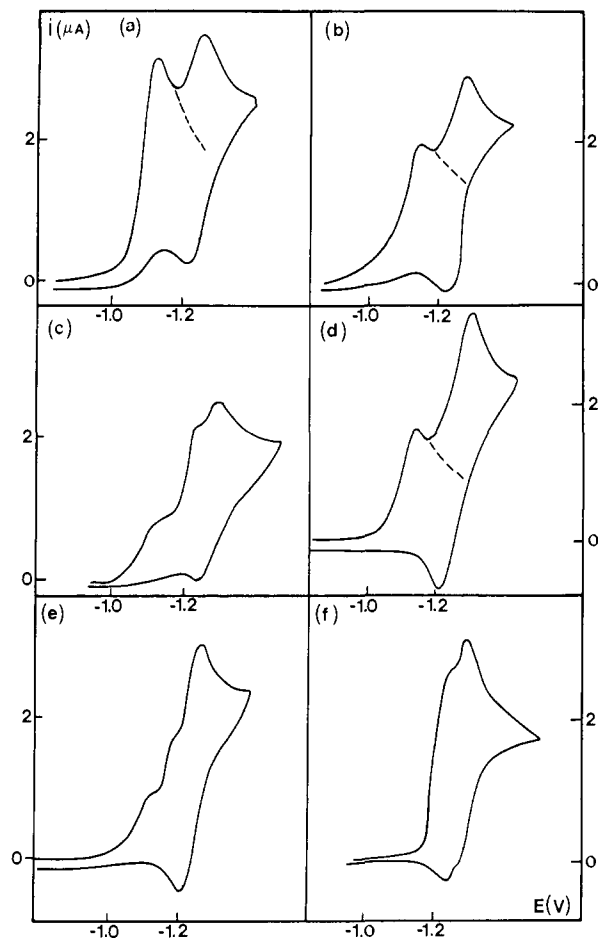


Figure 1. Cyclic voltammograms of 4-bromobenzophenone (2 mM) in liquid $\text{NH}_3 + 0.1 \text{ M KBr}$ at -40°C at a Hg electrode in the presence of 1 M urea. Sweep rate: $0.1 \text{ V}\cdot\text{s}^{-1}$. (a) Without addition of alcohol and protons; (b) in the presence of 100 mM 2-propanol; (c) in the presence of 480 mM 2-propanol; (d) in the presence of 16 mM benzhydrol; (e) in the presence of 80 mM benzhydrol; (f) benzophenone (2 mM) in the presence of 1 mM NH_4^+ .

H-atom-donor substrates¹² with use of the changes observed on the cyclic voltammograms of the aryl halides upon addition of these compounds to liquid ammonia.

Results and Discussion

Reduction of 4-Bromobenzophenone in Liquid NH_3 in the Presence of 2-Propanol and Benzhydrol. The cyclic voltammetry of 4-bromobenzophenone in liquid NH_3 in the presence of 0.1 M urea¹³ shows, at low sweep rates, a two-electron irreversible reduction peak followed by the one-electron reversible wave of benzophenone (Figure 1a). This behavior features the cleavage of the bromide ion from the initial anion radical (reaction 1) followed by the reduction of the ensuing 4-benzoylphenyl radical.⁵ It has been shown that the latter occurs in the solution (DISP mechanism) according to reaction 3' which matches the fact that the cleavage of the $\text{ArX}^{\cdot-}$ radical is slow, $k_1 = 590 \text{ s}^{-1}$ at -40°C .⁵

Upon addition of 2-propanol (Figure 1b,c), the first irreversible wave decreases gradually. Another irreversible wave located at the foot of the benzophenone one-electron reversible wave appears progressively. This new irreversible wave is the same as that

(12) (a) Data on the reactivity of various organic molecules as H-atom donors to aryl radicals can be found in ref 12b and 12c. (b) Bridger, R. F.; Russel, G. A. *J. Am. Chem. Soc.* **1963**, *85*, 3754. (c) Pryor, A.; Echols, J. T.; Smith, K. *J. Am. Chem. Soc.* **1966**, *88*, 1189.

(13) (a) Urea is a weak acid in liquid NH_3 , $\text{p}K_A = 12.9$.^{13b} It was added to the solution to avoid the reaction of NH_2^- ions, resulting from the neutralization of the $\text{Ar}^{\cdot-}$ carbanions, with the carbonyl group of 4-bromobenzophenone and benzophenone.^{5,13c} (b) Badoz-Lambling, J.; Herlem, M.; Thiébaud, A. *Anal. Lett.* **1969**, *2*, 35. (c) Amatore, C.; Chaussard, J.; Pinson, J.; Savéant, J. M.; Thiébaud, A. *J. Am. Chem. Soc.* **1979**, *101*, 6012.

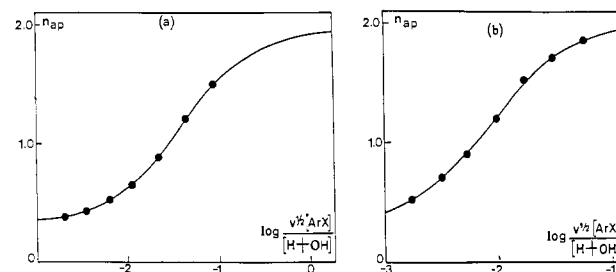


Figure 2. Cyclic voltammograms of 4-bromobenzophenone in liquid NH_3 at -40°C at a Hg electrode in the presence of 0.1 M urea. Variations of the apparent number of electrons, n_{ap} , with the concentration of benzhydrol (a) and 2-propanol (b) added to the solution. Sweep rate: $0.2 \text{ V}\cdot\text{s}^{-1}$ (a) $0.11 \text{ V}\cdot\text{s}^{-1}$; (b) 4-bromobenzophenone, concentration 2 (a) 1.15 mM (b).

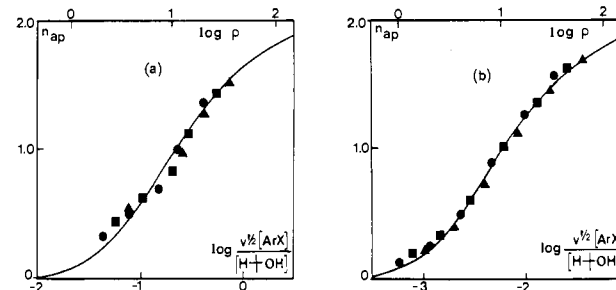


Figure 3. Cyclic voltammograms of 4-bromobenzophenone (2.9 mM) in liquid $\text{NH}_3 + 0.1 \text{ M KBr}$ at -40°C at a Hg electrode in the presence of a 0.5 M urea/ 10^{-2} M ureate buffer. Variations of the apparent number of electrons, n_{ap} , with concentrations of ArX and of alcohol and with the sweep rate $v = 0.38$ (\blacktriangle); 0.20 (\blacksquare); $0.11 \text{ V}\cdot\text{s}^{-1}$ (\bullet). (a) Benzhydrol, (b) 2-propanol. $\rho = (k_3/k_1^{1/2} k_2) ([\text{ArX}]/[\text{H}+\text{OH}]) (Fv/RT)^{1/2}$.

obtained upon adding to the solution a sub-stoichiometric concentration of a strong acid (NH_4^+). It features a proton-assisted reduction of benzophenone, giving rise to a wave which is partially governed by the diffusion of NH_4^+ ions toward the electrode.¹⁴ It increases at the expense of the further reversible wave, the latter disappearing when the concentration of NH_4^+ reaches that of benzophenone. These observations indicate that protons are generated during the reaction that causes the decrease of the 4-bromobenzophenone first wave upon addition of 2-propanol.

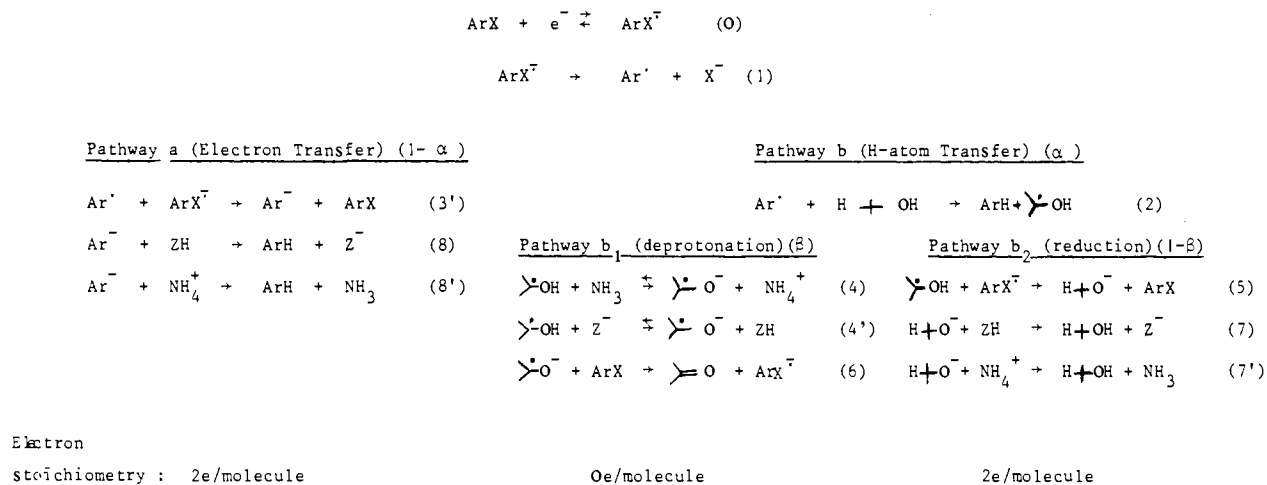
Similar observations are made when benzhydrol is added to the solution instead of 2-propanol (Figure 1d,e). There is, however, a difference: upon addition of the alcohol there is not only a decrease of the first wave of 4-bromobenzophenone but also an increase of the benzophenone wave. This shows that more benzophenone is formed as a consequence of the addition of benzhydrol to the solution. This is clearly confirmed by preparative scale experiments. Electrolysis of 2.8 mM 4-bromobenzophenone at -1.1 V ¹⁵ in the presence of 70 mM benzhydrol and 10 mM urea produces 5.2 mM benzophenone, i.e., almost twice the amount corresponding to the reductive cleavage of the starting compound. The reduction of all the 4-bromobenzophenone required 0.34 electron per molecule under these conditions.

Similarly, in the case of an aliphatic alcohol, 4-methyl-2-pentanol, which is not too volatile, the corresponding ketone, 4-methyl-2-pentanone, was found in the electrolysis products.

The decrease of the first peak of 4-bromobenzophenone upon addition of 2-propanol and benzhydrol is shown in Figure 2 in the case of an unbuffered medium containing urea and in Figure 3 for the case of a more basic urea/ureate buffered medium. The apparent number of electrons represented in these figures derives from the normalized peak current, $n_{\text{ap}} = 2 \times i_p/i_p^\circ$, where i_p and i_p° are the peak currents in the presence and absence of alcohol, respectively. It is observed that n_{ap} goes to zero upon addition

(14) Charlot, G.; Badoz-Lambling, J.; Tremillon, B. *Les Réactions Electrochimiques*; Masson: Paris, 1959; p 46.

(15) vs. $\text{Ag}/0.01 \text{ M Ag}^+$ which served as reference electrode in all the experiments in liquid ammonia described in this paper.



ZH : urea or other proton donors present in the solution (residual H₂O, NH₃...), Z⁻ : conjugate base of ZH.

Figure 4. Reaction scheme for the reduction of aryl halides in the presence of an alcohol.

Table I. Preparative Scale Electrolysis of 4-Bromobenzophenone in the Presence of Benzhydrol in Liquid NH₃^a

4-bromobenzophenone concn (mM)	benzhydrol concn (mM)	n_{ap} : electron stoichiometry (e/molecul)	$\alpha\beta^{d,e}$	benzophenone yield ^g $y = [\text{ArH}]/[\text{ArX}]$	$\alpha\beta^{d,f}$
2.8 ^b	70	0.34	0.83	1.88	0.88
7.0 ^c	41	1.0	0.50	1.50	0.50

^aTemperature -40 °C. Supporting electrolyte 0.1 M KBr. In the presence of 0.01 M urea. At -1.1 V vs. Ag/0.01 M Ag⁺. ^bWorking electrode Hg. ^cWorking electrode Pt. ^d α , fraction of the aryl radicals following pathways b (1 - α following pathway a); β , fraction of the alcohol radicals following pathway b1 (1 - β following pathway b2). ^eFrom the electron stoichiometry, $n_{ap} = 2 - 2\alpha\beta$. ^fFrom the benzophenone yield, $y = 1 + \alpha\beta$. ^gThe yield in benzophenone is determined by HPLC.

of the alcohol in the most basic medium (Figure 3) whereas it plateaus off at a constant value, between 0 and 1 in a more basic medium (Figure 2). In the latter case, the limiting value of n_{ap} matches that observed in preparative scale experiments.

These results suggest that the aryl radicals generated at the first reduction wave abstract H atoms to the alcohol molecules leading to the corresponding ketone. Concurrently electron transfer to Ar[·] yields, after protonation, ArH. The reaction scheme depicted in Figure 4 rationalizes the observations described above along the following lines.

The reduction of the aryl radical (pathway a, reaction 3') takes place in the solution rather than at the electrode because the cleavage reaction is slow as already discussed. The competing pathway, b, involves the abstraction of a hydrogen atom from an alcohol molecule leading to the corresponding neutral radical. This may deprotonate (pathway b1) upon reaction with the solvent, generating NH₄⁺ as observed experimentally in the presence of urea (reaction 4), or with the base of the buffer in the case where the solution is buffered (reaction 4') (experiments carried out in the presence of a urea/ureate buffer). In all cases, these reactions produce the ketyl anion radical which is further oxidized into the corresponding ketone. With 4-bromobenzophenone, owing to the slowness of the ArX⁻ cleavage, the oxidation of the ketyl anion radical is anticipated to occur in the solution (DISP regime) rather than at the electrode surface (ECE regime). The electron sink is then a molecule of the starting material, ArX, which triggers a chain process. Pathway b1 constitutes the electrocatalytic part of the overall reaction since it involves a zero electron/molecule stoichiometry in contrast with pathway a which corresponds to the exchange of two electrons per molecule. The alcohol radical may, however, undergo another reaction (pathway b2), viz, it may be reduced into the corresponding alcoholate ion (reaction 5).¹⁶ The latter will then be protonated by proton donors (for example, urea) present in the solution or by NH₄⁺ ions produced by reaction

4. By reference to previous studies,^{9,10} pathway b1 has been shown to predominate in the case where the H-atom donor was an alcoholate ion⁹ whereas pathway b2 prevailed in the case of Me₂SO or acetonitrile.¹⁰ In both cases, pathway a was competitively followed.

The existence of the competition between pathways a and b1 is attested by the decrease of the first peak height (featuring the apparent number of electrons per molecule) upon addition of alcohol. The existence of pathway b2 is attested by the fact that, when the pH is not too high, the decrease levels off as the concentration of alcohol increases and also that this limit is smaller and smaller as the medium becomes more and more alkaline. The fact that in unbuffered medium the n_{ap} limit is below one electron indicates that the ketyl radical deprotonates spontaneously (reaction 4).

The results of preparative scale experiments (Table I) are in keeping with the above reaction scheme. Let α designate the fraction of the aryl radicals that react along pathway b (1 - α follow pathway a) and β the fraction of alcohol radicals that follow pathway b1 (1 - β follow path b2). Then the total yield in benzophenone is $y = [\text{ArH}]/[\text{ArX}] = 1 + \alpha\beta$ and the apparent number of electrons per molecule is $n_{ap} = 2 - 2\alpha\beta$. It is seen (Table I) that there is an excellent agreement between the values of $\alpha\beta$ derived from n and y . We also note that the yield in benzophenone is significantly larger in the first than in the second experiment. There are two possible reasons for this. In the first experiment the concentration of benzhydrol is larger than in the second which favors pathway b vis-à-vis pathway a. The concentration of 4-bromobenzophenone is smaller in the first case than in the second which favors pathway b1 vis-à-vis pathway b2.

Another possible mechanism should, however, be considered, involving the prior deprotonation of the alcohol by the base of the buffer, or by electrogenerated bases in unbuffered medium, leading to the alcoholate which would then serve as the H-atom donor rather than the alcohol itself (alcoholates have been shown previously to be quite efficient H-atom donors toward aryl radical⁹). It is even conceivable that both reaction schemes can be followed simultaneously.

(16) Electron transfer to the alcohol radical should lead in a first stage to the corresponding carbanion. This is, however, very likely to be immediately converted into the alcoholate ion by intramolecular proton transfer.

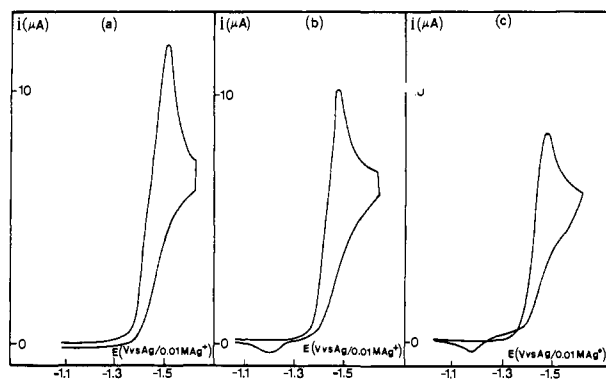
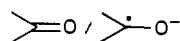


Figure 5. Cyclic voltammetry of 2-chloroquinoline (1.5 mM) in liquid $\text{NH}_3 + 0.1 \text{ M KBr}$ at -40°C at an Hg electrode in the presence of a 0.05 M urea/0.05 M ureate buffer. Sweep rate: $0.2 \text{ V}\cdot\text{s}^{-1}$. (a) Without benzhydrol; (b) with 60 mM benzhydrol; (c) with 180 mM benzhydrol.

Analyzing quantitatively the observed kinetics in the framework of the reaction scheme depicted in Figure 4¹⁷ leads to the following observations. The value of the kinetic parameter $k_3/k_1^{1/2}k_2$ can be derived from the experimental variations of n_{ap} in both the unbuffered (Figure 2) and buffered (Figure 3) cases.¹⁷ Using then the previously determined⁵ value of k_1 , 590 s^{-1} , and assuming that k_3 is close to the diffusion limit, $3 \times 10^{10} \text{ M}^{-1}\cdot\text{s}^{-1}$, in view of the fact that the reduction potential of 4-bromobenzophenone is much positive to the standard potential of the



couple, one obtains k_2 , the rate constant for H-atom abstraction. In the case of 2-propanol, the same value of k_2 , $4 \times 10^6 \text{ M}^{-1}\cdot\text{s}^{-1}$, is obtained from the experiments in buffered and unbuffered media. This indicates that the alcohol, rather than the alcoholate, is the actual H-atom source as expected from the very large difference between the pK_{A} s of urea (13.9^{13a}) and of 2-propanol (≈ 25 ¹⁸), leading to the conclusion that even if 2-propanol would react at a rate close to the diffusion limit ($3 \times 10^{10} \text{ M}^{-1}\cdot\text{s}^{-1}$), its equilibrium concentration is so small (10^{-11} times that of 2-propanol) that its participation can be regarded as negligible.

The situation is less unambiguous in the case of benzhydrol. The apparent value of k_2 is $2 \times 10^8 \text{ M}^{-1}\cdot\text{s}^{-1}$ in the urea/ureate buffer and $3 \times 10^7 \text{ M}^{-1}\cdot\text{s}^{-1}$ in the urea unbuffered medium. This points to a sizable participation of the alcoholate ion in the urea/ureate buffer and possibly in the urea unbuffered medium.¹⁹ This, however, also shows that benzhydrol itself, and not only the

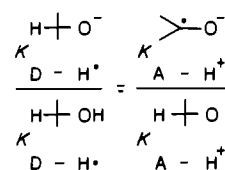
alcoholate, does participate in the reaction along the scheme depicted in Figure 4, at least in the unbuffered urea medium. The very fact that the n_{ap} limit obtained at high benzhydrol concentrations is well below 1 (0.34) also points to the same conclusion. Indeed, since benzhydrol certainly does not deprotonate spontaneously in liquid NH_3 ,¹⁹ H-atom abstraction from the alcoholate alone would lead to a limit of one electron per molecule.

Reduction of 2-Chloroquinoline in Liquid NH_3 in the Presence of Benzhydrol and 2-Propanol. The reduction of 2-chloroquinoline also shows an irreversible two-electron wave in the absence of added alcohol (Figure 5). The cleavage rate constant of the anion radical, $1.7 \times 10^4 \text{ s}^{-1}$,^{13c} is not very large which implies that the further electron transfer reactions are anticipated to take place in the solution, in a "DISP" context ($p = 45$ ^{6a}), as in the case of 4-bromobenzophenone.

The main difference with the latter compound is that the reduction potential is much more negative. Benzophenone, which is expected to be formed upon addition of benzhydrol to the solution, has a standard potential which is positive to the reduction potential of 2-chloroquinoline. The addition of benzhydrol should thus result in a decrease of the 2-chloroquinoline wave, down to a 1e/molecule stoichiometry leading to the anion radical of benzophenone rather than to benzophenone itself. The benzophenone anion radical thus formed should manifest itself by an anodic wave located in front of the 2-chloroquinoline wave. This is exactly what is observed experimentally (Figures 5, b and c).

We further note the tendency of the cyclic voltammograms to exhibit trace crossings as the concentration of benzhydrol increases. This has already been observed with related systems: reduction of aryl halides in the presence of alcoholate⁹ or in the presence of nucleophiles.⁷ This phenomenon²⁰ features the propagation of the chain propagation of the electrocatalytic process through reaction 6 (Figure 4).

A similar study was carried out with 2-propanol. In both cases, the reactivity of the 2-quinoyl radical was found smaller than that of the 4-benzoylphenyl radical:²¹ $k_2 = 10^6$ and $7 \times 10^4 \text{ M}^{-1}\cdot\text{s}^{-1}$ for benzhydrol and 2-propanol, respectively. The rate constant values for the corresponding alcoholates were found to be 2×10^7 and $2 \times 10^8 \text{ M}^{-1}\cdot\text{s}^{-1}$, respectively.⁹ Here again, diphenylcarbinolate is expected to participate in the reaction whereas this is not the case with isopropylate. As appears in the latter case, the alcohol is much less reactive (by more than 3 orders of magnitude) than the alcoholate.²² The relative driving forces for H-atom transfer of the alcoholate/alcohol couple are related to the relative basicities of the alcoholate and the corresponding ketyl anion radical:



(17) (a) The case where the apparent number of electrons goes to zero upon addition of alcohol, as observed in the urea/ureate buffer, corresponds to the competition between pathways a and b1. The interference of pathway b2 is then negligible as a consequence of the fact that the deprotonation reaction (4') overcomes the reduction reaction (5) owing to the strong basicity of the medium. The formal kinetics corresponding to this case is the same as previously developed for the electrochemical catalysis of SRN1 aromatic substitution and reaction of alcoholates with aryl halides.^{17b} The apparent number of electrons is then a function of a single parameter, $\rho = (k_3'/k_1^{1/2}k_2)([\text{ArX}]/[\text{H}-\text{OH}])^{1/2}$ according to the working curve shown in Figure 3b^{17b} which corresponds to the case where the alcohol is in excess over the aryl halide. This was applied to the case of 2-propanol. With the more reactive benzhydrol, the latter condition had to be removed and the theoretical analysis to be expanded to this case leading to the working curve shown in Figure 3a.^{17c} (b) Amatore, C.; Savéant, J. M.; Thiébaud, A. *J. Electroanal. Chem.* 1979, 103, 303. (c) Andrieux, C. P.; Savéant, J. M.; Thiébaud, A., submitted. (d) In the more acidic unbuffered urea medium, there is a competition between all three pathways. Competition between pathways a and b is governed by the same parameter ρ , while it is necessary to introduce an additional parameter describing the competition between pathways b1 and b2. The treatment of this kinetic problem is given elsewhere.^{17c}

(18) (a) In experiments described in ref 9a, it is seen that acetone is a stronger acid than 2-propanol. Thus the pK_{A} of 2-propanol is higher than 22.5.^{18b} (b) Herlem, M.; Thiébaud, A. *Bull. Soc. Chim. Fr.* 1971, 719.

(19) The pK_{A} of benzhydrol in liquid NH_3 is not known with certainty. Addition of benzhydrol to a solution of hydroxide ions causes the oxidation wave of these ions to decrease and not only to be shifted anodically. This indicates that the pK_{A} of benzhydrol is several units smaller than that of water (19^{18b}), and thus, presumably, only a few pK_{A} units larger than that of urea.

(20) Amatore, C.; Pinson, J.; Savéant, J. M.; Thiébaud, A. *J. Electroanal. Chem.* 1980, 107, 59.

(21) As are their compared reactivities toward nucleophiles.^{7b}

(22) (a) This is in keeping with previous work showing that methoxide ions are about 45 times more reactive than methanol toward H-atom abstraction by 4-nitrophenyl radicals which were produced by thermal decomposition of methyl 4-nitrophenyl azoether in methanolic CH_3ONa .^{22b} Competing iodine and electron transfer were, however, indicated as possible sources of uncertainty. H-atom transfer reactions from methanol-methoxide mixtures to aryl radicals produced in various ways, yielding formaldehyde, have been reported earlier.^{22c-e} The mechanistic descriptions of the reaction, iodide abstraction by the $^{\cdot}\text{CH}_2\text{OH}$ radical in one version,^{22c,d} H-atom abstraction from methanol rather than from methoxide ions in another,^{22e} were latter abandoned for reaction schemes^{22b} similar to that described in the present paper. (b) Boyle, W. J.; Bunnett, J. F. *J. Am. Chem. Soc.* 1974, 96, 1418. (c) Bunnett, J. F.; Wamser, C. C. *J. Am. Chem. Soc.* 1966, 88, 5534. (d) Brydon, D. L.; Cadogan, J. I. G. *J. Chem. Soc., Chem. Commun.* 1966, 744. (e) Bunnett, J. F.; Wamser, C. C. *J. Am. Chem. Soc.* 1967, 89, 6712. (f) By reference to SRN1 reactions,^{7,8} other ways than electrochemical are conceivable for inducing the production, from the aryl halides, of the aryl radicals that abstract the H atoms from the alcohols and alcoholates. This appears to be possible with use of photochemical induction or alkali metals dissolved in liquid ammonia.^{22g} (g) Bunnett, J. F., personal communication.

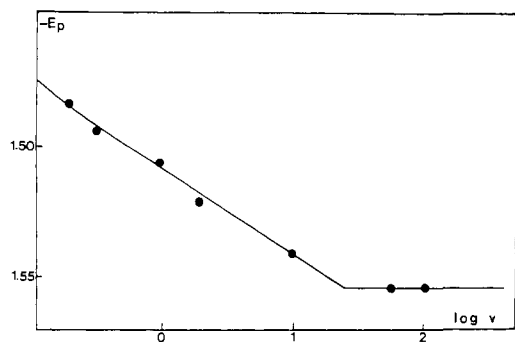


Figure 6. Cyclic voltammetry of 4-bromobenzophenone (2 mM) in 2-propanol + 0.1 M NBu_4BF_4 at 22 °C on a Hg electrode. Variations of the peak potential (in V vs. SCE) with the sweep rate (in $\text{V}\cdot\text{s}^{-1}$).

Table II. Reduction of 4-Bromobenzophenone in 2-Propanol. Apparent Number of Electrons^a as a Function of the Acidbasicity of the Reaction Medium and of the Sweep Rate

medium ^b	sweep rate ($\text{V}\cdot\text{s}^{-1}$)	apparent no. ^a of electrons
neutral	0.2	1.02
	1	0.99
	2	0.99
	10	1.02
H_2O (0.33 M) OH^- (0.015 M)	0.2	0.20
	1	0.39
	2	0.50
PhOH (0.01 M)	1	1.80

^aFrom the peak height in cyclic voltammetry. ^b2-Propanol + 0.1 M NBu_4BF_4 . ^c NBu_4OH .

Since ketyl radicals are weaker bases than the corresponding alcoholates,²³ it follows that, on thermodynamical grounds and thus probably from a kinetic point of view, the alcoholates are expected to be better H-atom donors than the corresponding alcohols as found experimentally here.

Reduction of Aryl Halides in Pure Alcohols. From a preparative point of view it is simpler to carry out the reaction with use of the H-atom donor, i.e., the alcohol, as the solvent. This is the reason why we performed the following set of cyclic voltammetry and preparative scale experiments using 2-propanol as the solvent and basing their interpretation on what was found in liquid ammonia as described above.

In 2-propanol at room temperature, 4-bromobenzophenone exhibits a wave which is irreversible at low sweep rate and becomes reversible upon raising the sweep rate. At low sweep rate this first wave is followed by the wave of benzophenone. The peak height of the first wave corresponds to the exchange of one electron per molecule. The variations of the peak potential with the sweep rate (Figure 6) indicate that the reduction follows an "EC" mechanism. The follow-up chemical reaction, viz. the cleavage of the anion radical, has a rate constant $k_1 = 10^3 \text{ s}^{-1}$ (i.e., faster than in liquid NH_3 as expected from the difference of temperatures) and a standard potential $E^\circ_{\text{ArX}^-/\text{ArX}^\cdot} = -1.52 \text{ V}$ as derived from the peak potential vs. sweep rate variations.²⁴

The apparent number of electrons, as derived from the peak height by comparison with a standard (fluorenone), appears to be a function of bases or acids added to the solution. The cyclic voltammetry results we obtained in this connection are summarized in Table II.

When no base or acid is added to the solution $n_{\text{ap}} = 1$ whatever the sweep rate. Since there is no variation of n_{ap} with the sweep rate, pathways b predominate over pathway a. In this context,

(23) (a) $(\text{Ph})_2\text{C}-\text{OH}$ has a $\text{p}K_{\text{A}}$ several units below that of benzhydrol.^{23b} The same is true for $\text{CH}_3\text{C}-\text{OH}$ and CH_3OH ^{23b} and probably for other alcohols.^{23c,d} (b) Porter, G.; Wilkinson, F. *Trans. Faraday Soc.* **1961**, *97*, 1686. (c) Sherman, W. V. *J. Am. Chem. Soc.* **1967**, *89*, 1302. (d) Steward, R. *Oxidation Mechanisms*; Benjamin: New York, 1964; p 60.

(24) Nadjo, L.; Savéant, J. M. *J. Electroanal. Chem.* **1973**, *48*, 113.

the hydroxyisopropyl radical is deprotonated by the bases generated from its reduction along pathway b2, i.e., OH^- from residual water or isopropylate from the solvent. In contrast with what was observed in liquid NH_3 there is no spontaneous deprotonation of the hydroxylalkyl radical as indicated by the fact that n_{ap} does not fall below 1. This is in keeping with ammonia being a stronger base than 2-propanol. When phenol is added to the solution, n_{ap} increases, becoming close to 2. This is explained by the fact that phenol being a stronger acid than water or 2-propanol itself, competition is in favor of pathway b2 over pathway b1.

In the alkaline $\text{H}_2\text{O}/\text{OH}^-$ buffer, n_{ap} is significantly smaller than 1 and increases with sweep rate. The parameter ρ , which measures the competition between pathway a and pathway b, has the same vanishingly small value as in the case of the neutral medium discussed above. The value of n_{ap} therefore reflects the competition between pathways b1 and b2.

As in the case of liquid NH_3 and benzhydrol, the question should again be raised of the compatibility of the experimental observations with another possible mechanism involving the alcoholate generated by deprotonation of the alcohol as the H-atom source. In this framework, the results obtained in neutral medium ($n_{\text{ap}} = 1$ whatever v) can be interpreted as reflecting the deprotonation of the alcohol into alcoholate by the base (Ar^-) resulting from the reduction of Ar^* (reaction 3') followed by an immediate and total H-atom abstraction by Ar^* of the alcoholate thus generated ultimately yielding the ketone through reaction 6. H-atom abstraction is thus fast as compared to the reduction of Ar^* . In the $\text{H}_2\text{O}/\text{OH}^-$ buffer, reaction of OH^- with 2-propanol, which is likely to be reversible and slightly endergonic, is an additional source of alcoholate. The latter would immediately react with Ar^* as seen before. Since there is no other reaction than competing with the formation of the ketyl anion radical and the ketone, the apparent number of electrons should then be zero. This is not what is experimentally observed, thus ruling out the mechanism in which the alcoholate is the source of H atoms and confirming the reaction scheme of Figure 4 in which the H-atom source is the alcohol itself.

Similar results were obtained with 9-bromoanthracene instead of 4-bromobenzophenone. The rate constant of the cleavage of the $\text{ArX}^{\cdot-}$ anion radical is only slightly larger (10^4 s^{-1} instead of 10^3 s^{-1}). The competition between pathway a and pathway b thus remains within the DISP regime. This is not the case with 1-bromonaphthalene where the apparent number of electrons is close to 2. This can be explained by the fact that the cleavage of the $\text{ArX}^{\cdot-}$ anion radical being now much faster (25 times faster than with 9-bromoanthracene in DMF ^{3a}) the competition takes place within the less favorable ECE regime as shown in the investigation of SRN1 reactions where the H-atom abstraction reaction is replaced by the addition of a nucleophile.⁷ The aryl radicals are then generated close to the electrode surface and have thus little chance to react with the alcohol before being reduced at the electrode surface.

Preparative scale experiments were carried out with 4-bromobenzophenone and 9-bromoanthracene as substrates. Acetone was found in the reaction products in amounts that depend on the substrate and the acidity of the medium. In all cases the starting ArX was quantitatively converted into the hydrogenolysis product ArH . The results are summarized in Table III.

As expected from the above discussion the yield of acetone increases with the basicity of the medium. From what has been seen earlier, the yield of acetone is equal to $\alpha\beta$ and n_{ap} to $2(1 - \alpha\beta)$, α being the ratio of pathway b over pathway a, and β that of pathway b1 over pathway b2. We can thus predict what should be the yield from the value of n_{ap} and compare to what was actually found. It is seen (Table III) that the agreement is quite satisfactory. The experimental yields are systematically slightly lower than the predicted yields which most probably result from some evaporation of acetone in spite of the care taken to avoid it.

Reduction of Aryl Halides in the Presence of Other Alcohols and Other H-Atom Donors. Table IV summarizes a series of preliminary cyclic voltammetry experiments in liquid ammonia involving 4-bromobenzophenone and several H-atom donors,

Table III. Preparative Scale Electrolysis in 2-Propanol^a

ArX	ArX concn (mM)	medium	n_{ap}	ArH concn (mM)	acetone concn (mM)	
					exptl	theoretical ^b
4-bromobenzophenone	10	0.015 M OH ⁻ /0.33 M H ₂ O	0.3	10	7.5	8.8
9-bromoanthracene	10	0.04 M PhOH	1.7	10	traces	1
	10	neutral	1.0	10	4	5
	10	0.015 M OH ⁻ /0.33 M H ₂ O	0.45	10	6	7.5

^a+0.1 M NBu₄BF₄ at 22 °C; mercury cathode. ^bFrom $n_{ap} = 2(1 - \{[(CH_3)_2CO]/[ArX]\})$.

Table IV. Reduction of 4-Bromobenzophenone in Liquid NH₃^a in the Presence of Various H-Atom Donors

H-atom donor	H-atm donor concn ^b	n_{ap} ^c
methanol ^e	800	1.22
ethanol ^f	400	0.86
3-methylbutanol ^e	550	0.96
4-methylpentanol ^f	320	0.92
1,2-ethanediol ^f	480	0.86
2,3-butanediol ^f	400	0.66
glycerol ^f	350	0.90
triethylamine ^e	630	0.56
<i>N,N</i> -dimethylformamide ^e	480	1.56 ^d
<i>N,N</i> -diethylformamide ^f	282	1.54

^a+0.1 M KBr, at -40 °C. ^bIn mM. ^cFrom the relative decrease of the peak height upon addition of the H-atom at 0.1 V·s⁻¹ unless otherwise stated. ^d0.2 V·s⁻¹. ^ePt electrode. ^fHg electrode.

alcohols, diols, amines, and amides. In all cases a significant decrease of the apparent number of electrons below 2 is observed, suggesting the existence of a reaction of the same type as with benzhydrol and 2-propanol.

A few additional experiments were carried out with *n*-butanol and dimethylformamide, using them as the solvent. The reduction of 9-bromoanthracene (10 mM) in *n*-butanol leads to the quantitative formation of anthracene and to half a mole of butanal per mole of 9-bromoanthracene consumed. This involves the passage of 1 electron per molecule.

In the reduction of 4-bromobenzophenone in DMF, the apparent number of electrons is one, as in 2-propanol when no acid or base is introduced in the solution. It decreases below 1 upon addition of NBu₄OH and comes back to 1 after neutralization. The same observations were made with 9-bromoanthracene. In this case, preparative scale electrolysis in neutral medium showed that anthracene is quantitatively produced after passage of one electron per molecule. Long time range experiments in alkaline media were precluded by the chemical instability of DMF.

Although the product in which DMF is converted has not been identified for the moment, these results suggest that a similar type of reaction, involving H-atom transfer and, competitively, deprotonation followed by reoxidation on one hand and reduction on the other, is operative as in 2-propanol. With this in mind we can now understand the previously observed variations of the apparent number of electrons between 1 and 2 in the reduction of a large series of aryl halides in DMF.^{3a} We note in this connection that $n_{ap} = 2$ for 10 compounds which all have ArX⁻ cleavage rate constants larger than 10⁷ s⁻¹ and ArX/ArX⁻ standard potentials more negative than -2.0 V vs. SCE. For all the other compounds, having k_1 s smaller than 10⁷ s⁻¹ and E°_{ArX/ArX^-} more positive than -2 V, n_{ap} decreases from 2 to 1 as k_1 decreases and E°_{ArX/ArX^-} increases. This can be rationalized in the context of a reaction scheme similar to that of Figure 4. A large k_1 leads to a fast reduction of Ar[•] at the electrode surface in the context of an ECE regime. The aryl radicals that would survive this reduction could abstract an H-atom to DMF, but the resulting radical would then be generated under very reducing conditions leading to a fast reduction in the solution (reaction 5) or at the electrode surface.

The situation met with acetonitrile and dimethyl sulfoxide is different in the following respects. As shown previously,¹⁰ H-atom abstraction also occurs but the resulting solvent radical is immediately reduced into the corresponding carbanion which is either

protonated or reacts with the aryl radical along a SRN1 process. This difference in behavior is likely to be mostly related to the fact that with MeCN and Me₂SO, the radical deriving from H-atom abstraction bears an electron-withdrawing group on the functional carbon and is hence easier to reduce than in the case of the compounds investigated in this work, where the functional carbon bears in contrast an electron-donating group (OR, NR₂, NCOR).

Conclusions

The above investigation of the reduction of aryl halides in the presence of alcohols has shown that the aryl radical generated upon reductive cleavage of the starting compound abstracts a hydrogen atom from the alcohol leading to the corresponding carbonyl compounds along an electrocatalytic process consuming a vanishingly small amount of electricity. This implies the deprotonation of the intermediate hydroxyalkyl radical by bases introduced in the solution or generated from side-reduction of the aryl radical and/or the hydroxyalkyl radical. In liquid ammonia, a spontaneous deprotonation reaction also takes place. Two main competing reactions were characterized involving the electrode or solution reduction of the aryl radical and/or the hydroxyalkyl. They both correspond to the consumption of two electrons per molecule of aryl halide. The kinetics of the competition have been analyzed and the predicted behaviors shown to agree well with the experimental data. In the cases where the rate constants of the H-atom abstraction could be determined, the alcohols were found to be less reactive than the corresponding alcoholates.

The role of the solvent or of other compounds introduced in the solution on electrochemical reductions or oxidation is usually thought of in terms of their Lewis and Brønsted acid-base properties: acids react on basic species generated upon reduction and bases on acid species generated upon oxidation. The results of the present work associated with those of previous studies¹⁰ underscore the importance of their H-atom donor character. Once an H-atom abstractor, here the aryl radical, is produced, the solvent or other added compounds may transfer a hydrogen atom, leading to products along an electron stoichiometry which varies between 0 and 2 according to the redox and acid-base properties of the resulting radical.

The present study has provided a new example, besides SRN1 processes,^{7,8} of a chemical reaction, not involving the transfer of an electrical charge, that can be induced by electron injection. It is likely that the electrochemical approach followed here is not unique and that other modes, photochemical and chemical, of electron injection can be used as well. The reaction amounts to the oxidation of electrically neutral substrates under reducing conditions where the key intermediates, viz., the aryl radicals, are produced. From the preliminary results obtained with other H-atom donors than alcohols there is little doubt that the scope of the reaction could be further enlarged.

Experimental Section

Instrumentation and Procedures. The electrochemical instrumentation and procedures in liquid ammonia were the same as already described.⁹ Mercury or platinum were used as working electrode material, and the reference electrode was 0.01 M Ag⁺/Ag electrode, the supporting electrolyte being KBr (0.1 M). In 2-propanol (distilled before use), NBu₄BF₄ was used as the supporting electrolyte in 0.2 M concentration. The working electrode was a mercury electrode in cyclic voltammetry as in preparative scale electrolysis. The reference electrode was an aqueous saturated calomel electrode (SCE). In preparative scale electrolysis the counterelectrode was a platinum grid. The anodic and cathodic com-

partments were separated by a Nafion membrane. The volatile compounds, and especially acetone which is the main product we looked for, are forced to remain in the solution by means of a condenser, the temperature of the circulating liquid being maintained at 5 °C. The reaction products, acetone and ArH, were titrated by gas chromatography with 10% FFAP and OV17 columns for the volatile and heavy products, respectively. When acetone is found in the cathodic compartment it is necessary to prove that it comes from the electrocatalytic reaction and not, through the Nafion membrane, from the anodic compartment where it is produced by oxidation of 2-propanol. This problem was handled as follows. The reduction of 1-bromonaphthalene in 2-propanol involves the exchange of two electrons per molecule and should not thus product acetone. We find acetone in the anodic compartment but not, as expected, in the cathodic compartment, showing that permeation of acetone

through the Nafion membrane separator is negligible during electrolysis. This shows that the acetone found in the cathodic compartment with other aryl halides does come from the cathodic electrocatalytic reaction.

Experiments were also carried out in *n*-butanol (distilled before use) with 9-bromoanthracene. In this case, butanal was formed and was identified by mass spectroscopy (*m/e* 15 (22), 27 (100), 28 (28), 39 (40), 41 (64), 43 (79), 44 (84), 72 (47)).

Registry No. MeOH, 67-56-1; EtOH, 64-17-5; (CH₃)₂CH(CH₂)₂OH, 123-51-3; (CH₃)₂CH(CH₂)₃OH, 1320-98-5; HO(CH₂)₂OH, 107-21-1; CH₃CH(OH)CH(OH)CH₃, 513-85-9; Et₃N, 121-44-8; Me₂NCHO, 68-12-2; PhOH, 108-95-2; OH⁻, 14280-30-9; 4-bromobenzophenone, 90-90-4; 2-chloroquinoline, 612-62-4; 9-bromoanthracene, 1564-64-3; 2-propanol, 67-63-0; benzhydrol, 91-01-0; glycerol, 56-81-5.

Reactions That Proceed with a Combination of Enantiotopic Group and Diastereotopic Face Selectivity Can Deliver Products with Very High Enantiomeric Excess: Experimental Support of a Mathematical Model

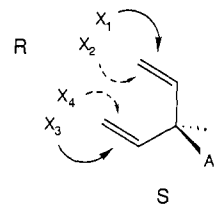
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Abstract: A generic class of reactions is described that involve the selective addition of a chiral, nonracemic reagent to one of four heterotopic faces of a substrate that contains a prosterogenic atom (or atoms) equipped with ligands that are enantiotopic and unsaturated. These reactions comprise a subclass of group selective transformations that couple a kinetic resolution to an initial asymmetric synthesis to provide primary products with enhanced levels of enantiomeric purity. Since four heterotopic faces are available for reaction with the reagent in the achiral substrate and two in the primary (monoaddition) products, the kinetics are complicated relative to the simple enantiotopic group selective reaction. A mathematical model of the above reaction process has been developed, and an analytical solution to the set of six simultaneous nonlinear differential rate equations has been obtained that provides an equation to evaluate the concentration of the substrate, reagent, and products as a function of time. Several reaction processes have been identified as probable candidates for membership to this reaction class. Finally, the Sharpless asymmetric epoxidation has been examined with three achiral substrates and shown to provide epoxy alcohol products whose enantiomeric purity increased as the reaction proceeded toward completion, a result that is in accord with the mathematical model.

An important feature of certain reactions that proceed with enantiotopic group selectivity is that a kinetic resolution will be coupled to the initial asymmetric synthesis, resulting in products with unusually high values of enantiomeric excess (ee). The first example of this process was described by Sih and co-workers as part of their studies of the enzyme-catalyzed hydrolysis of achiral diesters to chiral, nonracemic monoesters.¹ The initial hydrolysis takes place with enantiotopic group selectivity to provide an enantiomerically enriched monoester (asymmetric synthesis). The same enzyme catalyzes a second hydrolysis of the primary, monoester products with greater efficiency for the minor enantiomer (kinetic resolution). By this mechanism, the ee of the monoester products was demonstrated to increase as the reaction proceeded toward completion. Recently, a reagent mediated (nonenzymatic)

reaction process in this same category was described by Bosnich and co-workers that involved a group selective deuterium-hydrogen exchange in a chiral cobalt-glycine complex.²



The process of asymmetric synthesis can be achieved by group and/or face selective transformations.³ Reactions that proceed with a combination of group *and* face selectivity can have properties that are significant with regard to stereoselective synthesis. For example, a diastereotopic group and face selective spiroketalization reaction was recently employed to introduce multiple stereocenters along a chain of an ionophore subunit.⁴ In this paper, we report a mathematical model and examples of a class

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