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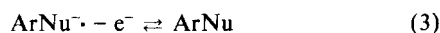
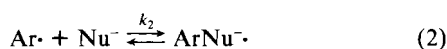
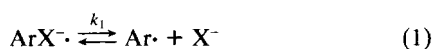
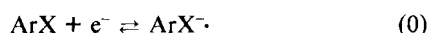
Nucleophile and Aryl Radical Reactivity in $S_{RN}1$ Aromatic Nucleophilic Substitution Reactions. Absolute and Relative Electrochemical Determination

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Abstract: Three electrochemical methods are used to obtain the rate constants of the $Ar\cdot + Nu^-$ reaction. In the direct cyclic voltammetric method, the data are derived from the decrease of the substrate peak current upon addition of the nucleophile while in the relative method they are obtained from the peak heights of the two substitution products observed upon repetitive cycling of the substrate solution in the presence of two nucleophiles. In the redox catalysis method, the reduction of the substrate is catalyzed by an exogenous reversible couple and the data are derived from the decrease of the catalytic current upon addition of the nucleophile. All three methods were combined to determine the reactivities of a series of 26 aryl radical-nucleophile couples. In most cases, the rate constant is close to the diffusion limit. The exceptions concern the 2-quinolyl and 2-pyridyl radicals. The results are discussed in terms of energy difference between the σ^* and π^* orbitals in the driving force of the reaction as related to characteristic standard potentials and bond energies.

$S_{RN}1$ aromatic nucleophilic substitution is henceforth a well-documented reaction.² To proceed at significant rates, it requires a reductive stimulation which can be effected chemically,^{2a,b,d,3} photochemically,^{2a,b,d} or electrochemically.^{2c} This feature, as well as the observed inhibiting effect of radical scavengers, led to the proposal⁴ that the actual electrophile in the substitution process is the aryl radical, $Ar\cdot$, formed upon reductive cleavage of the starting compound ArX , rather than ArX itself, suggesting the reaction mechanism

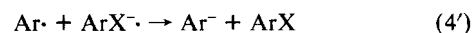


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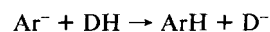


where $+e^-$ stands for the electron source and $-e^-$ for any electron sink present in the medium able to reoxidize the anion radical ($ArNu^{\cdot-}$) of the final substitution product, $ArNu$. The starting compound may itself act as an electron sink, hence giving rise to a chain process through reaction 3' which regenerates $ArX^{\cdot-}$, starting again a new cycle. Electrochemistry provides a convenient means for inducing $S_{RN}1$ reactions under controllable conditions since the electrode can serve as electron source and sink, the energy of which can be tuned by adjusting the potential.^{2c} Besides, electrochemical techniques, such as cyclic voltammetry, have

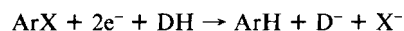
proved particularly useful for assessing the reaction mechanism, especially the central role of the aryl radical $Ar\cdot$ as sketched in the above scheme, taking advantage of the previously acquired knowledge of the electrochemical reduction mechanism of aromatic halides.^{5a} This involves the intermediacy of $Ar\cdot$ formed upon reactions 0 and 1 which can be traced back by means of its reduction at the electrode and/or by $ArX^{\cdot-}$ in the solution



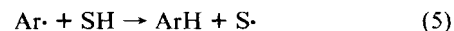
followed by the neutralization of $Ar^{\cdot-}$ by a proton donor (trace water or the solvent itself in most cases)



leading to an overall $2e^- + H^+$ hydrogenolysis of the starting molecule



Reactions 4 and 4' are the main modes for the deactivation of the aryl radicals produced by reactions 0 and 1 in poor H-atom-donating solvents such as liquid ammonia,^{5b,c} a solvent most frequently used for $S_{RN}1$ reactions.² In usual organic solvents, H-atom transfer from the solvent to the aryl radicals is an additional mode of deactivation of $Ar\cdot$



leading again to the hydrogenolysis product and to a 2e stoichiometry in the case where $S\cdot$ is easier to reduce than ArX .^{5d,6}

Reactions 4 and 4' are extremely fast, practically at the diffusion limit, owing to the fact that $Ar\cdot$ is much easier to reduce⁷ than most of the ArX commonly used as substrate in $S_{RN}1$ reactions. Reaction 5 is also quite fast which makes it able to compete, taking into account the fact that SH is present in large concentration, with reactions 4 and 4' in organic solvents.^{5d}

In the presence of a nucleophile, reactions 4, 4', and 5 compete with reaction 2, giving rise to a mixture of the desired substitution

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(2) (a) Bunnett, J. F. *Acc. Chem. Res.* **1978**, *11*, 413. (b) Wolfe, J. F.; Carver, D. R. *Org. Prep. Proced. Int.* **1978**, *10*, 225. (c) Savéant, J. M. *Acc. Chem. Res.* **1980**, *13*, 323. (d) Rossi, R. A.; Rossi, R. H. "Aromatic Nucleophilic Substitution by the $S_{RN}1$ Mechanism"; American Chemical Society: Washington, DC, **1983**; ACS Monogr. No. 78.

(3) (a) In most cases, solvated electron in liquid ammonia was the reductant. However, other reducing species can be used as well such as the anion radical of the substituted product^{3b} and various other aromatic and heteroaromatic anion radicals as described in ref 3c and d and in the present paper. (b) Amatore, C.; Pinson, J.; Savéant, J. M.; Thiébaud, A. *J. Am. Chem. Soc.* **1981**, *103*, 6930. (c) Swartz, J. E.; Stenzel, T. T. *J. Am. Chem. Soc.* **1984**, *106*, 2520. (d) Amatore, C.; Oturan, M. A.; Pinson, J.; Savéant, J. M.; Thiébaud, A. *J. Am. Chem. Soc.* **1984**, *106*, 6318.

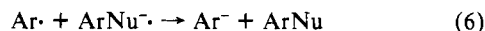
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(6) (a) Reaction 5 corresponds to a 2e stoichiometry for easily reduced $S\cdot$ which is the case with acetonitrile and Me_2SO .^{5d} With other solvents such as alcohols, DMF, etc., $S\cdot$ may undergo other follow-up reactions, leading to a 1e electron stoichiometry.^{6b} (b) Andrieux, C. P.; Combéllas, C.; Savéant, J. M.; Thiébaud, A.; Zann, D., unpublished results.

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product ArNu and the hydrogenolysis product ArH . An additional homogeneous electron transfer to Ar^\cdot takes place in the presence of the nucleophile involving the ArNu^\cdot as the electron source



For the same reasons as given above, its rate is likely to be close to the diffusion limit. In homogeneous systems, these reactions are the main termination steps of the chain propagation process.⁸ Another, more quickly obtainable, measure of the outcome of the competition is the height of the ArX wave in cyclic voltammetry. In the absence of nucleophile, this is a two-electron irreversible wave due to the rapid consumption of Ar^\cdot along reactions 4, 4', and 5.⁶ In the presence of Nu^- , the limit of the wave height corresponding to complete predominance of reaction 2 is zero election in the case where ArNu is more difficult to reduce than ArX and one election in the converse situation. The variation of the wave height between 2 and 0 or 2 and 1, according to the case, is therefore a quantitative measure of the rate of reaction 2 vis-a-vis that of reactions 4, 4', and 5. It is thus possible to predict the variations of the peak height with the available experimental variables: time scale (i.e., sweep rate in cyclic voltammetry) and ArX and Nu^- concentrations, in the context of the preceding mechanism. It has been shown, on several examples, that the predictions thus made do fit the experimental data.^{2c,3b,9}

The measurement of the decrease of the ArX wave upon addition of the nucleophile thus provides a means for determining the rate constant, k_2 , of the addition of the nucleophile on Ar^\cdot by what we will term, in the following, the direct electrochemical method. More precisely, in a poor H-atom-donating solvent, what is thus obtained is the ratio k_2/k_1 (k_1 is the cleavage rate constant of the ArX^\cdot radical) under ECE conditions, i.e., when the heterogeneous electron transfers (3) and (4) predominate over the homogeneous electron transfers, (3'), (4'), and (6), or $k_2k_1^{1/2}/k_d$ (k_d is the diffusion limit) under the converse (DISP) conditions. Several systems have been characterized by this procedure. It must be noted, however, that it requires the value of k_1 to be independently known which is not always possible. On the other hand, the method fails when either k_2 is so high that the current height too rapidly falls to its limiting value (0 or 1e) or when k_2 is so low that the nucleophilic attack cannot efficiently compete with the various reactions that deactivate Ar^\cdot (reactions 4, 4', 5, and 6). The latter point is particularly crucial when k_1 is large enough for ECE conditions to prevail: if $k_2[\text{Nu}^-]/k_1$ is less than 1%, the ensuing decrease of the ArX wave will itself be less than 10%, resulting in a poor accuracy in the determination of the ratio and therefore of k_2 .

In order to cover the largest possible range of systems in the aim of relating the $\text{Ar}^\cdot + \text{Nu}^-$ reactivity to the structures of Ar and Nu^- , implementation by other methods is clearly warranted.

In this connection, Galli and Bunnett¹⁰ have recently developed a method which allows the relative reactivities of two nucleophiles toward the same ArX to be measured. It is based on the determination of the ratio of the yields in ArNu_1 and ArNu_2 when the two nucleophiles Nu_1^- and Nu_2^- are reacted simultaneously on the substrate ArX under photochemical or solvated electron stimulation. Then

$$\frac{k_{2,1}}{k_{2,2}} = \frac{[\text{ArNu}_1]}{[\text{ArNu}_2]} \frac{[\text{Nu}_2^-]}{[\text{Nu}_1^-]}$$

The relative reactivity of the phenyl radical with several nucleophiles in liquid NH_3 has been determined in this way.¹⁰

(8) Amatore, C.; Pinson, J.; Savéant, J. M.; Thiébaud, A. *J. Am. Chem. Soc.* **1981**, *103*, 6930.

(9) (a) Amatore, C.; Chaussard, J.; Pinson, J.; Savéant, J. M.; Thiébaud, A. *J. Am. Chem. Soc.* **1979**, *101*, 6012. (b) Amatore, C.; Savéant, J. M.; Thiébaud, A. *J. Electroanal. Chem.* **1979**, *103*, 303. (c) Amatore, C.; Pinson, J.; Savéant, J. M.; Thiébaud, A. *J. Electroanal. Chem.* **1980**, *107*, 59. (d) Amatore, C.; Pinson, J.; Savéant, J. M.; Thiébaud, A. *J. Electroanal. Chem.* **1980**, *107*, 75. (e) Amatore, C.; Pinson, J.; Savéant, J. M. *J. Electroanal. Chem.* **1981**, *123*, 231.

(10) Galli, C.; Bunnett, J. F. *J. Am. Chem. Soc.* **1981**, *103*, 7140.

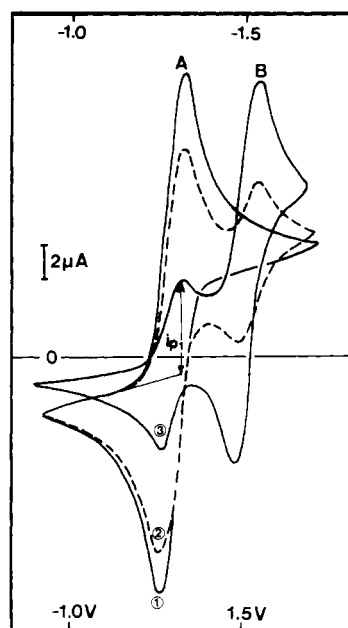


Figure 1. Repetitive cyclic voltammetry of 4-chlorobenzonitrile (3–8 mM) in the presence of PhS^- and $(\text{EtO})_2\text{PO}^-$ in liquid NH_3 + 0.1 M KBr on a bright platinum electrode. Temperature: -38°C . Sweep rate: 0.2 V s^{-1} . $[(\text{EtO})_2\text{PO}^-]$ (mM): 398 (1), 348 (2), 188 (3). $[\text{PhS}^-]$ (mM): 0 (1), 50 (2), 210 (3). A: Wave of (4-phenylthio)benzonitrile. B: Wave of (4-cyanophenyl) phosphonic acid diethyl ester.

In the following, we describe and apply two other, electrochemically based methods for measuring the rate constant k_2 . One is a relative method, allowing, as that of Galli and Bunnett, the determination of the relative reactivities of a series of nucleophiles on the same aryl radical. The other is based on redox catalysis of the electrochemical reduction¹¹ of ArX and provides, as the direct electrochemical method, the absolute values of the reactivity. A combination of all four methods are used to gather data on the reactivity of three nucleophiles, benzenethiolate, diethyl phosphite ion, and acetone enolate, with a series of nine different aryl radicals. Trends appearing in the comparison between the reactivity and the structure of Ar^\cdot and Nu^- will be discussed.

Results

Determination of Relative Reactivities by Cyclic Voltammetry.

Figure 1 shows the voltammograms obtained upon repetitive cycling with a solution containing 4-chlorobenzonitrile and various amounts of the two nucleophiles, PhS^- and $(\text{EtO})_2\text{PO}^-$. As expected, the irreversible reduction wave of 4-chlorobenzonitrile has disappeared whereas the reversible waves corresponding to the reduction of the two substituted products have reached steady heights.

Under these conditions, the ratio of the heights of the two peaks is given by

$$\frac{i_{p1}}{i_{p2}} = \frac{k_{2,1}[\text{Nu}_1^-]}{k_{2,2}[\text{Nu}_2^-]}$$

The measurement of this ratio provides the ratio of the two rate constants since the ratio of the nucleophile concentration is known. This is a very quick method for determining the relative reactivities of a series of nucleophiles with a given aryl radical. It has also the advantage of being a nondestructive method since the two substitution processes occur only within the diffusion layer and do not affect the bulk of the solution. The conditions of applicability are that both nucleophiles should react efficiently enough for the waves of the substituted products to be measurable and that the anion radicals of the latter be stable within the time scale of the repetitive cyclic voltammetry experiment.

(11) A brief description of the method illustrated by the reaction of 2-chlorobenzonitrile with benzene thiolate using 4-cyanopyridine as a catalyst has been given in a preliminary report.^{3d}

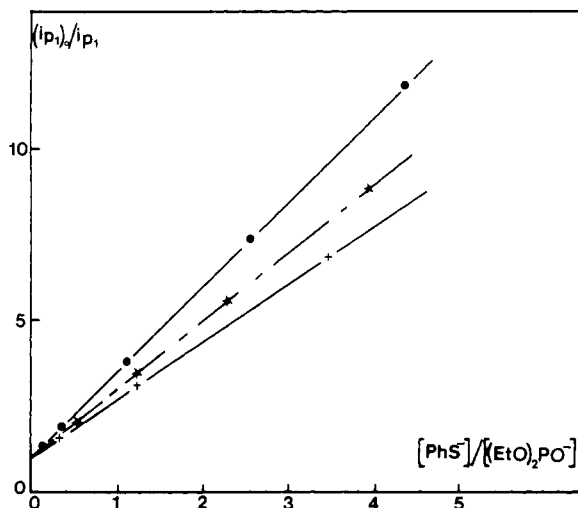


Figure 2. Repetitive cyclic voltammetry of 2-, 3-, and 4-chlorobenzonitrile in the presence of PhS⁻ and (EtO)₂PO⁻ in liquid NH₃ + 0.1 M KBr, on bright platinum electrode. Temperature: -38 °C. Sweep rate: 0.2 V s⁻¹. Variation of the $(i_{p1})_0/i_{p1}$ ratio with $[\text{PhS}^-]/[(\text{EtO})_2\text{PO}^-]$ (i_{p1} : peak current of the (4-cyanophenyl)phosphonic acid diethyl ester in the absence of PhS⁻; i_{p1} : same peak current in the presence of PhS⁻). (●) 4-Chlorobenzonitrile. (★) 3-Chlorobenzonitrile. (+) 2-Chlorobenzonitrile.

Table I. Electrochemically Determined Relative Reactivities

Ar. ^a	Nu ⁻		
	PhS ⁻	(EtO) ₂ PO ⁻	CH ₃ COCH ₂ ⁻
4-cyanophenyl	1	0.4	0.8
2-cyanophenyl	1	0.6	0.6
3-cyanophenyl	1	0.5	1.8
2-quinolyl ^b	1	1.9	6.6
4-quinolyl	1	0.5	1.7
3-quinolyl	1	0.4	2.0
3-pyridyl	1	0.7	1.6
2-pyridyl		+	
1-naphthyl	1	1.6	2.1
2-naphthyl	1	2.0	2.2
phenyl ^c	1	17.5	12.5

^a The leaving group of the starting compound used in the electrochemical experiments was Cl⁻ unless otherwise stated. ^b Experiments carried out with 2-bromoquinoline. ^c From ref 10.

It is somewhat cumbersome to measure the height of the second wave, i.e., to estimate the contribution of the first reduction at potentials of the second reduction peak.¹² To avoid this problem, we used the following procedure which has also the advantage of testing the predicted dependence of the result on the concentration ratio of the two nucleophiles. We first make sure that the concentration of the nucleophile is sufficient to render the formation of ArH negligible as compared to ArNu₁ and ArNu₂. This can be checked by the absence of the ArH/ArH⁻ wave on the repetitive cyclic voltammogram. Under these conditions,

$$\frac{(i_{p1})_0}{i_{p1}} = 1 + \frac{k_{2,2}[\text{Nu}_2^-]}{k_{2,1}[\text{Nu}_1^-]}$$

where $(i_{p1})_0$ and i_{p1} are the heights of the first peak in the absence and presence of Nu₂⁻, respectively. The ratio of the two rate constants is then given by the slope of the $(i_{p1})_0/i_{p1}$ vs. $[\text{Nu}_2^-]/[\text{Nu}_1^-]$ linear plot. This is illustrated in Figure 2 which shows the results obtained with PhS⁻ and (EtO)₂PO⁻ in the case of the three chlorobenzonitrile isomers.

The relative reactivities of PhS⁻ and (EtO)₂PO⁻ toward the series of aryl radicals listed in Table I were obtained by using this

(12) (a) This is however feasible without major difficulty by means of an appropriate numerical treatment of the voltammetric data.^{12b} (b) Bard, A. J.; Faulkner, L. R. "Electrochemical Methods, Fundamentals and Applications"; Wiley: New York, 1980; pp 232-235.

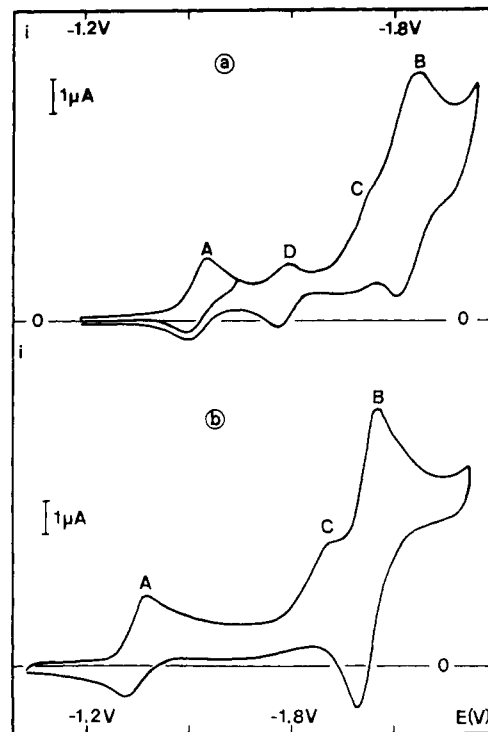


Figure 3. Repetitive cyclic voltammetry in liquid NH₃ + 0.3 M KBr on an Au electrode at -38 °C and 0.2 V s⁻¹ of (a) 2-chloroquinoline (5.5 mM) in the presence of 98.5 mM PhS⁻ and 129 mM CH₃COCH₂⁻, (b) 4-chloroquinoline (5.4 mM) in the presence of 102 mM PhS⁻ and 157 mM CH₃COCH₂⁻. The symbols on the waves correspond to the following reactions: (A) Ar-SPh + e ⇌ Ar-SPh⁻, (B) Ar-CHCOCH₃ + e ⇌ Ar-CHCOCH₂⁻, (C) Ar-SPh⁻ + e ⇌ Ar-SPh²⁻ + cleavage or protonation, (D) ArH + e ⇌ ArH⁻.

procedure with the exception of the phenyl radical which did not prove reactive enough toward PhS⁻ for this method to be employed. For Ph⁻, Table I includes the data previously obtained by Galli and Bunnett.¹⁰ 2-Chloropyridine was not sufficiently reactive for quantitative data to be obtained by the above method. It is practically unreactive with PhS⁻ and gives only a small amount of substitution with (EtO)₂PO⁻.

In the case of PhS⁻/CH₃COCH₂⁻ mixtures, more complex cyclic voltammetry patterns were obtained as illustrated in Figure 3 with the examples of 2-chlorobenzonitrile and 4-chloroquinoline. A second reduction peak of the PhS-substituted product is observed in both cases ahead of the reduction peak of the CH₃COCH₂-substituted product.¹³ In both cases, this additional wave is irreversible, indicating that the corresponding ArNu₁²⁻ dianion is unstable within the time scale of the experiments. In the case of 2-chlorobenzonitrile ArNu₁²⁻, PhS⁻ cleaves off, leading, after protonation, to ArH which gives rise to the benzonitrile/benzonitrile anion radical redox couple as seen on the repetitive cyclic voltammogram (Figure 3a). This benzonitrile wave does not result from incomplete substitution as can be seen on the first scan where this wave is absent. The ArNu₁⁻ → ArNu₁²⁻ wave itself disappears upon more prolonged repetitive scanning as expected for an irreversible wave. This behavior is reminiscent of what was previously observed in the case of the reduction of 3-chloro- and 3-bromobenzophenone in liquid NH₃.¹⁴ With 4-chloroquinoline,

(13) As illustrated in Figure 3, the acetone enolate substitution products give rise to very negative reversible reduction peaks, ca. 500 mV negative to the ArH wave in all cases. These are unlikely to feature the reduction of ArCH₂COCH₃ into ArCH₂COCH₂⁻, the potential of which should be close to that of ArH → ArH⁻ due to the lack of conjugation between the Ar and COCH₃ moieties. As pointed out earlier,^{9a} the wave is rather due to the reduction of the conjugate base, ArCHCOCH₃⁻ giving rise to the dianion radical. The protons on the central carbon atom of ArCH₂COCH₃ are likely to be mobile, owing to the conjugation of the resulting doublet with both the Ar and CO groups as in the case of 4-(2-oxopropyl)benzonitrile.²⁶ We check this point by cyclic voltammetry of an independently synthesized sample of 2-(2-oxopropyl)quinoline²⁷ in the presence and absence of acetone enolate.

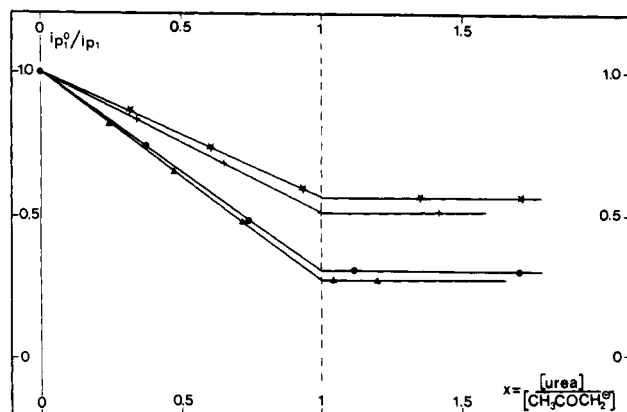


Figure 4. Determination of the relative reactivities of PhS^- and $\text{CH}_3\text{COCH}_2^-$ toward 3-cyanophenyl (\star), 4-cyanophenyl ($+$), 2-cyanophenyl (\bullet), and 1-naphthyl (\blacktriangle) by progressive neutralization of $\text{CH}_3\text{COCH}_2^-$ by urea. i_{p1} : Height of the first peak (ArSPh). $(i_{p1})_0$: Same quantity in the absence of urea. PhS^- concentration (mM): 100 (1), 102 (2), 98 (3), 96 (4). $\text{CH}_3\text{COCH}_2^-$ starting concentration (mM): 141 (1), 137 (2), 129 (3), 128 (4).

the $\text{ArNu}_1^-/\text{ArNu}_2^-$ wave is also irreversible but does not give rise to a cleavage reaction yielding the quinoline, the wave of which is not seen on the voltammogram. ArNu_2^- is likely to be protonated and further reduced similarly to what has been observed previously with fluorobenzophenones.¹⁴

In all cases, the $k_{2,1}/k_{2,2}$ ratio could be derived from the variations of the first peak height with the $\text{CH}_3\text{COCH}_2^-/\text{PhS}^-$ ratio as described above for the PhS^- , $(\text{EtO})_2\text{PO}^-$ mixtures. However, this would be a rather cumbersome and unreliable procedure in the present case, owing to the difficulty of preparing a series of solutions of the very basic $\text{CH}_3\text{COCH}_2^-$ ions having accurately known concentrations. We thus preferred to recourse to the following method. Fixed concentrations of PhS^- and $\text{CH}_3\text{COCH}_2^-$ were introduced in the solution of ArX , the concentration of PhS^- being sufficiently large for complete substitution to take place. The acetone enolate (strong base) was then progressively neutralized by successive additions of a weak acid, urea, which cannot protonate PhS^- . Then the peak current, i_{p1} , of the first wave obeys the relationship

$$\frac{(i_{p1})_0}{i_{p1}} = 1 - \frac{x}{1 + \frac{k_{2,1}[\text{Nu}_1^-]}{k_{2,2}[\text{Nu}_2^-]}}$$

where $(i_{p1})_0$ is the peak current of the first wave in the absence of urea, and x is the urea over $\text{CH}_3\text{COCH}_2^-$ concentration ratio. Figure 4 illustrates the procedure on the example of four of the aryl radicals we investigated. It has the additional advantage of checking the value of the starting concentration of $\text{CH}_3\text{COCH}_2^-$. The $k_{2,1}/k_{2,2}$ is then obtained either from the height of the horizontal position of the $(i_{p1})_0/(i_{p1})$ vs. x plot or from the slope of its initial oblique portion. The results obtained by using this method are summarized in Table I.

In the case of 2-chloroquinoline, k_1 is not too large and can thus be determined by cyclic voltammetry.^{9a} It is thus possible to measure k_2 by the direct method. This has already been done for PhS^- and $(\text{EtO})_2\text{PO}^-$ ^{9a} and is described in the following section for $\text{CH}_3\text{COCH}_2^-$. Using the values of k_2 thus obtained, one can compare the results obtained from relative electrochemical determinations as described above (Table I) and by the direct method (Table II) for the 2-quinolyl radical. The two methods are in satisfactory agreement. Comparison of the figures obtained gives an estimation of the degree of accuracy of the electrochemical determinations.

Determination of k_2 by Homogeneous Redox Catalysis. The principle of the method^{3d} consists in catalyzing the reduction of the starting ArX by means of a reversible one-electron couple

Table II. Relative Reactivities of PhS^- , $(\text{EtO})_2\text{PO}^-$, and $\text{CH}_3\text{COCH}_2^-$ with the 2-Chloroquinolyl Radical Derived from Direct Electrochemical Measurements

Nu^-	$k_2, \text{M}^{-1} \text{s}^{-1}$	$k_{2,\text{Nu}^-}/k_{2,\text{PhS}^-}$
PhS^-	1.4×10^7 ^a	1
$(\text{EtO})_2\text{PO}^-$	1.8×10^7 ^a	1.3 (1.9) ^c
$\text{CH}_3\text{COCH}_2^-$	1×10^8 ^b	7.2 (6.6) ^c

^a From ref 9a. ^b This work (vide infra). ^c From the relative electrochemical method (Table I).

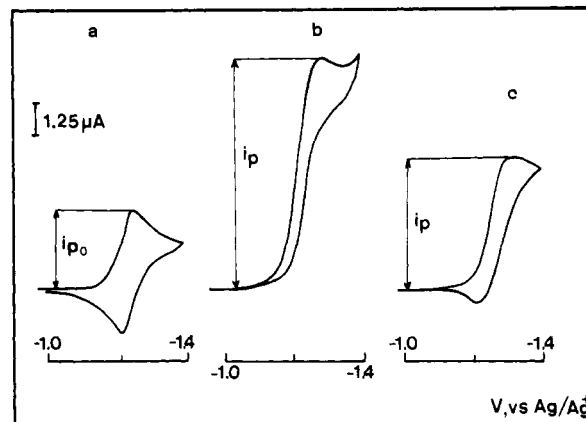
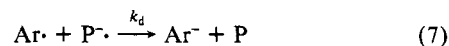
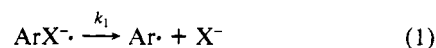
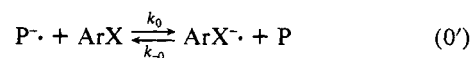
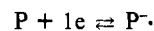


Figure 5. Homogeneous redox catalysis of the reduction of 2-chlorobenzonitrile by 4-cyanopyridine in the presence of PhS^- in liquid NH_3 + 0.1 M KBr (-38°C). (a) 4-Cyanopyridine (2.3 mM). (b) a + 4-chlorobenzonitrile (6.7 mM). (c) b + PhS^- (35 mM).

having its standard potential ahead of the ArX wave and to follow the decrease of the catalytic current upon addition of the nucleophile.

Five reversible one-electron redox couples were found suitable for redox catalysis of the reduction of the following haloaromatic compounds: 1-bromonaphthalene and 3-chlorobenzonitrile (2-cyanopyridine), 3-bromo- and 4-chloroquinoline (phthalonitrile), 3-chloropyridine (quinoline), 2-chlorobenzonitrile (4-cyanopyridine), and 2-chloropyridine (2,2'-bipyridyl).

Homogeneous Redox Catalysis of ArX Reduction in the Absence of Nucleophile. Redox catalysis of the reduction of aromatic halides in solvents of low proton availability in the context of cyclic voltammetry is a well-documented process.¹⁵ It involves the reaction sequence



(P/P^- is the redox catalyst couple). As discussed earlier,¹⁵ in most practical cases, reaction 7 is likely to prevail over reactions 4 and 4' which could conceivably serve for the reduction of Ar^\bullet . In liquid NH_3 , reaction 6 which could be another mode of reduction of Ar^\bullet is absent. Since Ar^\bullet is much easier to reduce than P , the rate of reaction 7 is likely to be close to the diffusion limit.

Under these conditions, the reduction wave of the catalyst, P , increases upon addition of ArX to the solution and concomitantly loses its reversibility (Figure 5). The catalytic enhancement of the P reduction current is under the kinetic control of reactions 0' and 1. It is a function of $k_0 C_{\text{P}^0}/v$ (v is the sweep rate, C_{P^0} the concentration of the catalyst), $k_{-0} C_{\text{P}^0}/k_1$, and of the excess factor $\gamma = [\text{ArX}]/C_{\text{P}^0}$.^{15c} Two limiting situations are reached when

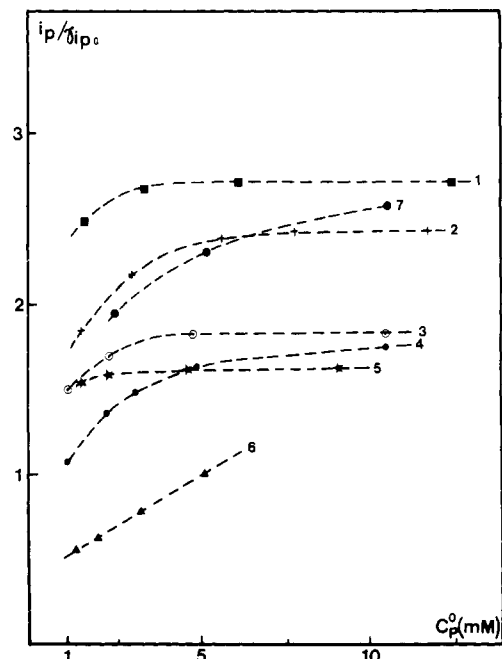
(15) (a) Andrieux, C. P.; Blocman, C.; Dumas-Bouchiat, J. M.; Savéant, J. M. *J. Am. Chem. Soc.* **1979**, *101*, 3431. (b) Andrieux, C. P.; Blocman, C.; Dumas-Bouchiat, J. M.; M'Halla, F.; Savéant, J. M. *J. Am. Chem. Soc.* **1980**, *102*, 3806. (c) Andrieux, C. P.; Blocman, C.; Dumas-Bouchiat, J. M.; M'Halla, F.; Savéant, J. M. *J. Electroanal. Chem.* **1980**, *113*, 19.

(14) Savéant, J. M.; Thiébaud, A. *J. Electroanal. Chem.* **1978**, *89*, 325.

Table III. Homogeneous Redox Catalysis of the ArX Reduction in the Absence of Nu⁻

ArX	E _p ^{ArX} , V ^a	catalyst	E _{p/P} ⁰ , V ^b	kinetic control	k ₀ , M ⁻¹ s ⁻¹	(k ₀ /k ₋₀)k ₁ , s ⁻¹
4-chloroquinoline	-1.34 ^{e,g}	phthalonitrile	-1.13	c		0.38
3-chlorobenzonitrile	-1.57 ^{e,h}	2-cyanopyridine	-1.43	c		7.5
3-bromoquinoline	-1.30 ^{e,g}	phthalonitrile	-1.13	c, d	1.4 × 10 ⁴	8.9
2-chlorobenzonitrile	-1.45 ^{e,g}	4-cyanopyridine	-1.25	d	2.5 × 10 ²	
1-bromonaphthalene	-1.60 ^{e,h}	2-cyanopyridine	-1.43	d	4.5 × 10 ²	
3-chloropyridine	-1.78 ^{f,g}	quinoline	-1.62 ₅	d	2.5 × 10 ³	
2-chloropyridine	-1.80 ^{f,g}	2,2'-bipyridyl	-1.63	d	1.2 × 10 ³	

^a Peak potential of the aromatic halide. ^b Standard potential of the catalyst couple. ^c Kinetic control by reaction 1 with reaction 0' acting as a preequilibrium. ^d Kinetic control by forward reaction 0'. ^e On a mercury electrode. ^f On a bright platinum electrode. ^g 0.1 M KBr as supporting electrolyte. ^h 0.1 M NaI as supporting electrolyte. ⁱ Temperature -38 °C.



curve no.	ArX	catalyst (P)	γ = C _p ⁰ /rate, ArX	sweep rate, V s ⁻¹
1 ^{a,c}	2-chlorobenzonitrile	4-cyanopyridine	2	0.1
2 ^{a,d}	1-bromonaphthalene	2-cyanopyridine	3	0.1
3 ^{a,c}	3-chloropyridine	quinoline	0.9	0.2
4 ^{a,c}	3-bromoquinoline	phthalonitrile	1	1.15
5 ^{a,d}	3-chlorobenzonitrile	2-cyanopyridine	1	2
6 ^{b,c}	4-chloroquinoline	phthalonitrile	0.5	0.1
7 ^{b,c}	2-chloropyridine	2,2'-bipyridyl	1	0.1

^a Temperature: -38 °C. Mercury electrode. ^b Bright platinum electrode. ^c 0.1 M KBr as supporting electrolyte. ^d 0.1 M NaI as supporting electrolyte.

Figure 6. Homogeneous redox catalysis of a series of ArX in liquid NH₃. i_p/γ(i_p)₀ current of P in the presence and absence of ArX, respectively.

k₋₀C_p⁰/k₁ is either very small or very large. In the first case (fast cleavages), the catalytic current is governed by forward reaction 0' and is a function of k₀C_p⁰/v and γ. In the second case (slow cleavages), it is controlled by reaction 1, reaction 0' acting as a preequilibrium, and is a function of (k₀/k₋₀)k₁/v. The two limiting behaviors can thus be recognized by investigating the dependence of the catalytic current upon C_p⁰. It is also noted that an increase of C_p⁰ tends to make the kinetic control pass from forward reaction 0 to reaction 1.

The results are summarized in Figure 6 under the form of an i_p/γ(i_p)₀ vs. C_p⁰ plot where i_p and (i_p)₀ are the peak currents of the P wave in the presence and absence of ArX, respectively. Appropriate treatment of the variations or lack of variation with C_p⁰ indicates the type of kinetic control in each case and allows the determination of either k₀ or (k₀/k₋₀)k₁ according to the case. The results thus obtained are listed in Table III.

The case of 3-bromoquinoline is particularly worth notice: the variation of C_p⁰ allows passage from the kinetic control by forward

Table IV. Absolute^a Rate Constants^b of the Reaction of Aryl Radicals with Nucleophiles

Ar•	Nu ⁻		
	PhS ^{-c}	(EtO) ₂ PO ^{-d}	CH ₃ COCH ₂ ^{-d}
2-cyanophenyl	1.4 × 10 ¹⁰	8.0 × 10 ⁹	2.4 × 10 ¹⁰
3-cyanophenyl	1.5 × 10 ¹⁰	7.5 × 10 ⁹	9.0 × 10 ⁹
4-cyanophenyl	3.4 × 10 ⁹	1.4 × 10 ⁹	2.6 × 10 ⁹
1-naphthyl	2.0 × 10 ¹⁰	3.2 × 10 ¹⁰	4.2 × 10 ¹⁰
3-quinolyl	1.9 × 10 ⁹	7.6 × 10 ⁸	3.8 × 10 ⁹
4-quinolyl	3.2 × 10 ⁹	1.6 × 10 ⁹	5.4 × 10 ⁹
2-quinolyl		2.6 × 10 ⁷	9.1 × 10 ⁷
	1.4 × 10 ^{7e}	1.7 × 10 ^{7e}	1.0 × 10 ^{8e}
3-pyridyl	1.0 × 10 ¹⁰	7.0 × 10 ⁹	1.6 × 10 ¹⁰
2-pyridyl	1.0 × 10 ⁸	>10 ⁸	

^a Taking k_{diff} = 3 × 10¹⁰ M⁻¹ s⁻¹. ^b M⁻¹ s⁻¹ at -38 °C. ^c From redox catalysis with addition of the nucleophile unless otherwise stated. ^d From electrochemical competition experiments unless otherwise stated. ^e From direct electrochemical experiments.

reaction 0 to control by reaction 1, thus allowing the determination of both k₀ and (k₀/k₋₀)k₁ and consequently of k₁/k₋₀. Since k₋₀ is likely to be close to the diffusion limit (i.e., ca. 3 × 10¹⁰ M⁻¹ s⁻¹), the value of k₁ ensues 2 × 10⁷ s⁻¹.¹⁶ The behavior exhibited by 3-chloropyridine is somewhat ambiguous. The treatment of the data does show that kinetic control by reaction 1 is followed at low values of C_p⁰. However the plateau obtained upon increasing C_p⁰ (Figure 6) fails to fit with the behavior predicted for the kinetic control by reaction 1. The plateau more likely reflects the in-

(16) (a) The values of k₁ can also be estimated in the case of 4-chloroquinoline, 3-chlorobenzonitrile, and 3-bromoquinoline by using another approach.^{15b,c} In all three cases, the peak potential of the ArX wave varies by ca. 20 mV per decade of sweep rate, indicating that the kinetics of the overall electrochemical reaction 0 + 1 is governed by the cleavage step 1 rather than the electrode electron-transfer 0.^{16b} It follows that

$$E_p^{\text{ArX}} = E^{\circ}_{\text{ArX}/\text{ArX}^{\cdot-}} - 0.78 \frac{RT}{F} + \frac{RT}{2F} \ln \frac{RT}{F} \frac{k_1}{v}$$

On the other hand

$$E^{\circ}_{\text{ArX}/\text{ArX}^{\cdot-}} = E^{\circ}_{\text{P/P}^{\cdot-}} + \frac{RT}{F} \ln k_1 + \frac{RT}{F} \ln \left(\frac{k_0}{k_{-0}} k_1 \right)$$

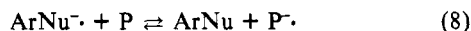
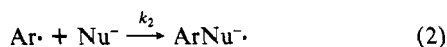
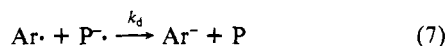
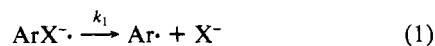
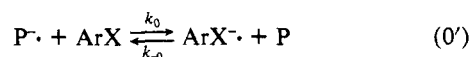
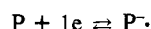
and thus

$$\frac{RT}{2F} \ln k_1 = \frac{RT}{F} \ln \left(\frac{k_0}{k_{-0}} k_1 \right) + (E^{\circ}_{\text{P/P}^{\cdot-}} - E_p^{\text{ArX}}) - 0.78 \frac{RT}{F} + \frac{RT}{F} \ln \frac{RT}{Fv}$$

All the quantities in the right-hand side are known from experiment (Table III). The values thus obtained, 4 × 10⁵, 4 × 10⁵, and 6 × 10⁶ M⁻¹ s⁻¹, for 4-chloroquinoline, 3-chlorobenzonitrile, and 3-bromoquinoline provide a rough estimation of k₁. They are, however, less accurate than those obtained by means of the variations of the catalytic current with C_p⁰ which was only possible in the case of 3-bromoquinoline or by the application of the redox catalytic method in the presence of the nucleophile combined with the direct electrochemical experiments as described below (the results are given in Table V). This is due to the fact that the method described here relies on the measurement of peak potentials while the two others are based upon variations of peak currents which can be measured with more precision. In addition, the peak potentials of ArX reduction exhibit a slow drift in time both on mercury and platinum electrodes, and frequent cleaning of the electrode surface is rather tedious in the context of experiments carried out in liquid NH₃. This problem does not arise with the reversible catalyst waves. (b) Nadjio, L.; Savéant, J. M. *J. Electroanal. Chem.* 1973, 48, 113.

interference of a secondary reaction, presumably the dimerization of the anion radical of quinoline, a reaction known to occur during the reduction of quinoline in liquid NH_3 ¹⁷ and expected to interfere more and more efficiently as the concentration increases.

Homogeneous Redox Catalysis of ArX Reduction in the Presence of a Nucleophile. In the presence of a nucleophile, the $\text{Ar}\cdot$ produced by the reaction of the catalyst $\text{P}\cdot$ with the starting ArX react competitively with $\text{P}\cdot$ as above and with Nu^- according to the reaction sequence



It follows that the addition of the nucleophile results in a decrease of the catalytic current, the wave of the catalyst becoming again reversible in the case where reaction 2 is very efficient (Figure 5). The decrease of $i_p/(i_p)_0$ upon addition of the nucleophile is thus a function of the ratio $k_2[\text{Nu}^-]/k_d\text{C}_\text{P}^0$. Determination of this ratio from the treatment of the kinetic data thus allows that of k_2 or at least that of the ratio k_2/k_d where k_d is the diffusion limit.

More precisely, the exact dependence of $i_p/(i_p)_0$ on $k_2[\text{Nu}^-]/k_d\text{C}_\text{P}^0$ is a function of the kinetic control of the homogeneous redox catalytic process by reactions 0 and 1. The concentration of the catalyst was adjusted in each case so as to obtain kinetic control either by forward reaction 0 or by reaction 1 with reaction 0 acting as a preequilibrium. The corresponding values of either k_0 or k_0k_1/k_{-0} were obtained from the catalytic increase of the peak current. These values were then entered into a computer program which numerically solves the pertinent partial derivative equation system with the accompanying initial and boundary conditions describing the kinetics of the redox catalytic process in the presence of the nucleophile. The other entries to the program were the value of the excess factor $[\text{ArX}]/\text{C}_\text{P}^0$ and of the observable $i_p/(i_p)_0$. The program was arranged so as to iteratively determine the $k_2[\text{Nu}^-]/k_d\text{C}_\text{P}^0$ value corresponding to the experimental $i_p/(i_p)_0$ ratio for each set of values of the other entries. More details about the formal kinetics and its treatment are available as supplementary material to this paper. This also contains the full set of values of $i_p/(i_p)_0$ and of the experimental parameters we used as well as the resulting values of $k_2[\text{Nu}^-]/k_d\text{C}_\text{P}^0$.

The results thus obtained are summarized in Table III.¹⁸ Among the three nucleophiles investigated in this work, only PhS^- could be used conveniently in the homogeneous redox catalysis experiments. With diethyl phosphite ions, the $\text{ArNu}/\text{ArNu}\cdot$ wave is located ahead of the ArX wave and overlaps with the redox catalyst wave in most cases, which renders the analysis of the system cumbersome and less accurate. The use of the redox catalytic method was impeded in the case of acetone enolate ions by the fact that most of the catalysts we tried were insufficiently stable in this highly basic medium.¹⁹

The case of 2-chloropyridine deserves particular attention. As mentioned in a preceding section, PhS^- appears as unreactive in direct electrochemical experiments both because the cleavage rate is presumably very large and the reactivity of the 2-pyridyl radical

Table V. Rate Constants of

$\text{ArX}\cdot \xrightarrow{k_1} \text{Ar}\cdot + \text{X}^-$		
ArX	k_1/k_2 , M	k_1 , s^{-1}
2-chlorobenzonitrile	1.8×10^{-2}	1.4×10^8
3-chlorobenzonitrile	1.3×10^{-4}	9.8×10^5
4-chlorobenzonitrile		9.3×10^{8b}
4-bromobenzonitrile	1.4	2.0×10^9
4-iodobenzonitrile	18	2.5×10^{10}
1-chloronaphthalene	6.0×10^{-4}	1.2×10^7
1-iodonaphthalene	5.0	1.6×10^{11}
2-chloroquinoline		1.7×10^{4c}
4-chloroquinoline	1.2×10^{-3}	1.9×10^6
3-bromoquinoline	2.0×10^{-2}	1.5×10^7
		2.0×10^{7d}
2-iodoquinoline	5.4	1.2×10^8
3-iodoquinoline	3.1	2.4×10^9

^a At -38°C ; determined, unless otherwise stated from redox catalysis experiments in the presence of Nu^- ($\rightarrow k_2$) and direct electrochemical experiments. ^b From ref 9c. ^c See text. ^d From the variations of the catalytic current with the catalyst concentration in absence of nucleophile.

on PhS^- is not very high. In the resulting ECE-substitution competition, the ECE pathway thus prevails over the substitution pathway. The redox catalysis experiments nevertheless give rise to a measurable effect which allowed the determination of k_2 . This is because $k_d\text{C}_\text{P}^0$ can be made small enough to become of the same order of magnitude as $k_2[\text{Nu}^-]$, thus allowing the determination of their ratio. For example, with $\text{C}_\text{P}^0 = 2.17$ mM and $[\text{Nu}^-] = 0.532$ M, $k_2[\text{Nu}^-]/k_d\text{C}_\text{P}^0 = 0.82$. This corresponds to a 20% decrease of the catalytic current which can easily be measured experimentally. This example illustrates the increased capabilities of the redox catalytic method as compared to the direct electrochemical method in cases where the cleavage rate of the substrate is large and the reactivity of the nucleophile toward $\text{Ar}\cdot$ not too high. The fact that no decrease of the ArX peak current could be detected with PhS^- concentrations up to 0.42 M implies that $k_1 \geq 10^{10} \text{ s}^{-1}$.

Additional Direct Electrochemical Determinations. The determination of k_2 by the direct method requires the cleavage rate constant to be known independently. This is the case for 2-chloroquinoline where k_1 is known from the measurement of the ArX reduction peak as a function of the sweep rate ($k_1 = 1.7 \times 10^4 \text{ s}^{-1}$). The reactions of 2-chloroquinoline with PhS^- and $(\text{EtO})_2\text{PO}^-$ have already been investigated, and the values of k_2 are recast in Table IV.^{9a} In the case of acetone enolate, the same kinetic investigation shows that the system is controlled by an ECE-substitution competition. This is shown by the fact that the ratio of the 2-chloroquinoline peak currents in the absence and presence of $\text{CH}_3\text{COCH}_2^-$ is independent of sweep rate and substrate concentration while it depends on the concentration of enolate according to the expected law.⁹ The k_2 value given in Table IV is derived from these experiments.²⁰

k_1 is not known with accuracy for the other substrates.¹⁶ For those in which k_2 could be determined by the redox catalytic method in the presence of PhS^- (preceding section) and for which k_1/k_2 could be determined by the direct electrochemical experiments (Table V), the value of k_1 ensues. The results thus obtained are listed in Table V. We note that in the case of 3-bromoquinoline, k_1 could be measured both by this method and from the variations of the catalytic current with C_P^0 in the absence of nucleophile. The agreement between the two values is seen to be quite satisfactory at the level of accuracy that can be expected for these types of measurements (Table V).

Discussion

The values of k_2 and k_1 obtained by the various methods as described above are summarized in Tables IV and V, respectively.

(17) Smith, W. H.; Bard, A. J. *J. Am. Chem. Soc.* **1975**, *97*, 649.

(18) (a) The diffusion limit was taken as equal to $3 \times 10^{10} \text{ M}^{-1} \text{ s}^{-1}$.^{9a}

(19) In the case of 2-bromonaphthalene, we were not successful in applying the redox catalysis method but this was merely due to solubility problems. 2-Bromonaphthalene is soluble at the millimolar level which allows the relative reactivities to be determined (Table I) but not at the larger concentrations required by the redox catalytic experiments.

(20) The value thus obtained is significantly different from that reported earlier.^{9a} The latter was in error, owing to a defectuous control of the enolate concentration in the previous experiments.

Table VI. Standard Potentials^a of the ArNu/ArNu⁻ Couples

Ar ⁻	Nu ⁻		ArH
	PhS ⁻	(EtO) ₂ PO ⁻	
2-cyanophenyl	-1.52 ^b	-1.37 ^b	-1.78 ₅
3-cyanophenyl	-1.58 ^c	-1.48 ^c	
4-cyanophenyl	-1.51 ^c	-1.29 ^c	
1-naphthyl	-1.74 ^c	-1.62 ^c	-2.02 ₅
2-naphthyl	-1.81	-1.67	
3-quinolyl	-1.39 ₅ ^b	-1.28 ₅ ^b	-1.62 ₅
4-quinolyl	-1.36 ^b	-1.16 ^b	
2-quinolyl	-1.48 ₅ ^b	-1.26 ^b	
3-pyridyl	-1.88 ^c	-1.73 ^c	-2.18
2-pyridyl	-2.03 ^c		

^a In volts vs. Ag/0.01 Ag⁺. ^b Mercury electrode. ^c Bright platinum electrode.

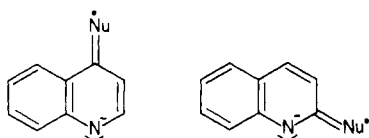
As an element for the following discussion, we have also listed the values of the standard potentials of the various ArNu/ArNu⁻ couples created by the substitution process with PhS⁻ and (EtO)₂PO⁻ (Table VI) and those of the ArH/ArH⁻ couple. The standard potentials of the ArCH₂COCH₃ derivatives can be considered as being close to those of the parent ArH compound.¹³

Although our main concern is the reaction of aryl radicals with nucleophiles, the variation exhibited by the standard potentials of the ArNu/ArNu⁻ couples and by the cleavage rate constants of the anion radical of the substrates is worth some comment.

The standard potentials of the ArNu/ArNu⁻ couple are significantly more positive than those of the ArH/ArH⁻ couple not only for (EtO)₂(O)P (by ca. 400 mV), which is expected from the easy delocalization of the unpaired electron in the anion radical on the oxygen atom through the d orbitals of the phosphorus atom, but also for PhS (by ca. 250 mV). In the latter case, this shows that the delocalization of the unpaired electron over the phenyl ring through the d orbitals of the sulfur atom is clearly a more important factor than mesomeric electron donation from the sulfur doublet to the Ar ring.

In the benzonitrile series this effect is, as expected, larger for the para and ortho isomers than for the meta isomer.

One expects something similar to occur in the quinoline series by means of concentration of the negative charge on the nitrogen atom, involving mesomeric forms such as



That this type of effect actually occurs is shown by the fact that the standard potentials for ArNu and ArH are significantly more positive with quinoline than with naphthalene (by ca. 350 mV). There should thus be an analogy between the 2,3,4-isomers of the quinoline series and those of the benzonitrile series. This is true for the 3-, and 4-isomers but to a much lesser extent for the 2-isomers. With P(O)(OEt)₂ as the substituent, the standard potential of the 2-isomer is much closer to that of the 3-isomer for quinoline than for benzonitrile. With SPh as the substituent, the effect is even bigger since the standard potential of the 2-isomer is now more negative than that of the 3-isomer.

These observations are best rationalized by the existence of an electronic repulsion between the lone pair electrons on the nitrogen and the electron of the C–Nu bond in the form shown above. This repulsion contributes to increase the energy of the σ* orbital in the C–Nu bond (which possesses in the present case a substantial π character due to conjugation by means of the d orbitals of the S and P atoms), thus decreasing the conjugation between the substitution and the Ar ring. The same type of rationalization has been previously put forward to account for the “ortho effect”²¹ in the cases where no significant steric hindrance²² between the

two adjacent groups is involved. This is obviously the case with quinoline, and the electron repulsion effect is expected to be much larger than with a CN substituent on a benzene ring where the nitrogen lone pairs are much more distant from the C–Nu bond.

It is interesting to note that the same effect is also present in the phenylthiopyridine series: the standard potential is more negative for the 2- than for the 3-isomer.

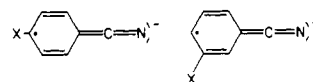
Regarding the variation of the anion radical cleavage rate constant of the haloaromatics serving as substrates (Table V), several trends appear that fall in line with previous observations.^{5a} For a given Ar, the average rate constants vary in the order I > Br > Cl. The 3-isomers cleave more slowly than the 2- and 4-isomers (benzonitrile series). In the quinoline series, the 2-isomer cleaves more slowly than the 4-isomer which underlines the particular behavior of the 2-position in this series already noted for the ArNu/ArNu⁻ standard potentials.

This is consistent with a picture of the cleavage kinetics which involves the transfer of the unpaired electron from the π* orbital of ArX to the σ* orbital of the C–X bond and then to a p orbital of the halogen.^{5a,23a,b} In this context, the slower cleavage of the 2-chloroquinoline anion radical as compared to the 4-isomer falls in line with the “ortho effect” discussed above which involves an increase of the energy of the σ* orbital as compared to the π* orbital.

Regarding now the reaction of the nucleophiles with the aryl radicals (Table IV), the first remark is that the rate constants that could be measured are all very large. This is not surprising in view of the very mechanism of the S_{RN}1 reaction which implies that the same process that initiates the reaction (injection of reducing species) gives rise at the same time to efficient termination steps.^{2c,3b} It follows that *k*₂ has to overcome a threshold value for the reaction to proceed with significant substitution yields.^{3b} In a large number of cases, the reaction rate constant is actually very close to the diffusion limit which hampers a detailed discussion of the relationships between the reactivity and the structure of the nucleophiles and aryl radicals. The only cases where *k*₂ is clearly below the diffusion limit are those of the

(22) Steric hindrance²¹ is expected to play a more important role in the case of 2-(EtO)₂(O)P-benzonitrile than in 2-PhS-benzonitrile which may explain why the difference in standard potentials with the corresponding 4-isomer is larger in the first (80 mV) than in the second case.

(23) (a) This stems from the fact that the energy of the π* orbital does not vary significantly when the C–X distance increases whereas the energy of the σ* orbital falls rapidly with the distance (see Figure 4 in ref 5a). A plausible representation of the transition state thus corresponds to the distance where the energies of the two orbitals become equal.^{5a} The cleavage rate constant is thus a function of the difference in energy between the σ* and the π* orbitals: the higher the σ* over the π* orbital in the anion radical, the slower the cleavage. For the same Ar, the distance between the σ* and π* orbitals is lower for Br than for Cl.^{5a} On the same grounds (enhanced π character of the σ* orbital due to the increased accessibility of the d orbitals in the halogen atom), it is expected to be lower for I than for Br. For a given halogen, it was shown^{5a} that for a large series of Ar, involving however only 4-isomers for aromatics activated by an electron-withdrawing group, the π* orbital energy does vary significantly with the nature of Ar while the σ* orbital energy does not. It follows that the transition-state C–X distance decreases and therefore so does the activation energy, as the π*-orbital energy increases. Since the π* orbital energy varies as the standard potential of the ArX/ArX⁻, this provides a rationalization of the approximate correlation observed between the cleavage rate constant and the standard potential. Solvation and interactions with counteraction are expected to lower the barrier offered by the passage of the unpaired electron from the π* to the σ* orbital since the negative charge is likely to be more concentrated in the transition state than in the anion radical. (b) 3-Isomers of aromatics bearing an electron-withdrawing group are among the compounds that fall the more markedly out of the above correlation: *k*₁ is much smaller than for the 4-isomer while the difference in standard potential is small. This can be rationalized considering that the σ*–π* energy difference is expected to be higher in the meta than in the para (and ortho) isomer: in the mesomeric forms shown below, the unpaired electron is more apt to jump in the σ* C–X orbital in the 4-isomer than in the 3-isomer.



(21) Zuman, P. “Substituent Effects in Organic Polarography”; Plenum Press: New York, 1967; pp 75–94.

(c) See, for example, the case of bromobenzene, substituted bromobenzenes, and bromonaphthalene.^{23d} (d) Wentworth, W. E.; Becker, R. S.; Tung, R. J. Phys. Chem. 1967, 71, 1652 and references cited therein.

2-quinolyl and 2-pyridyl radicals.

The free energy of activation of the reaction of the nucleophile with the aryl radical, ΔG_f^\ddagger , and that of the cleavage of the anion radical, ΔG_c^\ddagger are related by

$$\Delta G_f^\ddagger = \Delta G_{\text{ArNu}^\cdot}^\circ - \Delta G_c^\ddagger$$

where ΔG_f^\ddagger and ΔG_c^\ddagger are the free energies of activation for the formation and cleavage of the ArNu bond in the anion radical, respectively, and $\Delta G_{\text{ArNu}^\cdot}^\circ$ is the free energy of the formation of the anion radical from Ar \cdot and Nu $^-$. The latter quantity can be expressed as

$$\Delta G_{\text{ArNu}^\cdot}^\circ = \Delta G_{\text{Ar-Nu}}^\circ - FE_{\text{ArNu/ArNu}^\cdot}^\circ + FE_{\text{Nu}^\cdot/\text{Nu}}^\circ$$

where $\Delta G_{\text{Ar-Nu}}^\circ$ is the free energy of the Ar-Nu bond in the final product and $E_{\text{ArNu/ArNu}^\cdot}^\circ$ and $E_{\text{Nu}^\cdot/\text{Nu}}^\circ$ are the standard potentials of the subscript couples.

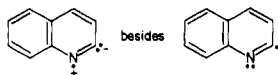
In the case of aryl halides, there is a rough linear correlation, for each given halide, between ΔG_c^\ddagger and $E_{\text{ArNu/ArNu}^\cdot}^\circ$ (here Nu is the halogen atom) with a slope close to 0.5.^{5a,23a} Since when passing from an aryl radical to the other, $\Delta G_{\text{ArNu}^\cdot}^\circ$ varies very little,^{23c} this amounts to an activation-driving force free energy relationship for the cleavage reaction. A symmetric relationship would thus relate ΔG_f^\ddagger and $\Delta G_{\text{ArNu}^\cdot}^\circ$, the latter factor being essentially governed by $E_{\text{ArNu/ArNu}^\cdot}^\circ$ in a series where Ar is varied while Nu remains the same. It is thus predicted that the more negative the standard potential of the ArNu/ArNu $^\cdot$, the faster the addition of the nucleophile on the aryl radical.

This is obviously not the case with the 2-quinolyl radical for which the low value of k_2 , the lowest in the series for the three nucleophiles, does not match a particularly negative value of the ArNu/ArNu $^\cdot$ standard potentials (Tables IV and VI). It is noteworthy that k_2 is significantly smaller in the 2-position than in the 4-position and even in the 3-position. We have already seen that the 2-position exhibits a particular behavior as far as the standard potentials of the ArNu/ArNu $^\cdot$ couples and the cleavage rate constants of the ArCl $^\cdot$ are concerned. In both cases, this particular behavior was shown to be consistent with an increase of the energy difference between the σ^* and π^* orbitals. In the context of the picture given above for the transition state of the nucleophilic attack and of the cleavage, this increased difference between the σ^* and π^* orbitals would also appear as responsible for the low value of k_2 for the 2-quinolyl radical, overwhelming the variation of the $E_{\text{ArNu/ArNu}^\cdot}^\circ$ factor. A similar observation has already been made for the cleavage of aryl halides when comparing ortho to para isomers in phenyl derivatives activated by an electron-withdrawing group.^{23b,24}

It is remarkable that the 2-position of pyridine shows the same particular behavior as compared to the 3-position as in the case of quinoline as far as k_2 values are concerned (Table IV), similarly to what was observed above for the standard potentials of the PhS derivatives.

Regarding the comparison between the nucleophiles for a given Ar, the above equations indicate that four main factors interfere ΔG_c^\ddagger which depends on the energy difference between the σ^* and π^* orbital in the anion radical, $\Delta G_{\text{Ar-Nu}}^\circ$ which can be approximated by the gas-phase bond energy,²⁵ and $E_{\text{ArNu/ArNu}^\cdot}^\circ$ and $E_{\text{Nu}^\cdot/\text{Nu}}^\circ$. Little is known about the last quantity. As discussed

(24) An alternative explanation of the low reactivity of the 2-position involves the contribution of the following structure of the Ar \cdot radical:¹⁰



However, these two structures are not strictly speaking resonant structures since the exchange of electron involves nonoverlapping sp^2 orbitals. In this context, one understands why such a structure could not interfere in the case of the 4-quinolyl radical where the distance between the two electron-exchanging orbitals is too large. With this precision in mind, there is probably not much difference between the two interpretations. The one we gave in the text has the advantage of unifying the interpretation of three different effects, revealing the particular character, viz, low reactivity of the 2-position toward Nu $^-$ in Ar \cdot , slow cleavage of ArCl $^\cdot$, and low electron affinity of ArNu.

(25) Ritchie, C. D. *J. Am. Chem. Soc.* **1983**, *105*, 7313.

earlier,¹⁰ data concerning the electron affinity of Nu $^\cdot$ in the gas phase exist, but solvation (and interactions with the counteranions) is likely to modify them substantially. Comparing, for example, acetone enolate and diethyl phosphite, it seems unlikely that $E_{\text{Nu}^\cdot/\text{Nu}}^\circ$ would play in favor of the former (the electron affinities in the gas phase are actually in the converse order¹⁰). The $E_{\text{ArNu/ArNu}^\cdot}^\circ$ is also in favor of diethyl phosphite by about 400 mV (i.e., ca. 9 kcal/mol). The energy difference between the σ^* and π^* orbital is also obviously in favor of diethyl phosphite. This points to the conclusion that acetone enolate is as good a nucleophile as diethyl phosphite (and may be even better) originates in the strength of the carbon-carbon bond.

Conclusions

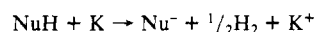
The main conclusions that emerge from the above results and discussion can be summarized as follows.

(i) It is important to dispose of several methods for measuring the absolute rate constants of the Ar \cdot + Nu $^-$ reaction in an extended series of aryl radical-nucleophile couples. This is illustrated by the fact that the data described in this study were obtained by the combination of three methods: the direct electrochemical method, the relative electrochemical method, and the redox catalysis method to which we added the results of the relative chemical method¹⁰ determined k_2 for the reaction of Ph \cdot with PhS $^-$, (EtO) $_2$ PO $^-$, and CH $_3$ COCH $_2^-$. In each case, when the comparison between the various methods was possible, satisfactory agreement between them was met.

(ii) Most of the 27 aryl radical-nucleophile couples that could be quantitatively characterized showed a rate constant close to the diffusion limit. Only in four cases were the values of k_2 clearly below this limit. They involve the 2-position in the quinoline and pyridine series. These data can be rationalized in terms of the energy difference between the σ^* and π^* orbitals in the anion radical, standard potentials of the ArNu/ArNu $^\cdot$ couple, and energy of the Ar-Nu bond in the final product. A quantitative description of the reactivity is, however, precluded by the small number of cases where absolute rate constants well below the diffusion limit have been observed.

Experimental Section

(1) **Preparation of the Nucleophiles.** They are prepared directly in the reaction vessel. In the case of PhS $^-$ and (EtO) $_2$ PO $^-$, their conjugate acids are strong acids in liquid ammonia. Both are prepared through the reaction of potassium on the protonated form



or through an acidobasic solution using KOH as the base. In the case of acetone enolate, the method of preparation involves the quantitative neutralization of a potassium amide solution, prepared in the cell, by acetone. The titration is followed by constant current potentiometry with two amalgamated gold electrodes.

(2) **Electrochemical Measurements.** The techniques used for the purification of ammonia as well as the electrolysis cells have already been described.^{9a} The working electrodes used in cyclic voltammetry are either mercury electrodes prepared from a gold disk (0.5-mm diameter) on which a mercury drop is attached or platinum (1-mm diameter) or gold (0.5-mm diameter) disks as indicated in the figure captions. The measurements were carried at -38°C . The supporting electrolyte was potassium bromide (0.1 M) except in the cases of 1-bromonaphthalene and 3-chlorobenzonitrile with 2-cyanopyridine as catalyst where 0.1 M sodium iodide was used. The Ag/Ag $^+$ 0.01 M electrode has been described as well as the electrochemical setup.^{9a} An authentic sample, 2-(2-oxopropyl)quinoline,²⁷ was prepared by standard procedures.

Acknowledgment. Support by the Centre National de la Recherche Scientifique (Unités Associées "Electrochimie Moléculaire" et "Chimie Analytique des Milieux réactionnels") is gratefully acknowledged.

Registry No. PhS $^-$, 13133-62-5; (EtO) $_2$ PO $^-$, 29800-93-9; CH $_3$ COC-H $_2^-$, 24262-31-5; 4-cyanophenyl, 56263-67-3; 2-cyanophenyl, 95936-64-4; 3-cyanophenyl, 95936-65-5; 2-quinolyl, 54978-39-1; 4-quinolyl, 54978-

(26) Gomper, R.; Vogt, H. H. *Chem. Ber.* **1981**, *114*, 2866, 2884.

(27) Achesson, R. M.; Procter, G. J. *Chem. Soc., Perkin Trans. 1* **1979**, 2177.

41-5; 3-quinolyl, 54978-40-4; 3-pyridyl, 29761-81-7; 2-pyridyl, 15905-71-2; 1-naphthyl, 2510-51-2; 2-naphthyl, 10237-50-0; phenyl, 2396-01-2; 2-chloroquinolyl, 95935-24-3; 4-chloroquinoline, 611-35-8; 3-chlorobenzonitrile, 766-84-7; 3-bromoquinoline, 5332-24-1; 2-chlorobenzonitrile, 873-32-5; 1-bromonaphthalene, 90-11-9; 3-chloropyridine, 626-60-8; 2-chloropyridine, 109-09-1; phthalonitrile, 91-15-6; 2-cyanopyridine, 100-70-9; 4-cyanopyridine, 100-48-1; quinoline, 91-22-5; 2,2'-bipyridyl, 366-18-7; 4-chlorobenzonitrile, 623-03-0; 4-bromobenzonitrile,

623-00-7; 4-iodobenzonitrile, 3058-39-7; 1-chloronaphthalene, 90-13-1; 1-iodonaphthalene, 90-14-2; 2-iodoquinoline, 6560-83-4; 3-iodoquinoline, 79476-07-6.

Supplementary Material Available: Determination of rate constants of nucleophilic attack of PhS^- and experimental variables and values (11 pages). Ordering information is given on any current masthead page.

Spectroscopic Assignment of d-d Transitions of Achiral Metal Complexes Using Circular Dichroism: DICD of Co(III) Complexes in Sugar Solutions

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Abstract: Circular dichroism may be used to probe the d-d transitions of an achiral metal complex by simply adding a sugar to the aqueous solution of the complex. The interaction between the sugar and the complex is postulated to be dispersive and orientationally unspecific, leading to the possibility of interpreting the induced circular dichroism in terms of the DICD (dispersion-induced circular dichroism) model. The experimental investigation of a range of Co(III) complexes of varying symmetry and in various sugar solutions supports the relevance of the DICD model and furthermore confirms that it constitutes a general method of assigning magnetic dipole allowed transitions in achiral transition-metal complexes.

Circular dichroism has proved a useful empirical tool in the study of magnetic dipole allowed d-d transitions in chiral metal complexes. Attempts at the theoretical description of the origin of this circular dichroism (CD) within the context of the independent systems approach (nonexchanging achiral d-d chromophore/chiral environment) has generated a multiplicity of distinct models,¹⁻³ each corresponding to a different physical mechanism for the induction of the CD into the achiral chromophore. This multiplicity of models can only serve to complicate any attempt to establish a *unique* relationship between the experimental spectrum and the electronic properties of the d-d chromophore. Such a relationship is crucial for the systematic exploitation of CD in the spectroscopic assignment of d-d transitions.

A unique relationship may be established in two ways. The first is through more detailed theoretical and experimental assessment of the models for chiral complexes in order to elicit the conditions under which each one may be expected to dominate, if more than one mechanism is important. We shall in fact pursue this approach in a forthcoming publication. The second method, and the one which we shall discuss in detail in this paper, is the exploitation of a physical limit, which is theoretically and experimentally realizable, in which only one of the models survives in leading to a nonvanishing CD.

The theoretical limit in which only one mechanism survives is the limit of free rotation between the achiral chromophore and the chiral inducer. The experimental realization of this limit is the measurement of the induced CD of an achiral complex in solution with a chiral solute with which it does not specifically associate. In such cases, the achiral chromophore and the chiral inducer have no orientational correlation. This is theoretically realizable through rotational averaging where all relative orien-

tations are assumed equally probable. All so-called first-order terms (i.e., resulting from first-order perturbation theory), which are the conceptual basis of both static and dynamic coupling mechanisms,^{1,2} rigorously vanish in this limit. However, second-order terms survive the averaging even within the dipole approximation, leading to the contributions which are characteristically referred to as the DICD (dispersion-induced CD) terms.

The persistence of induced CD of the achiral chromophore under these conditions potentially extends the utility of chiral spectroscopy to achiral chromophores without the need to introduce a chemically attached chiral center and without the need to apply static fields to the sample. In this context, it is worth pointing out that MCD studies (in which achiral chromophore become CD active through perturbation by a static magnetic field) effectively probe an electric dipole character; we shall see that the CD induced by another chiral molecular species is capable, however, of directly probing the magnetic dipole character.

The observation of the induced CD of achiral species in chiral solvents or in solution with chiral additives has been reported by a number of workers.⁴⁻⁹ Initial speculation suggested that definite association (with a fixed relative orientation) between the achiral and chiral moieties was a prerequisite for the induction of chirality into the chiral species; however, the experiments of Hayward and Totty⁶ and Axelrod et al.⁷ convincingly demonstrated that this was not the case. Subsequent theoretical studies dealing directly with the development of the DICD model¹⁰ and with somewhat more general symmetry arguments¹¹ confirmed that transmission of chirality between freely rotating systems is both possible and, in the case of dispersive coupling, allowed in the dipole approximation.

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