Electrochemical Reactions. Part XV.[1] Factors which determine the Rate of Carbon–Halogen Bond Fragmentation in Radical Anions illustrated by Some Halogenated Derivatives of Quinoline, Quinoxaline, and Phenazine

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The behaviour of some halogeno-derivatives of quinoline, quinoxaline, and phenazine in the potential region of the first reduction waves has been examined by polarography and cyclic voltammetry in dimethylformamide at a mercury cathode. 2-Chloro- and 2-bromo-phenazine, 6-chloroquinoxaline, and 6-fluoroquinoline form radical anions which show no tendency to fragment with loss of halide ion at room temperature on the time scale of cyclic voltammetry. 2-Iodophenazine, 6-bromo- and 6-iodo-quinoxaline, and 6-chloroquinoline form radical anions which fragment to halide ion and, after further reactions, the parent heterocycle. Radical cations from the diprotonated halogeno-quinoxaline and -phenazine salts are stable in perchloric acid. The stability of the carbon–halogen bond in a halogenated radical anion depends upon the strength of this bond and the redox potential of the substrate–radical anion couple. For the isomeric halogeno-derivatives of a given aromatic system we have shown previously that the rate of carbon–halogen bond cleavage is dependent on the free electron density in the radical anion at the carbon terminus of the cleaving bond.

MANY radical anions formed from an aryl halide by the addition of one electron to the lowest energy unoccupied π orbital decompose at a measurable rate by fragmentation of the carbon–halogen bond to give halide ion and a σ radical which abstracts hydrogen from the solvent. Cyclic voltammetry has been used to establish this mode of decomposition of the radical anions from some halogeno-derivatives of nitrobenzene,[2] benzophenone,[3] 4-styrylpyridine,[1] and benzonitrile [4] in the presence of tetra-alkylammonium counter cation. This fragmentation rate is temperature dependent and the radical anions from 4-iodonitrobenzene [5] and 4-(4-chlorostyryl)-pyridine [1] do not undergo significant fragmentation at

[1] Part XIV, K. Alwair, and J. Grimshaw, *J.C.S. Perkin II*, 1973, 1150.

[2] J. G. Lawless and M. D. Hawley, *J. Electroanalyt. Chem.*, 1969, **21**, 365.

[3] L. Nadjo and J. M. Saveant, *J. Electroanalyt. Chem.*, 1971, **30**, 41.

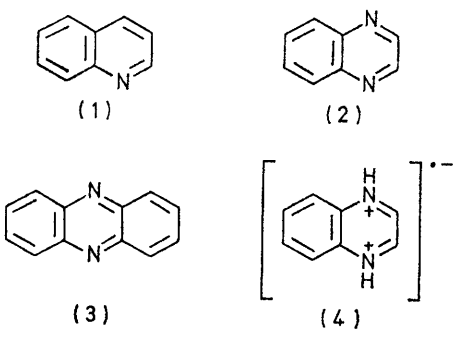
[4] D. E. Bartak, K. J. Houser, B. C. Rudy, and M. D. Hawley, *J. Amer. Chem. Soc.*, 1972, **94**, 7526.

[5] R. P. van Duyne and C. N. Reilley, *Analyt. Chem.*, 1972, **44**, 158.

254 K although fragmentation occurs at room temperature.

The literature also contains examples of halogenated radical anions which are sufficiently stable at room temperature to be generated and characterised by e.s.r. spectroscopy in a static system. Thus characterised are the radical anions from 3-chlorobenzophenone,[3] 2-chloro- and 2-bromo-fluorenone,[3] and 1- and 2-chlorophenazine [6] in dimethylformamide. The isoelectronic radical cations formed by reduction of the diprotonated 1- and 2-chlorophenazine salts in 30% perchloric acid have also been characterised.[7]

Intuitively we consider that the rate of carbon–halogen bond fragmentation is dependent on the bond strength and on the redox potential of the first formed radical ion which is a measure of the energy available for fragmentation. In this paper we have attempted to gain more systematic evidence for this dependence. Such evidence will enable us to predict the stability of a halogenated radical anion towards fragmentation at room temperature. For the isomeric halogeno-derivatives of a given aromatic system we have previously shown that the rate of carbon–halogen bond cleavage is dependent on the free electron density in the radical anion on the carbon atom terminus of the cleaving bond.[1]



(1) (2) (3) (4)

Halogenated derivatives of quinoline (1), quinoxaline (2), and phenazine (3) appeared to be suitable substrates. The free electron density at the relevant carbon atom in the heterocycle radical ions was calculated and differs little among the group. Parameters, $h_N = 0{\cdot}7$ and $k_{CN} = 0{\cdot}9$, proposed for the quinoline radical ion [8] were used for the dihydro-quinoxaline and -phenazine radical cations, $h_N = 1{\cdot}5$ and $k_{CN} = 1{\cdot}0$.[9] The results are included in Table 4. Quinoline shows one polarographic wave while quinoxaline and phenazine each show two polarographic waves in aprotic solvents.[10] The parameters for these waves, obtained under the conditions used for measurement of the halogeno-derivatives, are recorded in Table 2. The first wave in all cases corresponds to reduction to the radical anion. These are stable in dimethylformamide on the time scale of cyclic voltammetry and have been characterised by e.s.r. spectroscopy (quinoline,[8] quinoxaline, and phenazine [11]). The peak potentials in cyclic voltammetry for the first electron transfer process are all independent of the scan rate which is a criterion that the process has a negligible energy of activation.[12] Under these conditions and assuming the diffusion coefficients for the oxidised and reduced forms to be equal, the redox potential for a given couple is equal to the polarographic half-wave potential or to the mean of the cathodic and anodic peak potentials in cyclic voltammetry.[12,13] Quinoxaline and phenazine also show two polarographic waves in 30% perchloric acid. The product from the first reduction wave of quinoxaline is the radical cation (4) and an analogous radical cation is obtained from phenazine.[9] This series gives a range of values for the half-wave potential of the heterocycle–radical ion couple from −2·17 to +0·13 V (*vs.* s.c.e.).

The second electron transfer step at more negative potentials corresponds to the addition of one electron to the radical ion to give a dianion (or the neutral dihydro-species in perchloric acid). In this paper we will discuss only those polarographic waves and cyclic voltammetry curves due to the formation and chemical reaction of radical ions.

EXPERIMENTAL

Dimethylformamide was kept over anhydrous copper sulphate and then distilled under nitrogen, b.p. 42° at 12 mmHg. Nitrogen was purified over the BTS catalyst [14] and dried over a molecular sieve. The electrochemical apparatus has been described previously.[1,15] All potentials are measured *vs.* s.c.e. Halogeno-derivatives of quinoline, quinoxaline, and phenazine were prepared by standard methods.

Polarography.—The cell solution contained tetra-n-propylammonium perchlorate (0·1M) and the substrate ($1{\cdot}0 \times 10^{-3}$M) in anhydrous dimethylformamide at room temperature (23 °C). In another series of experiments the cell solution was made from one batch of 30% perchloric acid (w/w) and contained the substrate ($1{\cdot}0 \times 10^{-3}$M). This latter solvent allows electrochemical measurements in the range +0·35 to −0·30 V. Characteristics of the dropping mercury electrode in 0·1M-KCl were flow rate $1{\cdot}21 \times 10^{-3}$ g s^{-1}, drop time 6·3 s, mercury height 0·565 m.

Cyclic Voltammetry.—Each substrate was examined in the potential range where the parent heterocycle adds one electron to give the radical ion and at scan rates of 0·02—0·4 V s^{-1} using the cell solution as for polarography. Two types of voltagram were observed and a typical example of each is given in the Figure.

[6] A. E. Brodskii, L. L. Gordienko, and Yu. A. Kruglyak, *Teor. eksp. Khim.*, 1967, **3**, 98.
[7] L. L. Gordienko and A. G. Chukhlantseva, *Teor. eksp. Khim.*, 1965, **1**, 844; see also G. Cauquis, H. Delhomme, and O. Serve, *Tetrahedron Letters*, 1971, 4649.
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[12] R. S. Nicholson and I. Shain, *Analyt. Chem.*, 1964, **36**, 706.
[13] J. Heyrovsky and J. Kuta, 'Principles of Polarography,' Academic Press, New York, 1966, ch. VII.
[14] M. Schutze, *Angew. Chem.*, 1958, **70**, 697; Badische Anilin und Soda Fabrik AG, Technical Bulletin 'BTS Catalyst.'
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Reduction of 6-Bromoquinoxaline.—Tetra-n-propylammonium perchlorate (0·1M) in dimethylformamide was used as supporting electrolyte. 6-Bromoquinoxaline (0·15 g) was dissolved in the electrolyte (15 ml) and placed in the cathode compartment of a H type cell with mercury cathode (area 6·2 cm^2), platinum anode, and the electrolyte as anolyte. This was reduced at −1·40 V *vs.* s.c.e. (initial current 3×10^{-3} A) under nitrogen for the stated time. The catholyte was then diluted with water, *trans*-stilbene (R_t 9·4 min) added as internal standard, the products isolated with ether, and the proportions (Table 1) of quinoxaline

TABLE 1

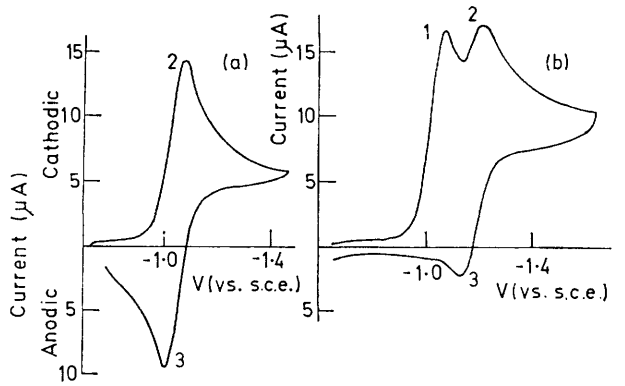
Product proportions during reduction of 6-bromoquinoxaline

	Compound (%)	
Reduction time (h)	6-Bromoquinoxaline	Quinoxaline
2	90	9
4	41	26
8	30	30
10	0	47

(R_t 1·7 min) and 6-bromoquinoxaline (R_t 4·2 min) determined by g.l.c. using a Perkin-Elmer F11 instrument, 2 m × 1/8 in column of 2·5% cyanoethylmethylsilicone, temp. 165 °C.

RESULTS AND DISCUSSION

6-Chloroquinoline shows two polarographic waves in dimethylformamide in contrast to 6-fluoroquinoline and quinoline which show only one wave. Cyclic voltammetry indicates that quinoline and 6-fluoroquinoline are reduced to the radical anion. The voltagram of 6-chloroquinoline resembles Figure (a) and the peaks 2 and 3 are superimposible on the voltagram of quinoline which resembles Figure (b). Thus we conclude that the radical anion of 6-chloroquinoline is formed during the first polarographic wave and fragments rapidly at room temperature to give eventually quinoline the reduction of which occurs at the second polarographic wave while 6-fluoroquinoline radical anion is stable. Japanese workers [16] have demonstrated the formation of quinoline by large scale reduction of 6-chloroquinoline in dimethylformamide. Since the second polarographic wave for 6-chloroquinoline must correspond to uptake of one electron per molecule and the heights of both waves are the same, cleavage of the carbon–chlorine bond requires only one electron. This is consistent with the σ radical abstracting a hydrogen atom from the solvent. The same mechanism has been found in the examples of



First scan cyclic voltammetry in dimethylformamide containing 0·1M-$Pr^n_4NClO_4$ with a Hg cathode: (a) 2-Bromophenazine (scan rate 0·07 V s^{-1}) which gives a stable radical anion and (b) 2-iodophenazine (scan rate 0·10 V s^{-1}) where the radical anion decomposes to give phenazine and iodide ion

carbon–halogen bond fragmentation discussed previously. Related carbon–halogen bond cleavages among the compounds in Table 3 also require only one electron per molecule.

6-Chloroquinoxaline shows behaviour on polarography and cyclic voltammetry which is parallel to that of quinoxaline and its radical anion is stable. 6-Bromo- and 6-iodo-quinoxaline however each show three polarographic waves and from the cyclic voltagrams it is

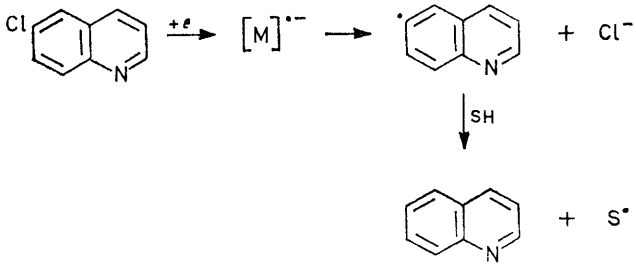


TABLE 2

Data from polarography and cyclic voltammetry of the unsubstituted heterocycles. Cyclic voltammetry is restricted to the potential region of the first polarographic wave and peak potentials are measured for a scan rate of 60 × 10^{-3} V s^{-1}

		Polarography			Cyclic voltammetry	
Compound	Solvent	$E_{\frac{1}{2}}$/V	$E_{1/4} - E_{3/4}$/V	Wave ht./μA	E_{pc}/V	E_{pa}/V
Quinoline (1)	Me_2NCHO	−2·12	0·070	4·5	−2·22	−2·12
Quinoxaline (2)	Me_2NCHO	−1·62	0·055	4·9	−1·68	−1·62
		−2·46	0·080	2·3		
Quinoxaline (2)	30% $HClO_4$	−0·06	0·055	2·5	−0·10	−0·04
		−0·22	0·050	2·3		
Phenazine (3)	Me_2NCHO	−1·17	0·055	3·8	−1·22	−1·15
		−1·84	0·060	3·8		
Phenazine (3)	30% $HClO_4$	+0·15	0·055	2·5	+0·09	+0·16
		−0·21	0·055	2·5		

[16] T. Fujinaga, K. Takaoka, T. Nomura, and K. Yoshikawa, *Nippon Kagaku Zasshi*, 1968, **89**, 185 (*Chem. Abs.*, 1968, **68**, 110,807).

TABLE 3

Data from polarography and first scan cyclic voltammetry of the halogenoheterocycles. Cyclic voltammetry is restricted to the potential region where the parent heterocycle gives its radical ion. The voltagram resembles Figure (a) or (b) as indicated and on which the peaks are numbered. Peak potentials are recorded for a scan rate of 60 × 10^{-3} V s^{-1}

		Polarography				Cyclic voltammetry		
Compound	Solvent	$E_{\frac{1}{2}}$/V	$E_{1/4} - E_{3/4}$/V	Wave ht./μA	Figure	E^1_p/V	E^2_p/V	E^3_p/V
6-Fluoro-(1)	Me_2NCHO	−2·05	0·055	2·75	(a)		−2·09	−2·01 [b]
6-Chloro-(1)	Me_2NCHO	−1·89	*a*	2·75	(b)	−1·97	−2·22	−2·13
		−2·18	0·060	2·80				
6-Chloro-(2)	Me_2NCHO	−1·53	0·055	5·0	(a)		−1·59	−1·53
		−2·35	0·080	4·5				
6-Bromo-(2)	Me_2NCHO	−1·42	*a*	} total ht.	(a)	−1·44	−1·68	−1·62
		−1·67		} 7·4				
		−2·50	0·090	2·0				
6-Iodo-(2)	Me_2NCHO	−1·32	*a*	} total ht.	(a)	−1·36	−1·68	−1·62
		−1·66		} 8·3				
		−2·53	0·090	2·5				
6-Chloro-(2)	30% $HClO_4$	−0·05	0·055	2·9	(b)		−0·05	+0·01
		−0·26	0·050	2·9				
6-Bromo-(2)	30% $HClO_4$	−0·04	0·050	2·5	(b)		−0·08	−0·02
		−0·25	0·050	2·4				
6-Iodo-(2)	30% $HClO_4$	−0·03	0·050	2·2	(b)		−0·05	+0·01
		−0·20	0·065	1·3				
2-Chloro(3)	Me_2NCHO	−1·05	0·050	4·1	(a)		−1·09	−1·02
		−1·74	0·065	2·8				
2-Bromo-(3)	Me_2NCHO	−1·04	0·055	4·0	(a)		−1·08	−1·01
		−1·80	*a*	9·0				
2-Iodo-(3)	Me_2NCHO	−1·01	*a*	4·0	(b)	−1·07	−1·22	−1·14
		−1·16	0·050	3·4				
		−1·80	0·10	3·5				
2-Chloro-(3)	30% $HClO_4$	+0·17	0·055	2·4	(b)		+0·12	+0·18
		−0·18	*a*	2·4				
2-Bromo-(3)	30% $HClO_4$	+0·18	0·055	2·3	(b)		+0·12	+0·18
		−0·21	0·050	2·3				
2-Iodo-(3)	30% $HClO_4$	+0·18	0·055	2·1	(b)		+0·13	+0·19
		−0·21	0·055	2·0				

[a] A maximum distorted the wave. [b] Radical anion ($t_{\frac{1}{2}}$ 4 s) more rapidly destroyed by protonation than the other examples.

TABLE 4

Stability of some halogen-substituted radical anions in dimethylformamide solutions (0·1M-$Pr^n_4NClO_4$)

Unsubstituted radical anion	$-E_0$/V (*vs.* s.c.e.)	Position of substituent	HMO Free-electron density	Stability of substituted radical anion			
				Cl	Br	I	Ref.
Benzonitrile	2·29	2,3,4,		*b*	*b*		4
Quinoline	2·17	6	0·033	*b*			*c*
4-Styrylpyridine	1·88	3′	0·003	*a*			1
		4	0·079	*b*	*b*		1
Benzophenone	1·67	3	0·006 [d]	*a*	*b*		3
		4	0·097	*b*	*b*		3
Quinoxaline	1·65	6	0·044	*a*	*b*	*b*	*c*
Phenazine	1·18	2	0·045	*a*	*a*	*b*	*c*
Fluorenone	1·18	2	0·007 [e]	*a*	*a*		13
Nitrobenzene	1·15	2	0·106 [f]	*a*	*b*	*b*	2,5,[g]
		3	0·005			*b*	
		4	0·124	*a*	*a*	*b*	
Quinoxaline + $2H^+$	0·07	6	0·045	*a*	*a*	*a*	*c*
Phenazine + $2H^+$	−0·13	2	0·051	*a*	*a*	*a*	*c*

[a] No noticeable decomposition of the radical anion on the time scale of cyclic voltammetry, *i.e.* over *ca.* 5 s. [b] Radical anion decomposes with halogen replaced by H in 1 s or less. [c] This paper. [d] S. V. Kalkani and C. Truff, *J. Amer. Chem. Soc.*, 1970, **92**, 4809. [e] D. K. Gupta, C. P. Poole, and H. A. Fatach, *Lettere Nuovo Cimento*, 1971, **2**, 20. [f] P. H. Rieger and G. K. Fraenkel, *J. Chem. Phys.*, 1963, **39**, 609; C. Ling and J. Gendell, *J. Chem. Phys.*, 1967, **47**, 3475. [g] T. Kitagawa, T. P. Layloff, and R. N. Adams, *Analyt. Chem.*, 1963, **35**, 1086.

clear that the first polarographic wave in each case corresponds to the uptake of one electron to give quinoxaline the reduction of which gives rise to the waves at more negative potentials. Thus the carbon–halogen bonds in the radical anions from 6-bromo- and 6-iodoquinoxaline rapidly fragment at room temperature Controlled potential reduction of 6-bromoquinoxaline at a potential near the foot of the first polarographic wave together with g.l.c. analysis of the reaction products indicated the reduction sequence 6-bromoquinoxaline ⟶ quinoxaline ⟶ other products.

2-Chloro- and 2-bromo-phenazine both show analogous behaviour to phenazine on polarography and cyclic voltammetry in the potential region for formation of radical anions. At more negative potentials where a dianion is formed, 2-bromophenazine shows a polarographic wave which is much higher than the corresponding waves for 2-chlorophenazine and phenazine. Probably the dianion decomposes to give bromide ion and eventually phenazine which is reduced further. A similar reaction of 2-chloro and 4-bromonitrobenzene, both of which give stable radical anions, has been described.[17] 2-Iodophenazine shows a cyclic voltagram illustrated in Figure (b). The first reduction peak corresponds to a reaction yielding phenazine which shows its characteristic voltagram with peaks 2 and 3.

The radical cations related to (4) derived by reduction of the halogeno-quinoxalines and -phenazines are stable in perchloric acid under the reaction conditions.

Table 4 summarises our own and related data on the stability of halogenated radical anions. The reaction pathway for this carbon–halogen bond fragmentation has been firmly established for 4-iodonitrobenzene, the halogenobenzophenones, and 4-(4-chlorostyryl)pyridine so it is reasonable to assume that this pathway will hold for all the examples in Table 4. With the exceptions discussed below, a smooth trend is observed which supports the hypothesis that carbon–halogen bond fragmentation is dependent on the strength of the bond and the reduction potential of the heterocyclic radical ion system. An approximate value can be given to the minimum reduction potential necessary before the carbon halogen bond will be broken. Chloro-substituted radical anions are stable when the E_0 value for the parent π system is less negative than −1·6 V and bromo-derivatives when E_0 is less negative than some value between −1·2 and −1·6 V. For iodo-derivatives this critical potential is known only to be less negative than −1·1 V.

Exceptions to the above fall into two classes. The radical anions from 4-(3-chlorostyryl)pyridine and 3-chlorobenzophenone have an unusually low free electron density on the carbon site substituted by chlorine and this accounts for their failure to undergo carbon–chlorine bond fragmentation.[1] 2-Bromonitrobenzene fragments at a faster rate than is expected from the behaviour of its isomers and of 2-bromophenazine. A steric effect has been proposed to account for this.[18] With a better understanding of the factors which govern the rate of these and related radical anion fragmentation processes it will be possible to predict the outcome of reactions where more than one group may be lost. We are extending our work to illustrate this possibility.

6-Fluoroquinoline radical anion did not lose fluoride ion and this result has been observed for the radical anions of 4-fluorobenzophenone and 4-(4-fluorostyryl)-pyridine so we did not examine other fluoro-derivatives. Reduction of 2- and 4-fluorobenzonitrile with sodium in liquid ammonia gives the radical anions which decompose in 1—2 s to benzonitrile, detected by e.s.r. spectroscopy after reduction to its radical anion.[19]

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[3/920 *Received*, 7*th May*, 1973]

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