Chronopotentiometric Studies of Ferrocene Derivatives. II. Directly Substituted Ferrocenes[1,2]

BY WILLIAM F. LITTLE, C. N. REILLEY, J. DONALD JOHNSON, AND ANN P. SANDERS[3]

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Chronopotentiometric quarter-wave potentials of monosubstituted ferrocenes were correlated with Hammett *para* σ-constants, according to the equation: $\Delta E_{1/4} = 0.450\sigma_p + 0.022$ v. Secondary *para* σ-constants were derived from quarter-wave potentials of additional derivatives. This same regression line was used to correlate 21 heteroannular disubstituted ferrocene data. Correlations with $\Sigma\sigma^*$ and $\Sigma\sigma_I$ are discussed.

Introduction

Substituent effects on chronopotentiometric quarter-wave potentials were first studied in acetonitrile by Kuwana, *et al.*,[4] and it was later recognized that these potentials were best correlated with Hammett *para* σ-constants,[5,6] much as rates of esterification of heteroannular substituted ferrocenoic acids are best correlated by *para* σ-constants.[7] Later, Komenda and Tirouflet[8] showed that polarographic potentials in 50% ethanol are also best correlated with *para* σ-constants and suggested the use of such potentials as an additional method for evaluating *p*-constants. Gubin and Perevalova[9] have measured normal oxidation potentials of directly substituted ferrocenes in acetic–perchloric acid by a titration procedure, but reported that two lines, rather than one, are necessary to correlate their data, ascribing the requirement of two *p*-values to a strong direct field effect of one group of substituents that is absent or negligible for the other group.

Discussion

Monosubstituted Ferrocenes.—We have measured the chronopotentiometric quarter-wave potentials of 15 monosubstituted ferrocenes, seven of whose quarter-wave potentials were reported by Hoh, *et al.*[4,5] The regression line given by eq. 1 (correlation coefficient, 0.993; standard deviation of $\Delta E_{1/4}$, 0.017 v.

$$\Delta E_{1/4} = 0.450\sigma_p + 0.022 \text{ v.} \qquad (1)$$

from the regression line) was established from the substituted ferrocenes whose *p*-substituent constants have been determined from ionization constants of benzoic acids.[10,11] Table I lists the groups used to establish eq. 1. By using $\Delta E_{1/4}$ (relative to the value of $E_{1/4}$ for

ferrocene), rather than the absolute value of $E_{1/4}$,[12] our data usually agreed within less than 10 mv. with the data of Hoh, *et al.*,[5] and Kuwana, *et al.*[4] This enabled us to use some of these data in establishing the regression line; whenever possible, averages of our data and theirs were used.

TABLE I

CHRONOPOTENTIOMETRIC QUARTER-WAVE POTENTIALS OF MONO-SUBSTITUTED FERROCENES AT 25° IN ACETONITRILE *vs.* S.C.E.

Substituent	$E_{1/4}$, v.	$\Delta E_{1/4}$, v.[a]	$\Delta E_{1/4}$, v. (lit. values)	$\overline{\Delta E_{1/4}}$, v.	σ_p[d]
CH$_3$	. . .	. . .	-0.060[b]	-0.060	-0.17
C$_2$H$_5$	. . .	. . .	$-.062$,[c] -0.060[b]	$-.061$	$-.151$
i-C$_3$H$_7$	. . .	. . .	$-.057$[b]	$-.057$	$-.151$
Si(CH$_3$)$_3$	. . .	. . .	$.005$[b]	$.005$	$-.07$
C$_6$H$_5$	0.346	0.031	$.025$[b]	$.028$	$-.01$
H	.315	.000	.000	.000	.000
I	.457	.142	. . .	.142	.18
CO$_2$H	.552	.237	0.243[a]	.240	.45
CO$_2$C$_2$H$_5$	.556	.241	. . .	.241	.45
COCH$_3$	.567	.252	0.266,[a] 0.246[b]	.255	.502

[a] Relative to $E_{1/4}$ of ferrocene, 0.315 v.   [b] From ref. 5.   [c] From ref. 4.   [d] From ref. 10.

Attempts to correlate the quarter-wave potentials with *meta* σ-constants or Taft's polar constants[13] were unsuccessful, as previously observed.[5,8,9] Significantly, attempted correlation with Brown's σ^+-constants[14] was unsuccessful. The fit of the potential data with *para* σ-constants rather than with polar constants indicates the importance of resonance contribution of the substituents with the carbocyclic ring to which they are attached; the failure of the correlation with Brown's σ^+-constants indicates that resonance with the reaction site, the central iron atom, is not important.[1,2,15]

The open circles in Fig. I show the correlation of the potentials of derivatives for which derived (secondary) σ-constants are available (see Tables II and III). Tables II and III contain secondary σ-constants derived from the chronopotentiometric quarter-wave potentials with eq. 1. It can be seen that the secondary σ-constants generally agree with literature values within 0.05 σ-constant unit.

Gubin and Perevalova,[9] reporting normal oxidation potentials of monosubstituted ferrocenes measured in acetic acid–perchloric acid by a potentiometric titration

(1) (a) Presented at the Southeastern Regional Meeting of the American Chemical Society, Gatlinburg, Tenn., November, 1962. See Abstracts, p. 70. (b) Part I of this series: W. F. Little, C. N. Reilley, J. D. Johnson, K. N. Lynn, and A. P. Sanders, *J. Am. Chem. Soc.*, **86**, 1376 (1964).

(2) Taken in part from a Ph.D. Dissertation submitted by J. Donald Johnson to the University of North Carolina, August, 1962.

(3) Petroleum Research Fund Scholar, Summer, 1962.

(4) T. Kuwana, D. E. Bublitz, and G. L. K. Hoh, *J. Am. Chem. Soc.*, **82**, 5811 (1960).

(5) G. L. K. Hoh, W. E. McEwen, and J. Kleinberg, *ibid.*, **83**, 3949 (1961).

(6) W. F. Little and R. Eisenthal, *J. Org. Chem.*, **26**, 3609 (1961).

(7) W. F. Little and R. Eisenthal, *J. Am. Chem. Soc.*, **83**, 4936 (1961).

(8) J. Komenda and J. Tirouflet, *Compt. rend.*, **254**, 3093 (1962).

(9) S. P. Gubin and E. G. Perevalova, *Doklady Akad. Nauk S.S.S.R.*, **143**, 1351 (1962).

(10) D. H. McDaniel and H. C. Brown, *J. Org. Chem.*, **23**, 420 (1958).

(11) Ideally primary substituent constants, derived from thermodynamic pK_a data of benzoic acid, should have been used for the purpose of establishing the regression line. However, the only primary substituent constants available were for the groups CH$_3$, C$_2$H$_5$, i-C$_3$H$_9$, and COCH$_3$. This was considered too few groups for establishment of a ρ-value, so we have arbitrarily used additional σ-constants derived from apparent acid constants and taken from the listing of McDaniel and Brown.[10]

(12) Owing to differences in junction potentials and traces of moisture in the solvent, absolute values of $E_{1/4}$ are not as reproducible as $\Delta E_{1/4}$. In our work $E_{1/4}$ for ferrocene remained constant at 0.315 v. *vs.* s.c.e. In the work of Hoh, *et al.*,[5] the value for ferrocene was 0.341.

(13) R. W. Taft, Jr., in "Steric Effects in Organic Chemistry," ed. by M. S. Newman, John Wiley and Sons, Inc., New York, N. Y., 1956, Chapter 13.

(14) H. C. Brown and Y. Okamato, *J. Am. Chem. Soc.*, **80**, 4979 (1958).

(15) W. F. Little, "Survey of Progress in Chemistry," ed. by A. F. Scott, Academic Press, Inc., New York, N. Y., 1963, p. 172; M. Rosenblum, J. O. Santer, and W. G. Howells, *J. Am. Chem. Soc.*, **85**, 1450 (1963).

TABLE II

CHRONOPOTENTIOMETRIC QUARTER-WAVE POTENTIALS OF MONOSUBSTITUTED FERROCENES AND SECONDARY σ-CONSTANTS

Group	$E^1/_4$	$\Delta E^1/_4$	$\Delta E^1/_4$ (lit. value)	$\overline{\Delta E^1/_4}$	Secondary σ-constants, σ_p Derived	Lit. value
n-C_3H_7	...	...	-0.055^a	-0.055	-0.171	-0.126^c
$CH_2C_6H_5$	...	...	$-.027^a$	$-.027$	$-.109$	
$CH(OH)C_3H_5$	0.324	0.009	$.011^b$	.010	$-.026$	
$CH(OCH_3)C_6H_5$	.332	.017	...	.017	$-.011$	
$C(C_6H_5)_3$	.372	.057	...	.057	.078	
$CH=CHC_6H_5$	...	...	-0.013	$-.013$	$-.078$	
$CH(OH)CH_3$	...	...	$-.009$	$-.009$	$-.069$	
COC_6H_5	0.571	0.256	$.264^b$	.260	.528	0.459^c
$CONH_2$	.531	.216	...	.216	.431	$0.312,^d 0.552^d$
$CONHC_6H_5$	.522	.207	...	.207	.411	
$CON(C_6H_5)_2$	.496	.181	...	.181	.353	
CO_2CH_3	.561	.246	...	.246	.497	$0.484,^d 0.45^e$
$CO_2CH(C_6H_5)_2$	.587	.272	...	.272	.555	0.55^e
CHO	...	...	0.257^a	.257	.522	

[a] From ref. 5.   [b] From ref. 4.   [c] From ref. 16.   [d] From ref. 17.   [e] From ref. 1b.

TABLE III

CHRONOPOTENTIOMETRIC QUARTER-WAVE POTENTIALS AND DERIVED σ-CONSTANTS FOR SUBSTITUTED PHENYLFERROCENES

Substituent	$\Delta E^1/_4{}^a$	σ(calcd.)	σ^b
p-$NH_2C_6H_5$	-0.072	-0.209	-0.23
p-HOC_6H_5	$-.022$	$-.097$	..
p-$CH_3OC_6H_5$	$-.018$	$-.088$	0.08
p-$CH_3C_6H_5$	.010	$-.070$	$-.03$
p-$C_6H_5C_6H_5$	.031	.020	$-.01$
p-ClC_6H_5	.046	.053	.14
p-BrC_6H_5	.053	.069	.14
p-$CH_3COC_6H_5$	.085	.140	..
p-CNC_6H_5	.115	.206	..
p-$NO_2C_6H_5$	.128	.226	0.30
p-$CO_2HC_6H_5$	.082	.133	..
p-$C_6H_5CONHC_6H_5$	.015	$-.016$	..
m-$NH_2C_6H_5$	.013	$-.020$	..
m-$COOHC_6H_5$	.066	.098	..
m-$CF_3C_6H_5$	.077	.122	..
m-$NO_2C_6H_5$	.108	.169	0.23
m-BrC_6H_5	.075	.118	0.14
m-$C_6H_5CONHC_6H_5$	.041	.042	..

[a] Relative to $E^1/_4$ for ferrocene, 0.315 v.; taken from ref. 1b.
[b] Calculated from data in ref. 18.

procedure with $K_2Cr_2O_7$, have divided substituents into two groups, each group demanding a different ρ-value and resulting in the requirement of two regression lines to correlate these data with Hammett *para* σ-constants. They ascribed the difference in the two groups of substituents to a direct field effect, in one case, of the substituent on the central iron atom. The substituents for which the direct field effect was considered important (the phenyl group, halogens, carboxyl, and carbomethoxy) determined a regression line with a ρ-value of -7.94. Our regression line (slope 0.450) requires a ρ-value of 7.61,[19] which is not far different. However, the second line of Gubin and Perevalova was established by the methoxy group, alkyl groups, hydrogen, and the acetoxy group, and determined a ρ-value of -4.23. These groups were assumed to exert a negligible direct field effect on the central iron atom.

(16) H. H. Jaffé, *Chem. Rev.*, **53**, 191 (1953).

(17) H. van Bekkum, P. E. Verkade, and B. M. Wepster, *Rec. trav. chim.*, **78**, 815 (1959).

(18) E. Berliner and E. A. Blommers, *J. Am. Chem. Soc.*, **73**, 2479 (1951).

(19) The slope, 0.450, was converted to a ρ-value in terms of log K/K_0 by dividing by 0.0591. This assumes that $\Delta E^1/_4 \cong \Delta E^0$. The difference in signs of our ρ-value and that of Gubin and Perevalova is due to the choice of sign conventions. We used the polarographers' conventions.

We question this interpretation for it does not seem reasonable that the direct field effect could be important for halogens, carboxyl, and carboalkoxy groups and unimportant for the methoxy and acetoxy groups. Our data, and those of Komenda and Tirouflet,[8] do not require different regression lines for the alkyl groups. The weight of the evidence requiring two ρ constants rested on the oxidation potentials of methoxy- and acetoxyferrocene. Komenda and Tirouflet did not report data on the acetoxy and methoxy groups, but we attempted to measure quarter-wave potentials for acetoxy- and phenoxyferrocene. Both

Fig. 1.—Relationship between $\Delta E^1/$ of substituted ferrocenes and Hammett *para* σ-constants. Closed circles are for the groups used to establish the regression line.

of these derivatives, in which the functional group is directly attached to ferrocene by an oxygen linkage, failed to give reversible chronopotentiograms. In both cases, the forward curves gave discontinuities (maxima) and the $E_{0.22}$ values, after current reversal, differed from the forward quarter-wave potentials (estimated at current densities where the discontinuities were minimized) by 10 mv. Of course, the estimated potentials of these two substrates ($\Delta E^1/_4 = 0.060$ for acetoxy and -0.19 for phenoxy) did not fit our Hammett plot, but it is believed that other factors are involved with these substrates, just as the expected values for m- and p-aminophenylferrocenes are obtained from freshly prepared solutions, but after the solutions stand, quarter-wave potentials from 60 to 100 mv. higher are obtained.[1b] The value of the oxidation potentials of
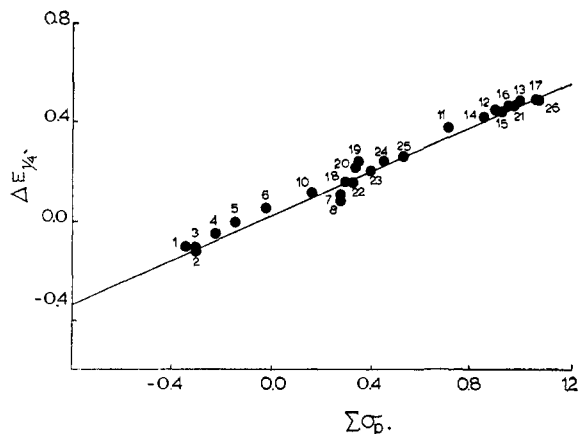
Fig. 2.—Relationship between $\Delta E_{1/4}$ of heteroannular disubstituted ferrocenes and Hammett *para* σ-constants. Numbers refer to Table IV. Regression line was established from monosubstituted derivatives.

m- and *p*-aminophenylferrocene obtained by Gubin and Perevalova similarly are considerably out of line with the expected values, indicating that both groups are electron withdrawing, rather than donating, as we have reported.[1b] Finally, if different ρ-values are required to correlate potentials of substituted ferrocenes, this requirement should be accentuated in cases of heteroannular disubstituted derivatives; such was not observed (*vide infra*).

The existence of a direct field effect of the substituent on the central iron atom is neither proved nor disproved by our data, but the correlations observed indicate that such an effect is either small or proportional to Hammett *para* σ-constants in this series.

The ρ-ratio, obtained from the slopes of the regression lines for substituted phenylferrocenes and for directly substituted ferrocenes, is 0.365, in substantial agreement with the ionization constant data of Berliner and Blommers[18] on diphenylcarboxylic acids, giving a measure of the transmissivity of electronic effects through a phenyl group.

As a method for obtaining secondary *para* σ-constants, this approach has the advantage of greater sensitivity than the use of phenylferrocenes,[1b] but there remains the inherent assumption that substitution on ferrocene is analogous to *p*-substitution in the benzene series.

Heteroannular Disubstituted Ferrocenes.—The chronopotentiometry of five heteroannular disubstituted ferrocenes with like substituents has been reported,[4,5] and these reports indicate that the potentials of such derivatives can be correlated with a summation of *para* σ-constants, although but a single example of a disubstituted derivative, where the two substituents are different, has been reported.[8] Consequently a series of 21 disubstituted ferrocenes with both like and unlike substituents were studied in order to test the additivity of substituent effects more rigorously, to confirm the requirement of a single ρ-value for this correlation, and to demonstrate more conclusively the noncorrelation of quarter-wave potential data with the alternative substituent constants. These data are listed in Table IV, along with the data on five substrates measured by Hoh, *et al.*[5]

Figure 2 shows that quarter-wave potentials of heteroannular disubstituted ferrocenes can be cor-

TABLE IV

QUARTER-WAVE POTENTIALS OF HETEROANNULAR DISUBSTITUTED FERROCENES IN ACETONITRILE RELATIVE TO $E_{1/4}$ FOR FERROCENE (0.315 V. *vs.* S.C.E.)

	Substituent	Preparation (ref.)	$\Delta E_{1/4}$, v.	σ_p constants used[a]
1	CH₃, CH₃	..	-0.100[b]	$-0.170, -0.170$
2	C₂H₅, C₂H₅	..	$-.115$[c]	$-.151, -.151$
3	*i*-C₃H₇, *i*-C₃H₇	20	$-.102$	$-.151, -.151$
4	CH₂C₆H₅, CH₂C₆H₅	..	$-.045$[b]	$-.109$[d]$, -0.109$[d]
5	Si(CH₃)₃, Si(CH₃)₃	..	$.005$[b]	$-.07, -0.07$
6	C₆H₅, C₆H₅	..	$.055$[b]	$-.01, -0.01$
7	*m*-BrC₆H₅, *m*-BrC₆H₅	21	$.109$	$.14,$[d]$ 0.14$[d]
8	*p*-BrC₆H₅, *p*-BrC₆H₅	21	$.084$	$.14,$[d]$ 0.14$[d]
9	CH(C₆H₅)₂, CH(C₆H₅)₂	21	$.010$	...
10	C(C₆H₅)₃, C(C₆H₅)₃	21	$.117$	$0.078,$[d]$ 0.078$[d]
11	CON(C₆H₅)₂, CON(C₆H₅)₂	22	$.384$	$.353,$[d]$ 0.353$[d]
12	CO₂H, CO₂H	23	$.453$	$.45, 0.45$
13	COCH₃, COCH₃	24	$.484$	$.502, 0.502$
14	COCH₃, CON(C₆H₅)₂	22	$.424$	$.502, .353$[d]
15	COCH₃, CONH₂	22	$.447$	$.502, .431$[d]
16	COCH₃, CO₂H	22	$.466$	$.502, .45$
17	COCH₃, CO₂CH(C₆H₅)₂	22	$.493$	$.502, .555$[d]
18	CO₂H, C₂H₅	22	$.182$	$.45, -0.151$
19	CO₂H, CHOHC₆H₅	22	$.242$	$.45, -.026$[d]
20	CO₂H, CH₂C₆H₅	22	$.220$	$.45, -.109$[d]
21	CO₂H, COC₆H₅	22	$.468$	$.45, 0.528$[d]
22	CON(C₆H₅)₂, CHOHC₆H₅	22	$.179$	$.353,$[d]$ -0.026$[d]
23	CO₂CH(C₆H₅)₂, C₂H₅	22	$.204$	$.555,$[d]$ -.151$
24	CO₂CH(C₆H₅)₂, CH₂C₆H₅	22	$.244$	$.555,$[d]$ -.109$[d]
25	CO₂CH(C₆H₅)₂, CHOHC₆H₅	22	$.263$	$.555,$[d]$ -.026$[d]
26	CO₂CH(C₆H₅)₂, COC₆H₅	22	$.486$	$.555,$[d]$ 0.528$[d]

[a] Values without superscripts come from ionization of benzoic acids, ref. 10. [b] From ref. 5. [c] Average value from ref. 4 and 5. [d] Calculated from eq. 1 (Table II).

related quite well with the regression line established for monosubstituted ferrocenes (standard deviation of $\Delta E_{1/4}$ from the regression line, 0.031 v.). It was necessary in this plot to use secondary σ-constants for many of the groups, since σ-constants from ionization constant data of benzoic acids were not available for all the groups studied (see Table IV). It should be pointed out that the correlation is good for like substituents and unlike substituents, whether the unlike substituents both be electron withdrawing or releasing or be they opposite to one another in their electronic properties.

The good correlation in Fig. 2 shows that but one ρ-value is required for potentials of substituted ferrocenes. If two ρ-values should be required to correlate such potential data with structure, as reported by Gubin and Perevalova, the present data, which should augment this requirement, do not bear it out.

Hoh, *et al.*,[5] have shown that for alkyl groups a quite good correlation of quarter-wave potentials is obtained with Taft's polar constants, σ^*. Our data also show this (Fig. 3) for alkyl groups and some additional groups, such as the carboxyl group, whose *para* σ-constants do not contain strong resonance components,[25] but the correlation breaks down for many other groups.

On the other hand, quarter-wave potentials of substituted ferrocenes, plotted *vs.* inductive σ-constants of Roberts and Moreland,[26] σ_I (as calculated from $\sigma^*_{X\text{-}CH_2}$ according to the method described by Taft[13]),

(20) W. F. Little and R. C. Koestler, *J. Org. Chem.*, **26**, 3247 (1961).

(21) W. F. Little, A. K. Clark, G. Benner, and C. Noe, *ibid.*, **29**, 713 (1964).

(22) W. F. Little and R. Eisenthal, *J. Am. Chem. Soc.*, **82**, 1577 (1960).

(23) M. Rosenblum, Ph.D. Thesis, Harvard University, 1953.

(24) M. Rosenblum and R. B. Woodward, *J. Am. Chem. Soc.*, **80**, 5443 (1958).

(25) See ref. 13, p. 594.

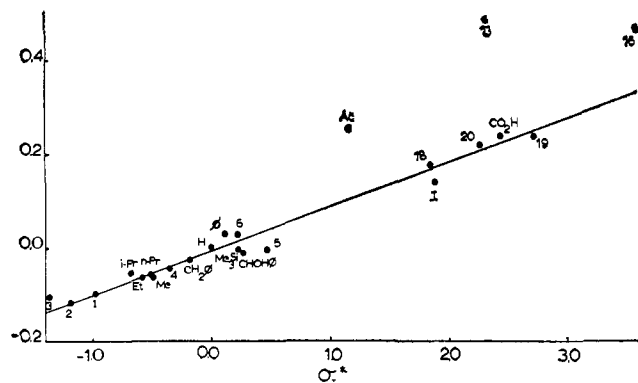(26) J. D. Roberts and W. T. Moreland, *J. Am. Chem. Soc.*, **75**, 2167 (1953).

Fig. 3.—Relationship between $\Delta E_{1/4}$ of substituted ferrocenes and Taft's polar constants (adjusted to $\sigma_H* = 0.00$). Numbered points refer to Table IV.
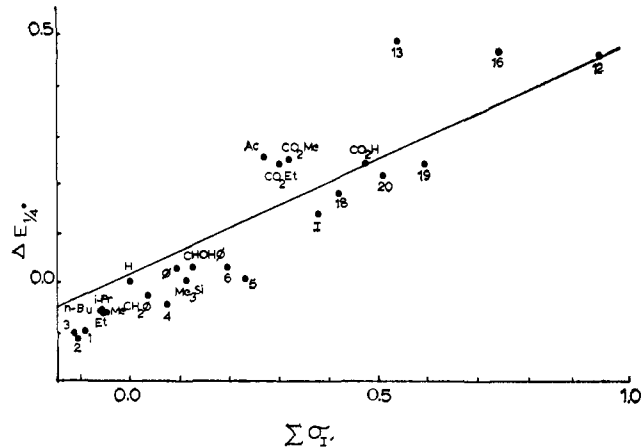

Fig. 4.—Relationship between $\Delta E_{1/4}$ of substituted ferrocenes and inductive σ-constants. Numbered points refer to Table IV. Regression line shown is that established with Hammett $para$ σ-constants.

give a poor correlation. Figure 4 shows this plot along with the regression line described by eq. 1. Electron-withdrawing groups (by resonance) tend to fall above the line and electron-donating groups drop below the line. For alkyl groups the observations above imply a linearity of $\sigma*$ with σ_p that does not exist with σ_I.[27] One would rather expect to observe linearity between values of $\sigma*$ and σ_I, but such a correlation is poor. These points raise the possibility that $\sigma*$ does not represent the purely inductive properties of substituent groups; rather it is suggested that the transition states of acid and alkaline hydrolyses of esters are affected to different extents by resonance with functional groups directly adjacent to the carboxyl carbon. Similar differences of resonance interaction of p-substituents with the carboxyl and carboxylate groups in benzoic acids have been suggested by Bekkum, Verkade, and Wepster[17] to account for inconsistencies in Hammett constants.

On the other hand, σ_I, which is related to $\sigma*_{X-CH_2}$ (where the group really described is insulated from the carboxyl group by a methylene group), shows the type of deviations from σ_p that one would expect for a purely inductive substituent constant. Leffler and Grunwald[28] have discussed dispersion from the $\rho*\sigma*$ equation, where resonance with the transition state of reactions studied (such as acid-catalyzed hydrolysis of acetals[29]) is credited with the cause of the dispersion, rather than the substituent constants themselves.

Secondary $para$ σ-constants derived from the data in Tables II, III, and IV, by eq. 1, show interesting trends for some of the groups. Successive replacement of the hydrogens of the methyl group by phenyl groups (Table V) change the value from -0.170 to $+0.078$ for triphenylmethyl. On the other hand, successive replacement of carboxamide hydrogens by phenyl groups changes the value of the carboxamide function in the opposite direction from 0.431 to 0.353 for the diphenylcarboxamide group, which is also counter to the direction of change of values for the carbomethoxy group (0.497) to the carbobenzhydroxy group (0.555).

(27) In fact, Hoh, et $al.$,[5] have expressed this linearity of σ_p and $\sigma*$ by the equation: $\Sigma\sigma* = 4.406\Sigma\sigma_p - 5.156$. The same equation should be derivable from tables of $\sigma*$ and σ_p constants.

(28) J. E. Leffler and E. Grunwald, "Rates and Equilibria of Organic Reactions," John Wiley and Sons, Inc., New York, N. Y., 1963, p. 231 ff.

(29) M. M. Kreevoy and R. W. Taft, Jr., $J.$ $Am.$ $Chem.$ $Soc.,$ **77**, 5590 (1955).

It is also interesting to note that $\Delta E_{1/4}$ for 1,1'-bistriphenylmethylferrocene (0.117 v.) is approximately twice the value for triphenylmethylferrocene (0.057 v.), indicating the independence of quarter-wave potentials from steric effects. Hoh, et $al.,$[5] similarly showed that the bulk of t-butyl groups had no effect on quarter-wave potentials.

TABLE V

DERIVED $para$ σ-CONSTANTS OF SELECTED GROUPS FROM QUARTER-WAVE POTENTIALS

Group	σ_p	Group	σ_p
CH_3	-0.170^a	$CONH_2$	0.431
$CH_2C_6H_5$	$-.109$	$CONHC_6H_5$	.411
$CH(C_6H_5)_2$	$-.038^b$	$CON(C_6H_5)_2$	.375
$C(C_6H_5)_3$	$+.078$	$COCH_3$	.497
		$COCH(C_6H_5)_2$	.555

^{a} From ref. 10. ^{b} Obtained from regression line in Fig. 1 with $1/2$ $\Delta E_{1/4}$ of the disubstituted compound.

More Highly Substituted Ferrocenes.—Table VI lists quarter-wave potentials for five 1,1',2,2'-tetrasubstituted benzylferrocenes. Such highly substituted

TABLE VI

QUARTER-WAVE POTENTIALS OF 1,1',2,2'-TETRASUBSTITUTED FERROCENES IN ACETONITRILE $vs.$ S.C.E. (RELATIVE TO $E_{1/4}$ OF FERROCENE = 0.315 V.)

Substituent	$\Delta E_{1/4}$, v.
$C_6H_5CH_2$	-0.062
p-$ClC_6H_4CH_2$	$-.013$
p-$FC_6H_4CH_2$	$-.040$
p-$CH_3C_6H_4CH_2$	$-.091$
m-$BrC_6H_4CH_2$	$+.012$

ferrocenes cannot be correlated by eq. 1, using a summation of σ-constants for the entire benzyl substituents. However, using σ-constants of the substituents on the phenyl groups, these five compounds form a series unto themselves that can be correlated among themselves with eq. 2 (correlation coefficient, 0.993; standard deviation, 0.004 v.).

$$\Delta E_{1/4} = 0.0466\Sigma\sigma - 0.058 \text{ v.} \tag{2}$$

Experimental

Materials.—All derivatives of ferrocene were known compounds. The substituted phenylferrocenes were described in ref. 1b. The carboxylic acid, carboxamide, diphenylcarboxamide, and the benzhydryl ester were described in ref. 7. The

monophenylcarboxamide was prepared by the method of Weliky and Gould.[30] The acetyl derivative was prepared by the method of Hauser and Lindsay[31] and the benzoyl derivative by the method of Weliky and Gould and was reduced to the α-hydroxybenzyl derivative according to the method of the same authors.[30] Both carbomethoxy-[32] and carboethoxyferrocene[33] were prepared by esterification of ferrocenemonocarboxylic acid in the appropriate alcohol with sulfuric acid catalysts. References to the preparation of the disubstituted ferrocenes are given in Table

(30) N. Weliky and E. S. Gould, J. Am. Chem. Soc., 79, 2742 (1957).

(31) C. R. Hauser and J. K. Lindsay, J. Org. Chem., 22, 482 (1957).

(32) R. A. Benkeser, D. Goggin, and G. Schroll, J. Am. Chem. Soc., 76, 4025 (1954).

(33) V. Weinmayr, ibid., 77, 3009 (1955).

IV. The preparation of the tetrasubstituted ferrocenes was reported by Little and Koestler.[34]

Measurements.—The potential measurements were made at 25° in acetonitrile with a LiClO₄ supporting electrolyte as previously described.[1b] The $E_{0.22}$ values were within 2 or 3 mv. of the $E_{1/4}$ values. In one case (bistriphenylmethylferrocene), approximately 5% of methylene chloride was added to the solvent because of the insufficient solubility of the compound in acetonitrile.

(34) W. F. Little and R. C. Koestler, J. Org. Chem., 26, 3245 (1961).

[Contribution from the Department of Chemistry, Stanford University, Stanford, Calif.]

Mass Spectrometry in Structural and Stereochemical Problems. XLV.[1] The Mass Spectrometric Fragmentation Behavior of Isohexyl Cyanide and Its Deuterium Analogs[2]

By R. Beugelmans, D. H. Williams, H. Budzikiewicz, and Carl Djerassi

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The mass spectral fragmentation behavior of isohexyl cyanide has been investigated by extensive deuterium labeling and high resolution measurements. The resulting generalizations are applicable to the interpretation of mass spectra of aliphatic nitriles.

Aside from occasional examples recorded in the earlier literature, the only systematic study of the mass spectral behavior of aliphatic nitriles published so far is due to McLafferty.[3] The interpretation of such spectra is complicated by the fact that standard resolution does not permit a differentiation between the isobaric pairs CH₂ and N or C₂H₂ and CN. Thus, it is frequently impossible to determine whether a given fragment contains the nitrile group or whether a certain peak is made up of two species, one with and the other without nitrogen. Such uncertainties make it more difficult to arrive at firm generalizations about the fragmentation behavior of aliphatic nitriles.

These reasons prompted us to investigate one specific example in detail using both deuterium labels and high resolution data. The availability of isohexyl bromides[4] substituted with deuterium in all possible positions but C-4 offered the possibility of preparing the corresponding labeled derivatives of isohexyl cyanide (I) by treatment with sodium cyanide in aqueous methanol. This procedure resulted in some back-exchange at C-2 and thus explains the isotopic impurity of the C-2 deuterated analog (see Table I).

The molecular ion region in the mass spectrum (Fig. 1) of I contains only peaks of very low intensity; indeed the molecular ion can hardly be recognized. Slightly more pronounced is the M − 1 fragment characteristic of all aliphatic nitriles.[3] As Pottie and Lossing have demonstrated[5] that the dissociation energy of hydrogen attached to C-2 is nearly identical

(1) For paper XLIV see D. H. Williams, H. Budzikiewicz, Z. Pelah, and C. Djerassi, Monatsh., 95, 166 (1964).

(2) This work was supported by the National Institutes of Health of the U. S. Public Health Service (grant No. AM-04257). R. B. is indebted to N.A.T.O. for a grant while on leave from the Institut de Chimie des Substances Naturelles, Gif-sur-Yvette, S. et O., France.
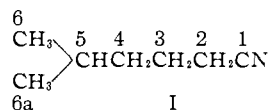
(3) F. W. McLafferty, Anal. Chem., 34, 26 (1962); see also Chapter 6 in ref. 6.

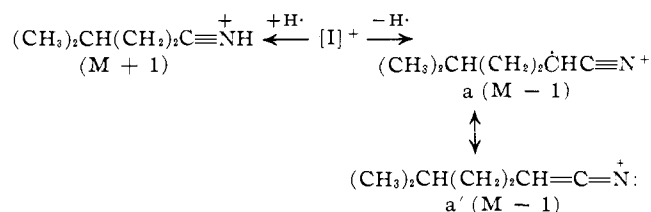(4) C. Beard, J. M. Wilson, H. Budzikiewicz, and C. Djerassi, J. Am. Chem. Soc., 86, 269 (1964).

(5) R. F. Pottie and F. P. Lossing, ibid., 83, 4737 (1961).

TABLE I

Isotopic Purity of Deuterated Isohexyl Cyanides

Compound	Number of deuterium atoms	
	d_1, %	d_2, %
2-d_2-I	60	40
3-d_2-I	6	94
5-d_1-I	99	0
6,6a-d_2-I	3	97

$$\begin{matrix} 6 \\ CH_3 \\ \diagdown \\ CH_3 \\ 6a \end{matrix} \begin{matrix} 5\ 4\ 3\ 2\ 1 \\ \text{CHCH}_2\text{CH}_2\text{CH}_2\text{CN} \\ \\ I \end{matrix}$$

with that of allylically bound hydrogens, it seems plausible to represent the M − 1 ion as a hybrid of two resonance forms a and a'. The deuterium labels seem to support this conclusion, although quantitative measurements are not possible because of the low abundance of the ions concerned.

$$(CH_3)_2CH(CH_2)_2C\!\equiv\!\overset{+}{N}H \xleftarrow{+H\cdot} [I]^+ \xrightarrow{-H\cdot} (CH_3)_2CH(CH_2)_2\overset{\cdot}{C}HC\!\equiv\!N^+$$
$$(M + 1) \qquad\qquad\qquad a\ (M - 1)$$

$$(CH_3)_2CH(CH_2)_2CH\!=\!C\!=\!\overset{+}{N}\!:$$
$$a'\ (M - 1)$$

In addition to the M − 1 ion, the mass spectrum of I (Fig. 1) also shows a peak one mass unit above the molecular weight, another characteristic feature of aliphatic nitriles.[3] Such M + 1 ions are produced by capture of a hydrogen radical by the molecular ion and the intensity of the M + 1 peak is, therefore, pressure dependent.[3] The low intensity and especially the complexity of the molecular region makes it impossible to use the molecular ion itself for establishment of the isotopic purity of the labeled compounds. For this purpose, the M − 15 peak (m/e 96) had to be used. The results summarized in Table I are based on the