An Examination Of The Effects Of Ortho Substituents In Polarography.

AN EXAMINATION OF THE EFFECTS OF ORTHO SUBSTITUENTS IN POLAROGRAPHY

by

William W. Hussey

A Dissertation

Presented to the Graduate Faculty

of Lehigh University

in Candidacy for the Degree of

Doctor of Philosophy

Lehigh University

1965

CERTIFICATE OF APPROVAL

Approved and recommended for acceptance as a dissertation in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

May 24, 1965
Date

Professor in charge

Special committee directing the doctoral work of Mr. William W. Hussey

Jerome Daen

Irving Borowitz

Velmer B. Fish

Charles Kraihanzel

ACKNOWLEDGEMENTS

The author is indebted to Dr. A. James Diefenderfer as director of this investigation, as well as to the members of his special committee for their aid and advice, without which this project could not have been completed.

Gratitude is also expressed to Lehigh University for the Heim Fellowship and to the National Science Foundation for their financial support.

TABLE OF CONTENTS

INDEX OF FIGURES

INDEX OF TABLES

ABSTRACT

When substituted aromatic compounds are reduced at the dropping mercury electrode, it is often noted that ortho substituted compounds reduce much more easily than their meta or para isomers. No satisfactory explanation has been offered for this phenomenon, commonly known as the "ortho effect." The purpose of this work is to offer an interpretation of this ortho effect.

A large series of substituted bromo and iodobenzenes were polarographically reduced under carefully controlled conditions. These data indicated that no previous explanation of the ortho effect, such as hydrogen bonding, was reasonable, and also indicated that no change in mechanism was involved for the ortho case.

The half-wave potentials of the meta and para substituted compounds were plotted versus their Hammett sigma values, forming a straight line. It was found that the half-wave potentials of the ortho substituted compounds could be correlated with this line by applying a formula based on the following principles: 1) that the inductive effect of a substituent is proportional to, but greater than the inductive effect of that substituent in the para position; 2) that the resonance interaction of a substituent is hindered when it is placed in a position adjacent to a bulky group such as the halides. For the bromo and iodobenzenes, this formula had the form:

$$\sigma_{ortho} = 2.4\,\sigma_{I,p} + (1\text{-steric factor})\,\sigma_{R,p}$$

Preliminary attempts to extend the treatment to other systems was limited by several factors, most importantly that no other reducible system is exactly analogous to the phenyl halides.

INTRODUCTION

A number of studies have been performed to determine the effect of substituent groups on the electrochemical reduction of aromatic compounds (1,2,3,4,5). These have confirmed the electronegativity rule of reduction potentials formulated by Shikata and Tachi (1). This rule states that organic compounds are more easily reduced as more electronegative groups are substituted on the same molecule. Thus electron donating substituents such as -OH, $-CH_3$ and $-OCH_3$ groups make reduction more difficult than for an unsubstituted compound, while electron withdrawing substituents such as -Cl, -C≡N and $-CF_3$ groups aid the reduction. This is reasonable since reduction will always involve the addition of an electron to the molecule, and anything which would decrease the electron density at the reduction site should make this addition easier.

In many cases it has been noted that ortho substituted compounds are much easier to reduce than would have been predicted. For example, the half-wave potential of a reducible aromatic compound is almost always lower for the ortho substituted compound than for the meta or para substituted compounds. Furthermore, many electron donating groups aid rather than hinder reduction when they are placed in the ortho position. This abnormal polarographic behavior has been termed the "ortho effect".

These low half-wave potentials were first observed for compounds such as o-nitrophenol (6) and o-hydroxybenzaldehyde (7), and were widely attributed to hydrogen bonding (4,6,7,8). However, the ortho effect was subsequently observed to be a rather general

phenomenon, often occuring in cases such as the reduction of ortho chloroiodobenzene (9), where there are no hydrogens involved. A recent review of the subject (10), points out the wide occurrence of marked positive ortho shifts in cases where hydrogen bonding is unacceptable as an explanation and states that the contribution of the formation of hydrogen bonds to the shift of half-wave potential cannot be taken as proven in any case so far reported.

In some studies the unusually low half-wave potentials of ortho substituted compounds were simply called "anomalies" and ignored. Many times half-wave potentials were being compared to reaction rates in solution and the lack of correlation was discussed in terms of the reaction rates rather than in terms of the half-wave potentials. For the most part, quantitative studies concentrated on compounds with substituents in the meta and para positions and avoided the problems of the ortho case.

Anomalous effects caused by substituents in the ortho position are not confined to polarography, but are widely found in aromatic chemistry. For example, nearly all ortho substituents exert an acid strengthening effect, whether they are electron withdrawing or electron donating, and the effect is unusually large. The acidity constants for the chlorobenzoic acids are: para Cl = 9.3×10^{-5}, meta Cl = 15.5×10^{-5}, ortho Cl = 132×10^{-5}. This represents a more than tenfold increase in acidity. Similarly, unusual effects are noted for the reaction rates of ortho substituted compounds and in the ortho-para ratios obtained in aromatic substitution. Many of these can be partially explained as steric

hindrance with reaction or steric inhibition of resonance. However a standard text in organic chemistry (11) states that: "This ortho effect is not understood; it undoubtedly has to do with the nearness of the groups involved, but is more than just steric hindrance arising from their bulk."

A recent paper on ortho effects in polarography (10) summarizes the work done to date. It shows that the half-wave potentials of ortho substituted compounds do not follow the linear free energy treatment of Taft and says that another parameter must be introduced or a set of ortho σ constants should be derived. However, no suggestions for the parameter or a set of σ_o constants are given. This paper also points out that ortho enhancement of reduction is a fairly consistent phenomenon in various reaction series, but it does not offer an explanation of this effect.

The purpose of this paper is to examine the ortho effect and offer an interpretation thereof. Since no previous experimental work had been specifically concerned with ortho compounds, it was necessary that we thoroughly investigate a reaction series under controlled conditions to properly evaluate these effects.

BASIC CONSIDERATIONS

Polarography - The fundamentals of polarography are well known and easily accessible in standard monographs (12,13). For this reason the discussion herein will be limited to those areas which are germane to the present investigation.

In theory, polarographic analysis is ideally suited for the investigation of organic compounds. It constitutes a reaction system where one of the two reactants, the electrode, is an easily controlled constant. Solutions for analysis are easily prepared and analyses can be run in a few minutes. In addition the results of the reduction are read out directly in numerical quantities, the half-wave potential and the diffusion current, which involve no further calculations for interpretation.

In practice, however, the advantages of polarographic analysis can be obtained only by the careful consideration of many factors. Both the half-wave potential and the diffusion current are very sensitive to changes in electrolyte, solvent, rate of scan apparatus and temperature. In addition they are sometimes sensitive to changes in concentration or pH. Thus accurate polarographic analysis depends upon the careful control of all factors which affect the system.

For this study we chose to work with the aromatic halides since their reduction is not affected by pH (14). They are also convenient because of the large number of substituted aromatic halides which are commercially available.

Sign Convention - The European or IUPAC sign convention will be used throughout this work. Under this convention, reductions will usually take place at negative potentials referred to the saturated calomel electrode. The current arising from the reduction is taken as being positive and is referred to as cathodic current. Statements

saying that compound A is more easily reduced than compound B, or that A has a lower half-wave potential than B mean that compound A reduces at a less negative potential than compound B.

Transfer Coefficient - Additional information may be obtained from an individual polarogram by plotting the function $\log(i/i_d-i)$ versus E, where i is the current at any voltage E and i_d is the diffusion current. The slope of this line is equal to the function αn where α is the transfer coefficient and n is the number of electrons involved in the reduction. The transfer coefficient, α, has been defined as that fraction of the change in electrode potential, ΔE in the cathodic direction which acts to increase the rate of the cathode reaction (15). The most useful facet of the transfer coefficient is that it does not change as long as the reduction mechanism remains the same. Thus if a series of similar compounds has a constant αn value, it may be assumed that the same reduction mechanism is operative throughout the series.

Hammett Equation - The Hammett equation (16) is an empirical relationship based on the observation that a series of meta or para substituents often have the same relative effects on different reactions. It may be expressed in the form $\log K/K_o = \rho\sigma$ where K and K_o are the equilibrium constants for the reaction of the substituted and unsubstituted compound respectively. Rho (ρ) is the reaction constant characteristic of the series at hand and is a measure of the sensitivity of this type of reaction to ring substitution, while sigma (σ), called the substituent constant, is

characteristic only of the substituent and represents the effect which the substituent has upon the electron density at the reaction site.

Hammett examined a large number of equilibria and rates of reactions with the ionization constants of benzoic acid as a reference (16). From this data he determined a σ value for each substituent in both the meta and para positions. Substituents in the ortho position do not behave in a regular manner, so ortho substituent constants were not derived. These values for σ vary over a small range and a "best value" was determined by Hammett for each group. Revised values for the constants have been compiled from new and better data (17,18). However, it should be pointed out that these σ values are only semiquantitative in nature and values used by various authors vary slightly. Jaffe has estimated the overall precision of σ values to be only $\pm$ 15% (18).

The linear relationship of the Hammett equation involves the logarithms of equilibrium constants, which implies that the substituents exert their effect through changes of free energy. Hence it is referred to as a linear free energy relationship. The Hammett equation applies not only to equilibria, but to rates of reactions, in which case rate constants are used in place of equilibrium constants.

The half-wave potentials of reversible systems are proportional to the logarithms of the corresponding equilibrium constants. The half-wave potential of an irreversible process is proportional to the logarithm of the rate constant of the electrode

process k^o, according to the equation

$$E_{\frac{1}{2}} = RT/\alpha nF \ln 0.87 \, k^o\sqrt{t/D}$$

where t is the drop time in seconds and D is the diffusion coefficient in $cm.^2/sec.$(19) The condition necessary for the linear relationship between the half-wave potentials and the logarithms of the rate constants according to the equation above is a constant value for the transfer coefficient α. Fortunately this condition is approximately fulfilled for many structurally related compounds, including the series in this paper.

Since the Hammett function is linearly related to the log of k^o, it will be linearly related to $E_{\frac{1}{2}}$. This can be verified by the appearance of a straight line when the half-wave potentials of a series of substituted compounds are plotted against the σ values of the substituents.

EXPERIMENTAL DETAILS

Instrumentation - The basic instrument was an electronic polarograph constructed in this laboratory from a design by Duffield (20). This had no moving parts, functioning entirely with operational amplifiers. A three electrode system was used. All polarograms were recorded on a Houston model HR921 XY recorder with the scan range set at 100 mv./inch. The potential applied was measured with a potentiometer constructed in this laboratory utilizing a built-in Weston Cell for constant standardization. All pH measurements were made with a Beckman Zeromatic pH meter using a Beckman glass electrode, model # 41263.

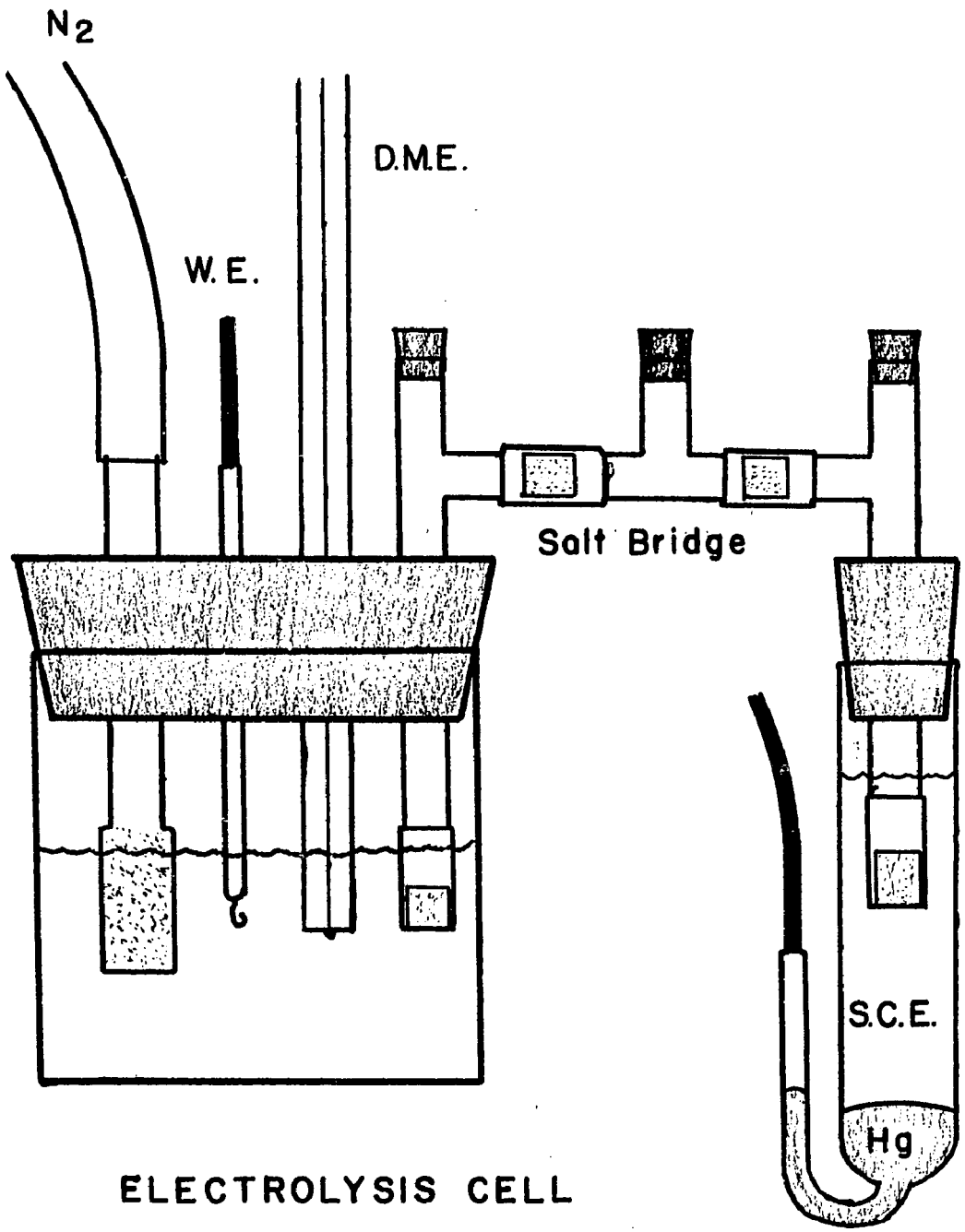
Electrolysis Cell and Accesories - The electrolysis cell (Figure I) was a four ounce glass jar, 6cm. in diameter and 6cm. deep. A rubber stopper was used to support the dropping mercury electrode (DME), the working electrode (WE), a salt bridge and gas dispersion tube. A large calomel electrode connected to the cell by the salt bridge served as a reference electrode. The entire assembly was placed in a water bath thermostated at 25.0 C^{o} $\pm 0.1^{o}$.

The DME was constructed from 0.03mm. marine barometer tubing (Corning Glass Works, Corning, N.Y.) cut to a length of approximately 20cm. so as to give a drop time of about 9 seconds with a 110cm. head of mercury at open circuited conditions. The DME was centered between the working electrode and the salt bridge connection to the SCE. The working electrode was a platinum wire.

A medium frit gas dispersion tube was used to pass pre-purified nitrogen (Matheson) into the solution to remove dissolved oxygen. The nitrogen was passed through a pre-saturator consisting of solvent of the same composition as that in the cell so that no changes in cell composition would take place. The gas dispersion tube could be lowered into the solution for the initial deaeration, then raised above the solution during analysis to provide a blanket of nitrogen which prevented oxygen from re-entering the system.

The salt bridge was constructed of three glass sections connected by Tygon tubing. Inserted in the tubing were ¼ in. Vycor plugs which had a relatively low resistance, but passed very little solution. These were made by breaking off small sections of raw Vycor rods (Corning) and boiling them in 1M HCl for several days to

FIGURE 1



ELECTROLYSIS CELL

leach them, leaving porous plugs. These were washed thoroughly in distilled water to remove the HCl. When lithium perchlorate was the supporting electrolyte, the three sections of the salt bridge contained 2.5 M KCl in the compartment in the calomel, 2.5 M LiCl in the center compartment and 2.5 M $LiClO_4$ in the compartment in the electrolysis cell. When 0.1 M tetramethylammonium chloride was the supporting electrolyte, the three sections contained 2.5 M KCl, 1.0 M $(CH_3)_4NCl$ and 0.5 M $(CH_3)_4NCl$ respectively.

Reagents - Substituted bromo and iodobenzenes were obtained from Distillation Products Inc. (Rochester, N.Y.), City Chemical Corp. (New York, N.Y.) and Columbia Organic Chemicals Corp. (Columbia, S.C.). Substituted benzophenones were obtained from K & K Labs., Inc. (Plainview, N.Y.). Reagent grade chemicals were used without further modification, as they were found to be sufficiently pure for polarography.

Tetramethylammonium chloride was obtained from J.T. Baker Chemical Co. (Phillipsburg, N.J.) and recrystallized twice from methanol. Sodium acetate and acetic acid (J.T. Baker) were used without further modification.

Lithium perchlorate was prepared by the neutralization of reagent grade lithium carbonate with perchloric acid (both from J.T. Baker). The resulting solution was acidified and boiled to remove carbon dioxide. The pH was then adjusted to 7.0 with lithium hydroxide and diluted to make a stock solution of 2.5 M lithium perchlorate.

Ortho and para iodobenzyl alcohol were prepared by the lithium aluminum hydride reduction of the corresponding iodobenzoic acids in a modification of the method of Nystrom and Brown (21). Approximately one gram of $LiAlH_4$ was mixed with 50ml. of anhydrous ethyl ether in a 200 ml., 2 neck flask fitted with a reflux condenser, a dropping funnel and a magnetic stirring bar. 5 Grams of the iodobenzoic acid dissolved in 50ml. of anhydrous ether were added slowly with stirring. The reaction was protected from moisture by $CaCl_2$ drying tubes. Fifteen minutes after completion of the addition, and with continued stirring and cooling, 30ml. of 10% H_2SO_4 were cautiously added to decompose the excess $LiAlH_4$, resulting in a clear solution. This was transferred to a separatory funnel and extracted twice with ether, saving the ether layers. The ether was then evaporated to give a crude product which was subsequently recrystallized from methanol. The carbon and hydrogen analysis for the iodobenzyl alcohols prepared was:

	C	H
Calculated	35.91	3.02
Found - para	35.87	2.65
Found - ortho	34.65	2.66

The melting point of the ortho compound was 89-90°C compared to the literature value of 90°C (22). The melting point of the para iodobenzyl alcohol was 72-78°C. The literature value is 71-75°C (22).

Typical Procedure - Polarographic stock solutions of the electroactive species were prepared by weighing out 50 millimoles of the aromatic halide and dissolving it in 100ml. of methanol to give a

0.005 M solution. These were found to be stable for periods of two weeks to six months, depending upon the compound. In general, all measurements were made with stock solutions which were less than one week old.

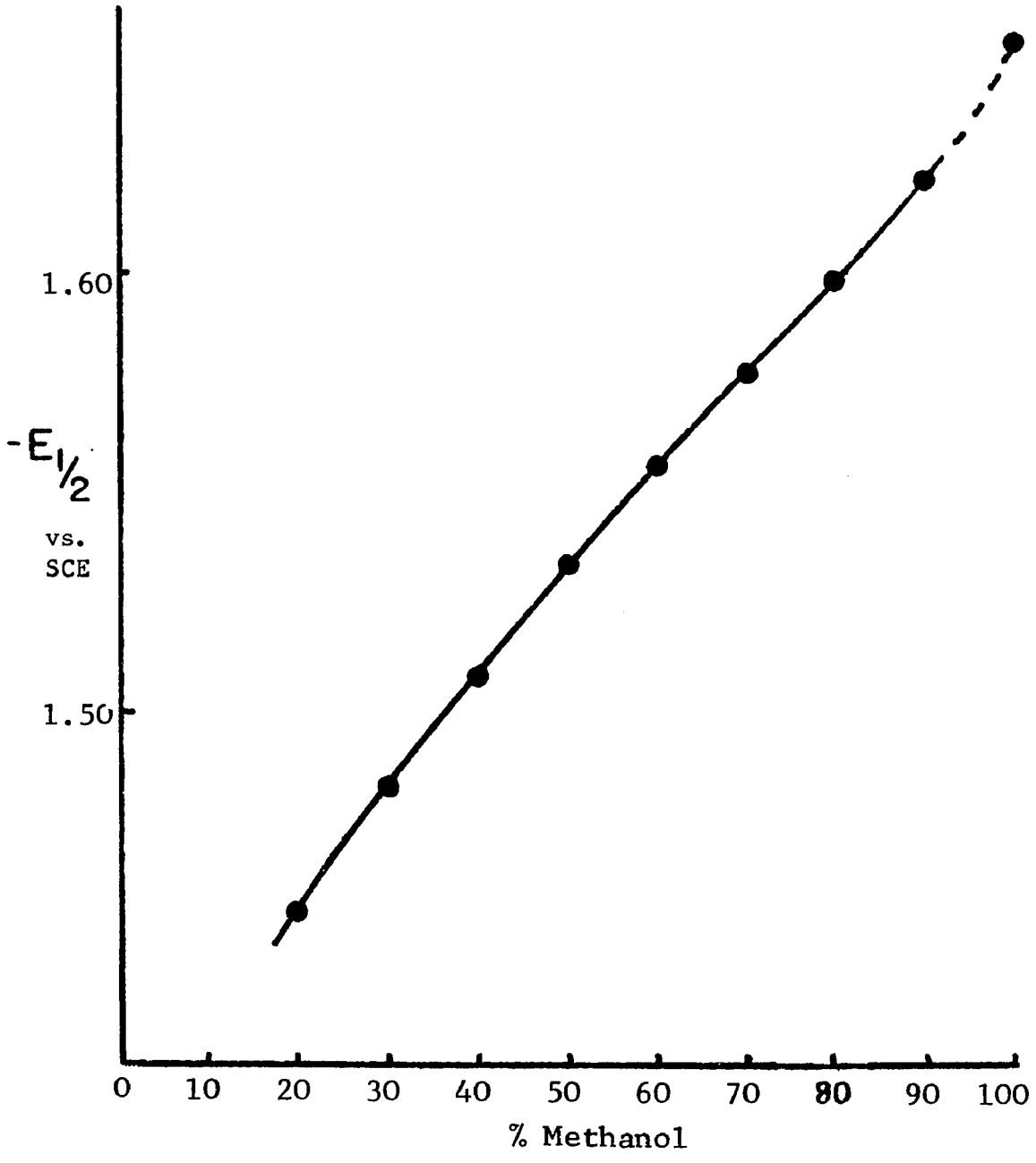
Solutions for analysis were made by pipetting 20ml. of supporting electrolyte stock solution, 10ml. of the electroactive species stock solution and 20ml. of methanol into a cell. This gave a 1.0×10^{-3} M solution of the electroactive species in 60% methanol. This solution was then deaerated for one minute before running the polarogram. During the analysis a blanket of nitrogen covered the solution to keep out oxygen.

RESULTS

The Influence of Conditions During Analysis

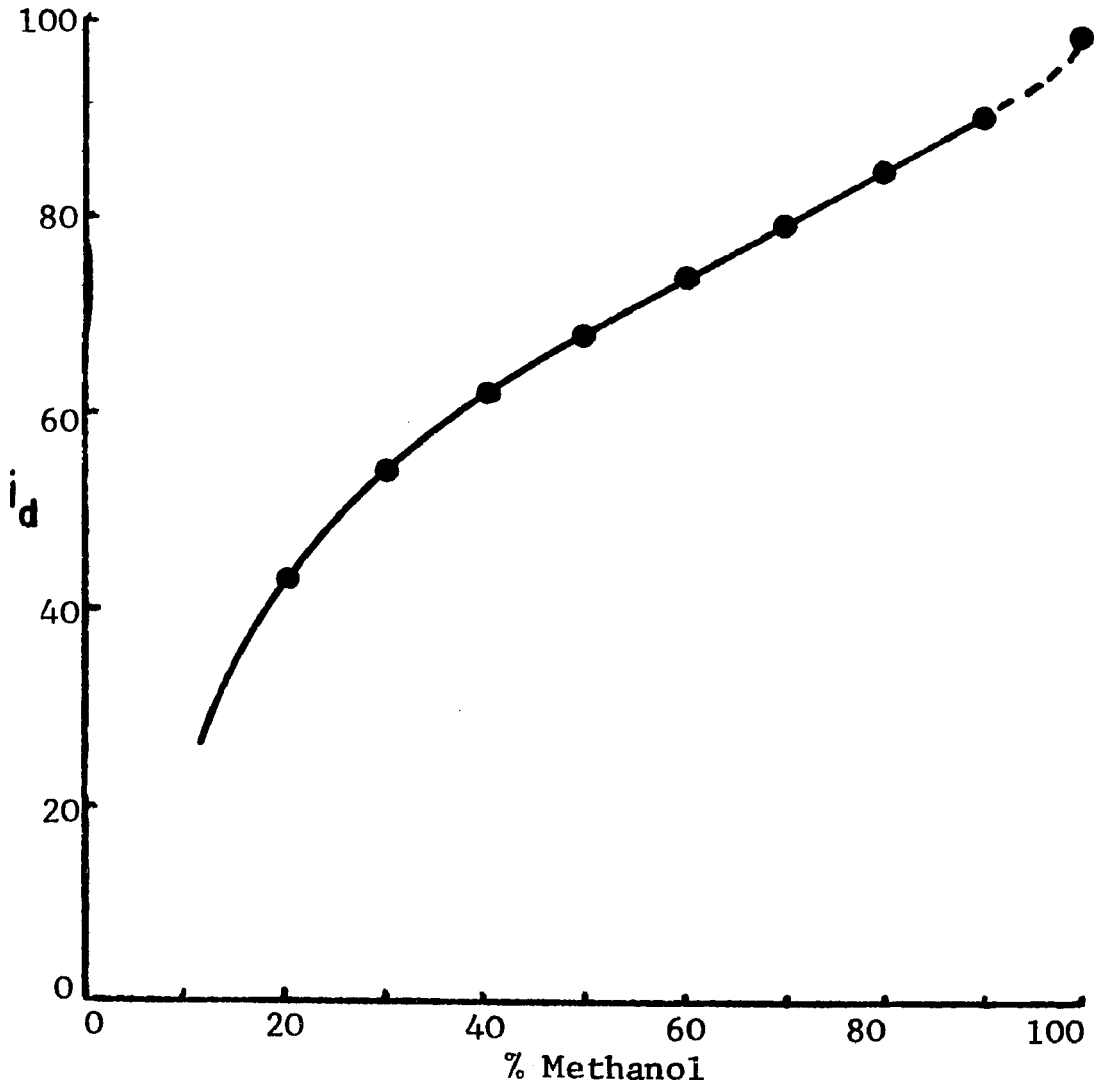
Solvent - The standard solvent used in this investigation was a 60% methanol, 40% water solution. Iodobenzene and p-chloroiodobenzene were polarographically reduced in solutions of varying percentages of methanol to examine the effects of this solvent change. Increasing the percentage of methanol in the solvent had the dual effect of increasing the half-wave potential and increasing the diffusion current for both compounds. Both of these factors varied in an approximately linear manner from 90% down to 20% methanol. (Figures 2 and 3) This may be due to a change in the diffusion coefficient. The diffusion current starts to decrease sharply at 20% methanol and disappears if the concentration of methanol is below 10%,

FIGURE 2



$-E_{1/2}$ for p-Chloroiodobenzene versus % Methanol

FIGURE 3



i_d for p-Chloroiodobenzene versus % Methanol

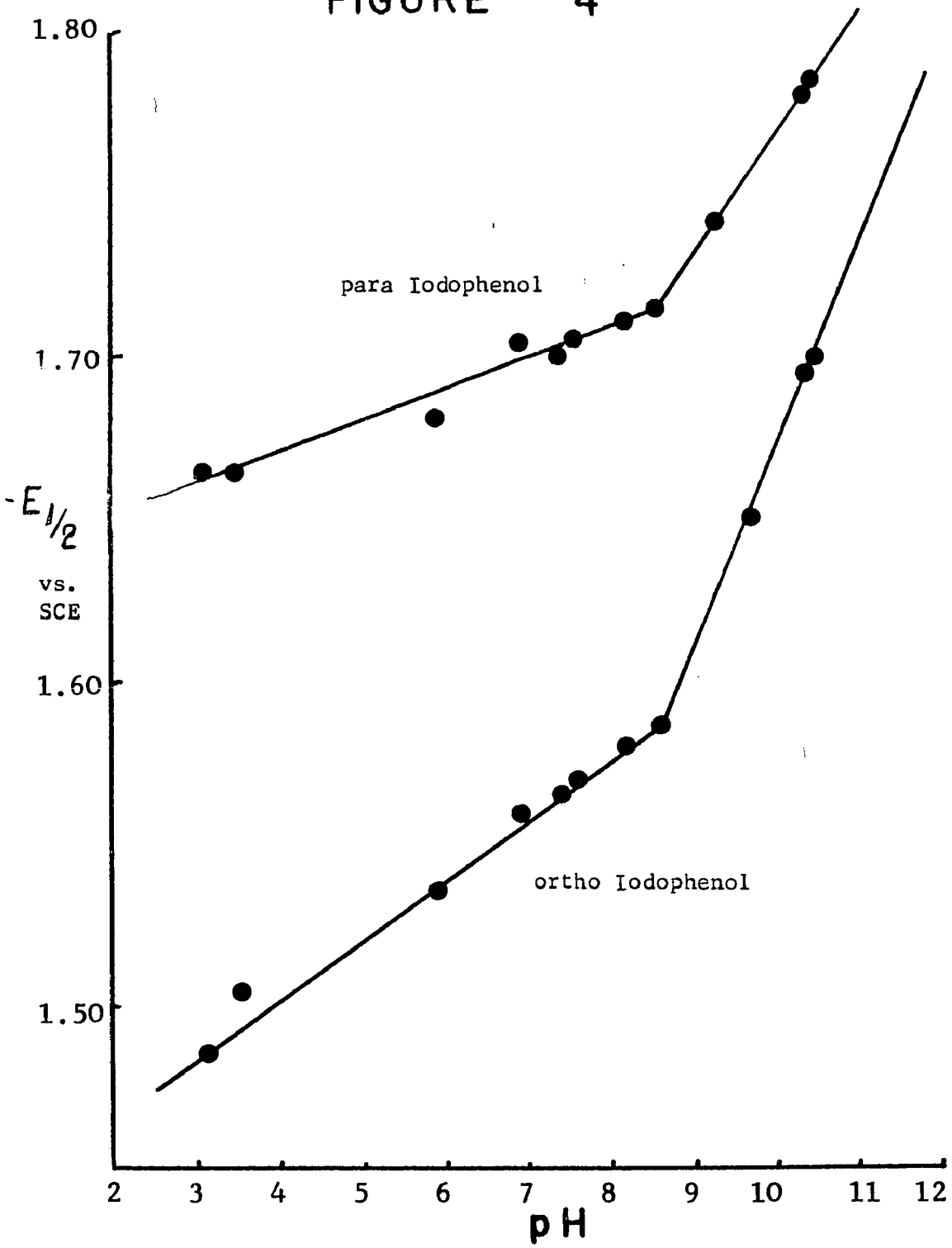
probably due to insolubility of the iodobenzene. The values which were obtained in 100% methanol varied slightly from the linear functions. The values calculated for α increased slightly with the percent of methanol in the solvent.

pH Effect - Iodobenzene, ortho and para aminoiodobenzene and ortho and para chloroiodobenzene were polarographically reduced in solutions of pH 3.1, 5.2, 6.8 and 10.0; (the measurement of pH in 60% methanol should be considered to be a relative, not an absolute value). No changes in half-wave potential were observed for any of these. Polarograms obtained from very acidic solutions were somewhat difficult to interpret due to the hydrogen wave which occurs prior to the reduction of the iodobenzene. At a pH of more than 10 the diffusion current drops, probably because of a lack of hydrogen to replace the reduced iodine atom. The lack of pH dependence for iodobenzene reductions is in agreement with previous work (14).

Substituted iodobenzenes whose half-wave potentials do have a marked pH dependence are the iodophenols and the iodobenzoic acids. This is not surprising since both the phenols and the acids can dissociate to an extent determined by the pH of the medium. The half-wave potentials of ortho and para hydroxyiodobenzene vary with pH in a semi-linear manner with a break in the line occuring about pH 8. (Figure 4) This corresponds to the pK_a value of the phenol.

Concentration of electroactive species - Solutions of 5×10^{-3}; 1×10^{-3} and 5×10^{-2} molar iodobenzene, o and p-chloroiodobenzene and p-methoxyiodobenzene were reduced at the dropping mercury electrode

FIGURE 4



E1/2 for o and p Iodophenol versus pH

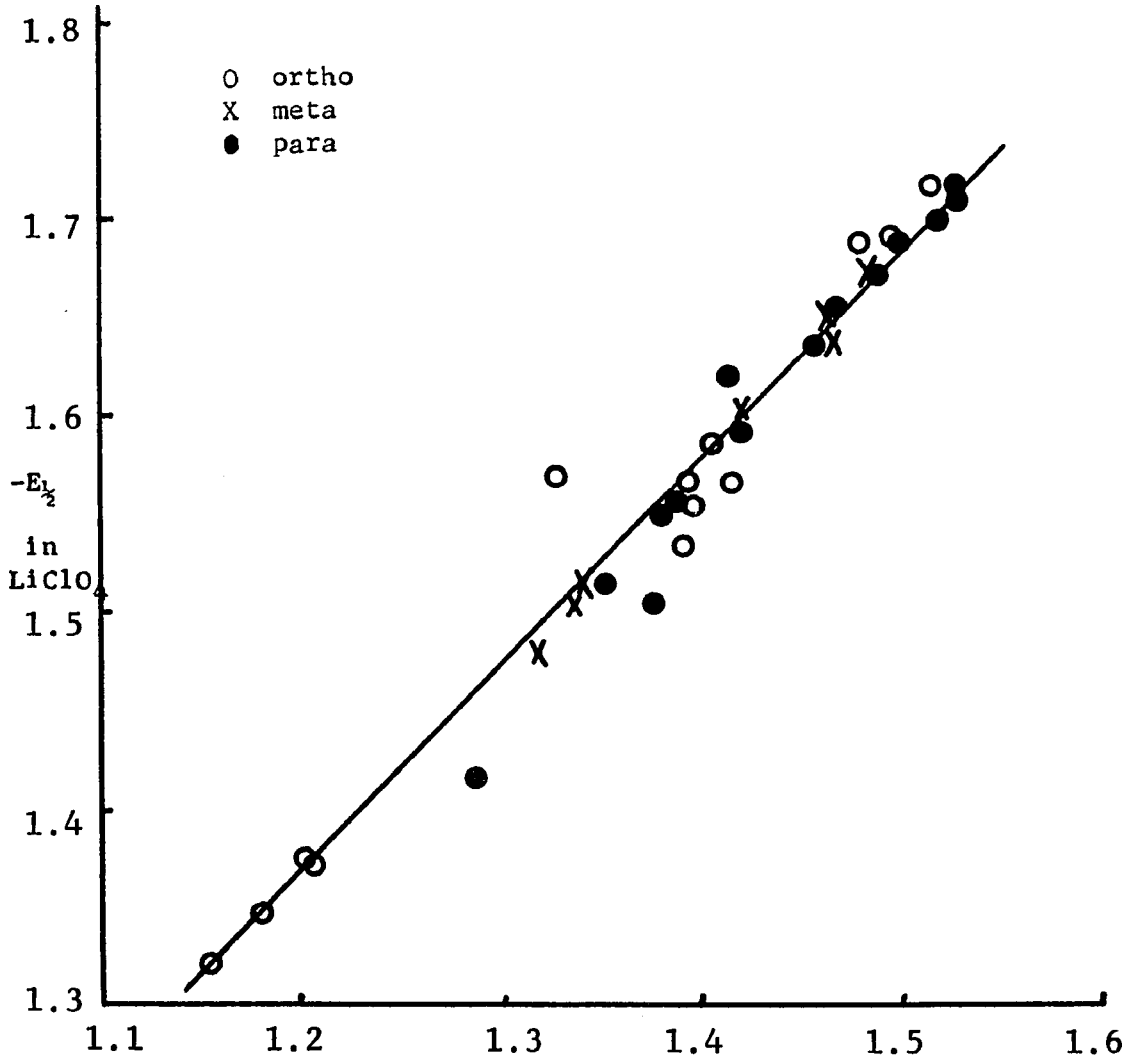
and there was no change in half-wave potentials with concentration.

Electrolyte Effects - When reducing nonionic compounds such as the aromatic halides, it is necessary to introduce a supporting electrolyte into the system to carry the current arising from the reduction. These supporting electrolytes are chosen for their high decomposition potentials. Unfortunately, these electrolytes affect the half-wave potentials of organic compounds.

The effect of the supporting electrolyte is dramatically illustrated by the iodobenzene series investigated in this work. All thirty five substituted iodobenzenes were reduced in both 1 M lithium perchlorate and 0.1 M tetramethylammonium chloride. The most striking fact is that the half-wave potentials are all about 170mv. lower in the tetraalkyl salt than in the perchlorate medium. Though this lowering effect is present for all the substituted iodobenzenes, there is a substantial variation in the amount of $E_{\frac{1}{2}}$ lowering. This varies from 128mv. for p-iodobenzoic acid to 243mv. for o-phenyliodobenzene. A comparison of the iodobenzene series reduced in lithium perchlorate versus the same series run in tetramethylammonium chloride is shown in Figure 5. The deviations for the acids and phenols may be partially explained as a function of pH, for the lithium perchlorate solution was neutral, while the tetra alkyl ammonium salt was slightly basic.

The effect of a change in the cation of the perchlorate salt was also checked by comparing polarograms obtained in sodium perchlorate to those run in lithium perchlorate. No difference in half-wave potential or wave shape was observed.

FIGURE 5



E 1/2 for Iodobenzenes in $LiClO_4$ versus
E 1/2 for Iodobenzenes in $(CH_3)_4NCl$

Results of Reductions - Thirty five substituted iodobenzenes were reduced at the DME in 1 M $LiClO_4$ and 0.1 M $(CH_3)_4NCl$. The half-wave potentials recorded are shown in Table I. These are the results of multiple determinations and are reproducible to within ± 4 mv.

The half-wave potentials recorded for twenty four substituted bromobenzenes are shown in Table II to within ± 10mv. The accuracy with which the bromobenzene half-wave potentials can be determined is limited by the fact that many of them reduce at potentials above -2.00 volts and are too close to the decomposition potential of the supporting electrolyte to form a good diffusion plateau. An example of this problem is shown in the polarograms of p-aminobromobenzene compared to p-aminoiodobenzene (Figure 6).

In addition to the compounds listed in Table II, several other substituted bromobenzenes were reduced. These included ortho and para cyanobromobenzene and the three isomeric bromobenzoic acids. However, in all these cases the substituent was reduced prior to the bromine reduction. This was evident because of the marked changes in both wave height and wave shape, or more exactly, changes in both n and α.

It was hoped that the insights gained from the halobenzene work could be applied to a completely different system. So twenty eight substituted benzophenones were reduced in 1 M sodium acetate adjusted to a pH of 5.2 with acetic acid. The choice of conditions were those of previous workers in this field (3), since we hoped to extend and expand upon their earlier work. The half-wave potentials and α values obtained are shown in Table III.

TABLE I

Half-Wave Potentials of Substituted Iodobenzenes

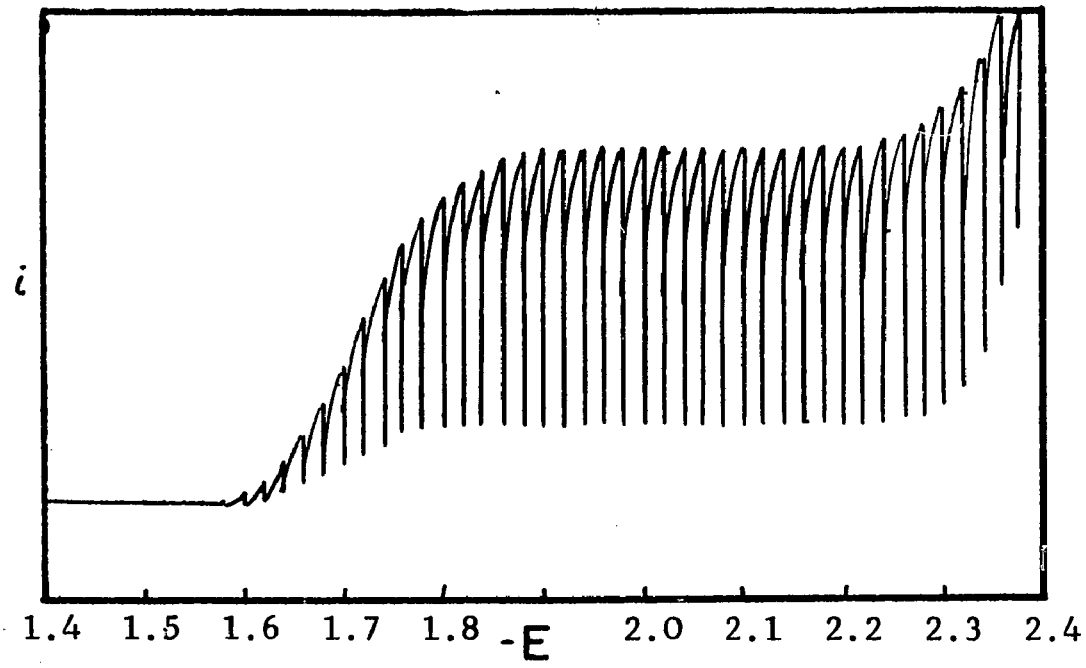
Compound	$-E_{\frac{1}{2}}$ in $LiClO_4$	$-E_{\frac{1}{2}}$ in $(CH_3)_4NCl$
Iodobenzene	1.655	1.467
o-Methyliodobenzene	1.688	1.495
m-Methyl "	1.673	1.483
p-Methyl "	1.687	1.497
o-Ethyl "	1.685	1.478
2,6 Dimethyl "	1.718	1.516
2,4 Dimethyl "	1.718	1.527
o-Phenyl "	1.570	1.327
p-Phenyl "	1.622	1.413
o-Amino "	1.565	1.416
m-Amino "	1.650	1.463
p-Amino "	1.710	1.529
o-Hydroxy "	1.535	1.391
m-Hydroxy "	1.637	1.463
p-Hydroxy "	1.700	1.520
o-Methoxy "	1.567	1.393
m-Methoxy "	1.603	1.421
p-Methoxy "	1.672	1.488
o-Ethoxy "	1.587	1.405
p-Ethoxy "	1.672	1.488
p-Cyano "	1.417	1.287
o-Trifluoromethyl "	1.343	1.190
m-Trifluoromethyl "	1.517	1.343
p-Trifluoromethyl "	1.515	1.351
o-Fluoro "	1.374	1.205
p-Fluoro "	1.593	1.420
o-Chloro "	1.375	1.203
m-Chloro "	1.509	1.337
p-Chloro "	1.557	1.388
o-Bromo "	1.322	1.153
m-Bromo "	1.482	1.318
p-Bromo "	1.550	1.383
p-Iodobenzoic Acid	1.505	1.377
o-Iodobenzyl Alcohol	1.555	1.396
p-Iodobenzyl Alcohol	1.636	1.456

TABLE II

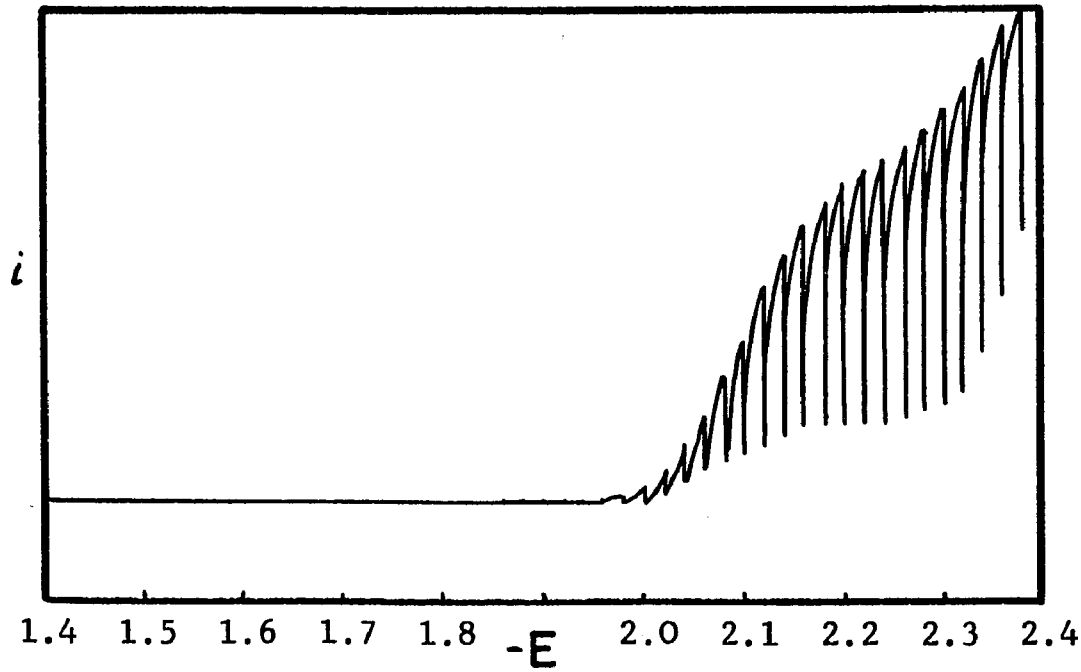
Half-Wave Potentials of Substituted Bromobenzenes

Compound	$-E_{\frac{1}{2}}$ in $(CH_3)_4NCl$
Bromobenzene	2.07
o-Methylbromobenzene	2.12
m-Methyl "	2.09
p-Methyl "	2.11
p-Phenyl "	1.99
o-Amino "	2.01
m-Amino "	2.07
p-Amino "	2.15
o-Hydroxy "	1.97
m-Hydroxy "	2.06
p-Hydroxy "	2.14
o-Methoxy "	1.93
p-Methoxy "	2.10
o-Ethoxy "	1.99
p-Ethoxy "	2.10
o-Trifluoromethyl "	1.67
m-Trifluoromethyl "	1.89
p-Trifluoromethyl "	1.90
o-Fluoro "	1.69
p-Fluoro "	2.00
o-Chloro "	1.69
m-Chloro "	1.87
p-Chloro "	1.96
3,4 Dichloro "	1.77

FIGURE 6



Polarogram of p-Amino Iodobenzene



Polarogram of p-Amino Bromobenzene

TABLE III

Half-Wave Potentials of Substituted Benzophenones

Compound	$-E_{\frac{1}{2}}$ in NaAc	α
Benzophenone	1.176	.95
4 Bromobenzophenone	1.118	.95
4 Chlorobenzophenone	1.137	.95
4,4' Dihydroxybenzophenone	1.319	1.00
4,4' Dimethoxy "	1.282	.90
2,4 Dimethyl "	1.262	1.00
2,5 Dimethyl "	1.254	.95
3,4 Dimethyl "	1.204	.95
4,4' Dimethyl "	1.231	.95
3 Hydroxy "	1.143	.95
4 Hydroxy "	1.253	.90
4 Hydroxy,3 Methyl "	1.260	.95
4 Hydroxy,4' Methyl "	1.270	.95
4 Methoxy "	1.227	.95
4 Methyl "	1.204	.95
2 Amino "	1.186	1.50
3 Amino "	1.136	1.50
4 Amino "	1.223	1.50
4,4' Dicarboxyl "	.996	1.50
2 Chloro "	1.151	1.45
2,2' Dihydroxy "	1.273	1.20
2,4 Dihydroxy "	1.314	1.20
2,2' Dihydroxy,4 Methoxy "	1.335	1.20
2,2' Dihydroxy 4 Dimethoxy	1.388	1.20
2 Fluoro "	1.136	1.40
4 Fluoro "	1.196	.80
2 Hydroxy "	1.220	1.15
2 Hydroxy,4 Methoxy "	1.278	1.20

DISCUSSION

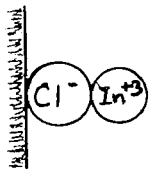
An examination of the half-wave potentials of the meta and para substituted iodobenzenes in Table I shows that they are markedly affected by the substituents in a manner consistent with the electronegativity rule of reduction potentials. The compounds with meta or para substituents which are electronegative are all easier to reduce than unsubstituted iodobenzene, while those with electron donating meta or para substituents have higher half-wave potentials than iodobenzene. A more exact idea of the consistency of this data may be obtained by comparing it to the Hammett linear free energy function (16).

The half-wave potentials of the meta and para substituted iodobenzenes and bromobenzenes are easily correlated with the Hammett function by plotting $E_{\frac{1}{2}}$ versus the σ values. (Fig.9,10,11) The only significant deviation from the linear relationship is the case of the para amino isomers. Both para aminoiodobenzene and para aminobromobenzene are reduced much more easily than the Hammett σ function would predict. This same deviation has been noted for the para amino group in several other series such as the benzophenones (3). Since the Hammett σ function is based on benzoic acid, it may be that the value derived for the amino group is influenced by intermolecular acid-base reaction. It has been suggested that a σ value of about -.30 be used for the para amino group in polarographic reductions (5).

The data in tables I and II clearly show the ortho effect. For every substituent except the alkyl groups, the ortho substituted

compounds are much easier to reduce than the corresponding meta or para compounds. As stated in the introduction, there is no existing explanation for this ortho effect.

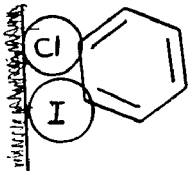
One possibility which was considered was that the ortho substituent was acting as a bridge for electron transfer similar to that proposed by Heyrovsky to explain the increased ease of Indium III reduction in the presence of halide ions (23). In this paper, Heyrovsky noted that Indium III was more easily reduced in the presence of chloride ions and proposed a situation where the chloride ion acted as a bridge between the electrode and the Indium III as in Figure 7a. By analogy, the ortho substituents in organic polarography might act as a bridge for electron transfer as in Figure 7b. This



a.

FIGURE 7

b.



would seem to agree with the fact that the ortho effect is not found for alkyl substituents. One would expect groups such as the chloro group with free electron pairs to be able to act as a much better bridge for electron transfer than the saturated methyl group.

In order to gain further information concerning this theory, the isomeric iodobenzyl alcohols were synthesized and polarographically reduced. These compounds were chosen because they have a $-CH_2-$ group between the hydroxyl group and the ring. This isolates the electrons of the hydroxyl group from the π system of the aromatic ring and would preclude a facile electron transfer from the hydroxyl group to the reduction site through the ring. The half

wave potentials of ortho and para iodobenzyl alcohol were 1.555 and 1.636 volts respectively when reduced in lithium perchlorate. Thus the ortho effect is operative. This indicates that the ortho effect is not dependent upon a bridge for electron transfer.

Another factor which must be considered is the effect of ortho substitution on the transfer coefficient, α. As is shown in Table IV, the value of α is substantially the same for ortho substituted iodobenzenes as for meta and para substituted iodobenzenes.

TABLE IV

Forward Transfer Coefficients of Substituted Iodobenzenes

Substituent	α para	α meta	α ortho
-H	.63	-	-
$-CH_3$	.63	.63	.62
$-NH_2$	.65	.64	.65
$-OCH_3$	.63	.64	.63
$-OC_2H_5$	.63	.63	.60
-Cl	.66	.66	.66
-Br	.67	.67	.68
-OH	.49	.45	.38

This shows that the ortho effect cannot be ascribed to a change in mechanism. The one exception in Table IV is the case of iodophenol. These isomers differ not only among themselves, but from the values of the other compounds. This is probably related to their pH sensitivity.

In addition, it has been noted (10) that the ortho effect operates with relative consistency in such divergent series as the

benzaldehydes and the iodobenzenes. Since the ortho effect is operative on the same scale in reductions that proceed by entirely different mechanisms, it would seem that it is not related to the particular mechanism, but exerts an effect which is operative on most mechanisms.

One of the factors known to affect some ortho cases is steric hindrance of coplanarity. The π electron interaction which leads to conjugation effects is fully operative only when the interacting bonds are coplanar. A bulky substituent attached in the vicinity of the conjugated bonds may prevent them from achieving coplanarity and so limit their interaction by its steric effect. This is called steric hindrance of coplanarity or steric inhibition of resonance.

Steric hindrance of coplanarity has been clearly and unambiguously demonstrated for substituted nitrobenzenes (10,24,25). Since the methyl group does not exibit the positive ortho effect, the data for the reduction of methylated nitrobenzenes at pH 4.9 offer a good example of this (24). (Table V) The shift for the

TABLE V

Half-Wave Potentials of Methylated Nitrobenzenes

Compound	$E_{\frac{1}{2}}$
Nitrobenzene	-0.55 volts
p-Methylnitrobenzene	-0.58 volts
o-Methylnitrobenzene	-0.64 volts
2,4,6-Trimethylnitrobenzene	-0.76 volts

ortho methyl group is negative by 0.06 volts compared to the para methyl group. The shift for the 2,4,6-trimethynitrobenzene can be broken down into a -0.03 v. shift for the para methyl group and two -0.09 v. shifts for the two ortho methyl groups. In each case, -0.06 volts of the ortho shift are attributed to steric hindrance of coplanarity. The shift of potential for the ortho methyl group is accompanied by a change in the value of the transfer coefficient α (cf. Fig. 4 in reference 24). This change in the value of α is characteristic of steric hindrance of coplanarity (10).

Similarly, the influence of steric hindrance on half-wave potentials has been pointed out for nitrobenzoic and nitrotoluic acids (26) and for p-dinitrobenzenes (27).

Another case, which has not been discussed in the literature, where steric hindrance of coplanarity is seemingly effective, is found in the reduction of the halo-nitrobenzenes (4). The data

TABLE VI

Half-Wave Potentials of Halogenated Nitrobenzenes

Compound	$-E_{\frac{1}{2}}$ para	$-E_{\frac{1}{2}}$ ortho
Chloronitrobenzene	.930 v.	.866 v.
Bromonitrobenzene	.854 v.	,860 v.
Iodonitrobenzene	.780 v.	.816 v.

in Table VI show that the effect of halogen substitution in the ortho position is not the same for chlorine, bromine and iodine. With the chloride group, the ortho substituted nitrobenzene is easier to reduce than the para substituted compound. With bromine,

the half-wave potentials of the ortho and para isomers are about the same, while ortho iodonitrobenzene is much harder to reduce than the para isomer.

In this case, both the ortho effect and steric hindrance of coplanarity are factors influencing the half-wave potentials. When the chloride group is the ortho substituent, ortho enhancement of reduction is a larger factor than steric hindrance, so the half-wave potential of the ortho substituted compound is lower than that of the para. When iodine is the ortho group, the steric hindrance is greater than that for ortho chloronitrobenzene because of the larger size of the iodide group. This steric effect is so much larger for the iodide group that it outweighs the ortho effect and the half-wave potential of ortho iodonitrobenzene is higher than that of the para isomer. In the case of the bromide group, the two effects are of approximately the same magnitude and cancel each other so that the half-wave potentials are about the same. Unfortunately, transfer coefficients were not calculated for this data so that the above explanation cannot be confirmed by observing a change in α corresponding to a change in steric hindrance.

In the case of substituted iodobenzenes it is difficult to attribute characteristics of their reduction to steric hindrance of coplanarity of the iodide group. The iodine does not have the obvious planar configuration of the nitro group which would require a large area, and would not be expected to be sensitive to steric hindrance. Supporting this is the fact that the value of α is constant throughout most of the substituted iodobenzene series.

It has been noted several times that ortho substitution of iodobenzenes causes no change in the reduction mechanism as indicated by the transfer coefficient, α. In addition, it was stated that a relatively constant value of α was the major prerequesite for conformance of a reduction series with the Hammett function. It was also noted that the half-wave potentials of meta and para substituted iodobenzenes and bromobenzenes correlated well with this function as represented by the substituent constants. In view of this, it seems reasonable to discuss the effect of ortho substitution in the halobenzenes within the framework of Hammett's linear free energy treatment.

The substituent constants were said to represent the effect of a substituent on the electron density at the reaction site. This effect arises from two sources, induction and resonance and the Hammett σ values represent their sum. A method has been developed to determine the relative contributions of induction and resonance to the σ values (28). Initially, σ' values were obtained for a series of acids and esters in a structure where the substituent could exert an effect only through induction (29). This series was expanded by Taft and called the inductive substituent constant, σ_I. The resonance sigma value, σ_R, is then obtained by subtracting σ_I from Hammett's σ value.

First we will examine the effects on the resonance interaction which might occur when a substituent is in the ortho rather than the para position. According to resonance theory, the basic resonance interaction for the ortho and para positions is the same.

However, since steric hindrance of resonance of a reaction center by an ortho substituent is an established fact, it seems logical that the resonance interaction of the substituent can in turn be seriously inhibited by a bulky reacting group in the adjacent ring position. Both the bromo and iodo groups are bulky enough to cause steric hindrance of coplanarity. For example, in o-dibromobenzene the two bromine atoms are bent 15^{o} in opposite directions out of the plane of the ring, whereas they are planar in the para isomer (30).

Steric hindrance of coplanarity would effectively decrease the resonance contribution of the ortho substituent to the electron density at the reaction site. This would correspond to a decrease in σ_R compared to the value for the para position. For those substituents which have large negative values of σ_R corresponding to a large resonance electron donating effect, a decrease in this electron donation would aid reduction significantly. This would fit the ortho effect nicely. For example, the para methoxy group shifts the half-wave potential of iodobenzene about -20mv. compared to unsubstituted iodobenzene,while this same group in the ortho position shifts the half-wave potential about +100mv. The negative para shift is in accord with its negative sigma value of -.26. This σ value of -.26 is a composite of a σ_I of +.25 and a σ_R of -.51. In other words, the para methoxy group is electron withdrawing through induction and electron donating through resonance, with the latter effect predominating. If ortho substitution interfered with the coplanarity of the methoxy group to such an extent that its resonance interaction disappeared, the resulting sigma would be σ_I

which is positive. This qualitatively agrees with the positive shift in half-wave potential observed.

However, the assumption that the steric hindrance of coplanarity is so great that all resonance disappears is rather rash, and even with this assumption, the σ values of -.26 for the para and +.25 for the ortho do not quantitatively account for the potential shifts of -20 and +100 mv. Furthermore, the ortho effect is observed for groups which do not have large negative σ_R values, including the $-CF_3$ group which has a positive value of σ_R so that hindrance of resonance would make reduction more difficult in this case. Thus it is obvious that steric hindrance of resonance is not the whole answer to the ortho effect. However, it still seems logical as a contributory cause.

Let us now consider how the other factor in the linear free energy function, induction, could be changed by the fact that a substituent is in the ortho rather than the para position. According to Taft (28), inductive interactions between a substituent R and a functional group Y are associated with coulombic forces which result from charge separation within groups R and Y. Inductive interactions require for transmission either a sigma bond (internal inductive or bond interaction) or space (field interaction). If the inductive interactions are transmitted through the sigma bonds of the ring, it seems reasonable to assume that the effect should decrease linearly with distance from the substituent. If the inductive interactions are field effects transmitted through space they should decrease as the square of the distance from the

substituent in a relationship similar to Coulomb's Law. Some authors feel that inductive effects are a composite of both field and internal effects (31). In either case, the inductive effect of a substituent should decrease in strength as you go from the ortho to the meta to the para position. In addition, this decrease in strength should be a constant ratio, independent of the substituent group involved. Thus, by this line of reasoning, the inductive effect of the ortho position should have a constant ratio to that of the para and the effect should be greater in the ortho position.

Unfortunately, there is great disagreement about the relative effects of substituents in the ortho and para positions. Some authors claim to be able to accurately predict isomer distribution in certain reactions by assuming 1) no field interactions at distances over two Angstroms and 2) the inductive effect is equal on all carbons (32). Others claim that the influence of para substituted groups on benzoic and phenylacetic acids can be quantitatively correlated by assuming that only direct field effects are involved. (33). Others use a model of alternating charges with the charges appearing at the ortho and para positions (34,35). In a theoretical discussion, Price (36) uses a model for chlorobenzene based on the assumption that the inductive effect spreads its charge so that each succeeding carbon atom has one half the charge of the preceding atom. Prominent texts about structure and mechanism in organic chemistry by Ferguson (37), Gould (38), Hine (39) and Wheland (40) make no reference to the relative inductive effect of a substituent in the ortho and para positions or to the exact

mode of transmission of this effect. It is not surprising that Roberts (29) says that the present situation with regard to theoretical speculation in the field is fairly described as chaotic.

In his recent review (10), Zuman starts the section on polarographic ortho shifts with the statement: "According to the deductions of theoretical organic chemistry the polar effect of a particular substituent operates with approximately equal strength from the ortho and para positions." In view of the discussion above, this statement is certainly open to question. The review uses the model of alternating charges without making any attempt to substantiate this or mentioning that other theoretical models do exist. It should be noted that Zuman could offer no explanation for the ortho effect.

There is a substantial body of experimental evidence which supports the view that inductive effects decrease with distance from the substituent and refutes the other theories. One article (41) uses the electronic effects of the trimethylammonium group to attack the old system of preferential relay of the inductive effect of a substituent group to the ortho and para positions of the ring. They calculated the σ constants for the trimethylammonium group in four different systems including the ionization of benzoic acids and ultraviolet spectra. While there was quite a bit of variation in the σ values obtained from the different systems, the meta σ value for any given system was always about .15 greater than the σ value for the para position. Irrespective

of the absolute value of the σ constants for the trimethylammonium group, it is obvious that it has a considerably greater electron attracting influence at the meta position than at the para position. This is in opposition to the effect predicted by the alternating charge theory. To explain their results, they state that: "the inductive effect of a substituent group on an aromatic ring appears to be best regarded as falling off smoothly with distance, possibly in accord with the Coulomb Law."

Support for this hypothesis is found in the results of a study of the electrical effect of the trimethyl silyl group (42). The trimethyl silyl group is electron releasing relative to hydrogen. The σ constants of the group indicate a higher electron density at the meta than the para position as would be expected from an inductive effect which falls off smoothly with distance. The effect is significant, since none of the usual electrical influences postulated by the alternating charge theory seem to be capable of explaining the electrical effects of the trimethyl silyl group. Unfortunately, no data are available to indicate if this hypothesis extends to the ortho position, but if the inductive effect falls off smoothly from the meta to the para position, the extension of the theory to the ortho position seems logical.

Other evidence that the inductive effect decreases with distance is found in the nitration of the halobenzenes. Nitration of the aromatic ring is an electrophilic substitution reaction and as such is slowed down by electron withdrawing substituents such as

the halogens. The fluoro group is the strongest electron withdrawing group and would exibit the largest negative effect on nitration. This electrical effect decreases from fluoro to chloro to bromo to the iodo group. One other factor in the nitration is steric hindrance due to the substituent already present hindering attack of the ortho positions adjacent to it by its bulk, an interferance to which the more distant para position is not susceptible. Since the halo groups increase markedly in size from fluoro to iodo, the steric hindrance at the ortho position should be greatest for the iodo group. Experimentally, it is found that the percentage of ortho isomer obtained increases along the series from fluoro to iodo, despite the increase in size of the substituent. Thus the data show that something is influencing the ortho position strongly enough to override the large steric effect present. According to Sykes (43), this is due to the fact that the electron withdrawing inductive effect influences the adjacent ortho positions much more powerfully than the more distant para position. The inductive effect decreases considerably on going from fluoro to iodobenzene resulting in easier attack at the ortho position despite the size of the group already present.

Other statements can be found in the literature which support the hypothesis. Dewar (44) discusses the fact that the o:2p ratio is less than unity for substitution of deactivating (-E) substituted benzenes and greater than unity for activating (+E) substituted benzenes, and this effect increases with the inductive activity of the substituent. He states that this is due to the

greater inductive effect at the ortho position compared to the para. An organic text by Branch and Calvin states that the inductively transmitted polar effect of a group should be greater from the ortho than from the para position (45). Thus there is a substantial body of opinion which supports the hypothesis that the inductive effects of a substituent should be substantially greater at the ortho position than at the para position.

Assuming that the inductive effect is greater from the ortho position, this could be expressed in the linear free energy relationship by increasing the σ_I values for the para position. On scanning Table VII it is noted that the values of σ_I are positive for every substituent except two. A positive value denotes an electron withdrawing effect, which in turn causes an easier reduction. Thus an effect which would increase the positive value of σ_I would also decrease the half-wave potential. Thus the ortho effect can be at least partially explained in terms of a stronger inductive effect from the ortho position for those groups with positive σ_I values.

It was mentioned that two of the groups in Table VII have negative inductive substituent constants. In these cases the increase of inductive effect would not aid reduction, but hinder it. These two groups are the methyl and ethyl groups. Significantly, these are the only two groups in the entire series which do not exibit the ortho effect. Thus the data for both the bromo and iodo benzene series are in at least qualitative agreement with the assumption that inductive effects are greater at the ortho position.

TABLE VII

Sigma Values Tabulated by Taft (17)

Substituent	σ_I Inductive	σ_R Resonance	σ_p Para	σ_m Meta
-H	.00	.00	.00	.00
$-CH_3$	-.05	-.11	-.16	-.07
$-C_2H_5$	-.05	-.10	-.15	-.07
$-C_6H_6$	.10	-.09	.01	.06
$-NH_2$	.10	-.76	-.66	-.15
-OH	.25	-.60	-.35	.08
$-OCH_3$	.25	-.51	-.26	.09
$-OC_2H_5$	.25	-.51	-.26	.09
-COOH	.33	.12	.45	.37
-CN	.58	.10	.68	.62
$-CF_3$	.41	.09	.50	.43
-F	.52	-.44	.08	.35
-Cl	.47	-.25	.22	.37
-Br	.45	-.22	.23	.39
-I	.39	-.21	.18	.35

It seems probable, therefore, that both the inductive and resonance effects of a substituent are changed when a substituent is in the ortho position. It should be emphasized, however, that these changes are changes of degree only and not changes in the type of effect. This is indicated by the constant ρ values for the three ring positions. Thus the linear free energy equation for the ortho position should have the same form as that for the meta and para cases. The modified equations for the meta and para positions have the form: $\log k/k_o = \sigma_{I,p} + \sigma_{R,p}$ and $\log k/k_o = \sigma_{I,m} + \sigma_{R,m}$ so that the general equation for the ortho case is:

$$\log k/k_o = \sigma_{I,o} + \sigma_{R,o}.$$

Our problem is to determine the values of the inductive and resonance substituent constants for the ortho position from the existing values for the para position. According to the inductive theory developed above, the inductive ortho substituent constant, $\sigma_{I,o}$ should have a constant ratio to the para inductive constant that is greater than one. In equation form this can be expressed:

$$\sigma_{I,o} = X\,\sigma_{I,p} \quad \text{where } X > 1.$$

The resonance in the ortho position should be the same as that for the para except where there is steric hindrance of coplanarity. This would interfere with the resonance of the substituent and the resonance constant would have to be reduced. In equation form:

$$\sigma_{R,o} = \sigma_{R,p} - \text{resonance interference}$$

This resonance interference should be related to the amount of steric hindrance of coplanarity. If there is no steric hindrance, the resonance would be simply $\sigma_{R,p}$. At the other extreme, if

steric interference was so great that there was no resonance at all $\sigma_{R,o}$ would be zero. The resonance will also be proportional to the $\sigma_{R,p}$ value. If the unhindered resonance interaction is large, any hindrance of this resonance will have a greater effect than if the unhindered resonance was small. Thus the equation for $\sigma_{R,o}$ can be rewritten as:

$$\sigma_{R,o} = \sigma_{R,p} - \text{steric hindrance factor} \times \sigma_{R,p}$$

$$\sigma_{R,o} = (1\text{-steric hindrance factor})\,\sigma_{R,p}$$

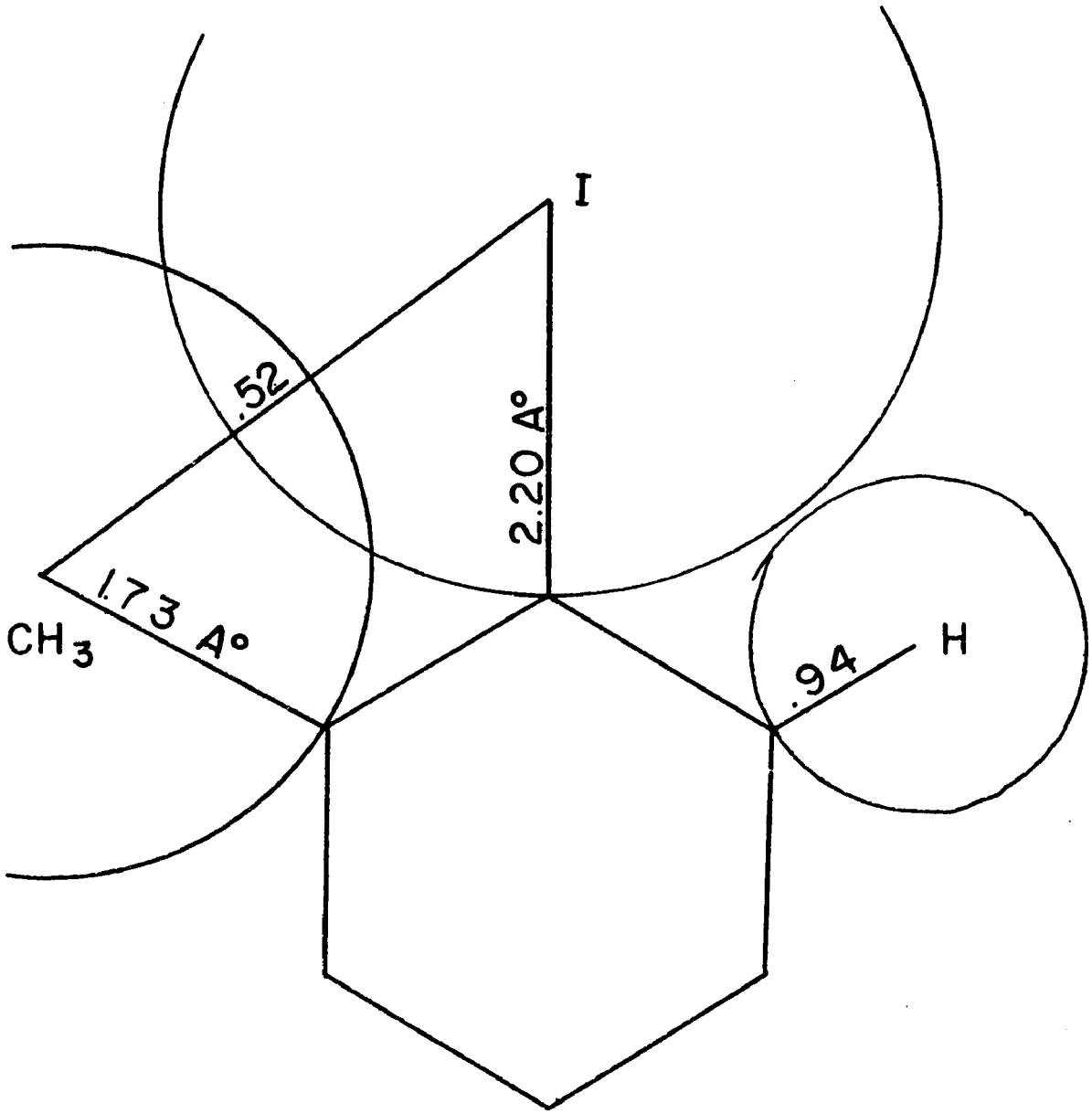
The ortho substituents may then be related to the para substituent values by an equation which combines the above.

$$\sigma_o = \sigma_{I,o} + \sigma_{R,o} = X\,\sigma_{I,p} + (1\text{-steric hindrance factor})\,\sigma_{R,p}$$

It is difficult to determine just what this steric hindrance factor should be. This interference will obviously increase with the size of the groups involved. One estimation of the size of the various groups has been obtained from data on the resolvability of ortho substituted biphenyls (46). If these groups are treated as spheres attached to the benzene nucleous, it is possible to visualize the amount of steric interference between them by drawing a series of circles to scale on a benzene ring in the position ortho to a circle representing the iodo group (Figure 8). The amount of overlap of the two circles should be roughly proportional to the steric hindrance of coplanarity between the two groups.

The difficulty lies in assessing the many unknowns involved. To start with, the amount of interference of the groups,

FIGURE 8



The Estimation of Steric Hindrance of
Adjacent Substituents

which is depicted as an area of overlap of two circles, is actually the interference of the volumes of two spheres. This in turn is a gross simplification since all the substituent groups were treated as simple spheres and obviously many are not spherical. Then this volume interference of the spheres is translated into a rotation of the groups out of the plane of the ring. There is no simple way to assess how much of this rotation is assumed by each group when the two ortho groups are different. In addition, there is no indication of just what relationship exists between degrees of rotation out of the plane of the ring and inhibition of resonance.

In the absence of any clear and direct method of attack on the compound problems involved in assessing the resonance hindrance, the simplest method consistant with the basic precepts was chosen. This assumed that the steric hindrance was directly related to the linear overlap of the two circles drawn to scale. Using the group radii derived from the ortho biphenyls, it was found that groups with radii of less than .95 A. did not interfere with the iodo group at all, while two ortho iodo groups overlap by .80 A. Using the method depicted in Figure 8, values were obtained for the relative amount of steric hindrance between each group and the reacting group. These were measured in Angstrom units and used as the steric hindrance factor. It should be emphasized that this steric hindrance factor has no units, but is just a crude adjustment coefficient.

The other unknown factor in the equation is X, the coefficient for increased inductance of the ortho over the para position.

Due to the lack of knowledge of the mechanism of induction, there is no reliable way to derive a theoretical value of X. The theoretical models used by various authors in discussions of substituent effects are usually couched in only qualitative terms. For those who did use quantitative models, the ratios for inductive effects in the ortho compared to the para position varied from one (34) to four (36). Using the data obtained in this work, a value of X= 2.4 was empirically obtained. No other value within the range of one to four will fit the polarographic data for the phenyl halides.

The final form of the equation which allows one to calculate σ_o values from the corresponding para σ values is:

$$\sigma_o = 2.4\,\sigma_{I,p} + (1\text{-steric hindrance factor})\,\sigma_{R,p}$$

The calculations for each substituent are shown in Tables VIII and IX, and were obtained using the σ values tabulated by Taft (17).

It should be noted that it is not correct to use the term "sigma values" for the results obtained for the ortho groups, for the term σ is defined as a substituent constant and the ortho values are not constants, but depend upon spatial relationships between the two groups. However, we will speak of "ortho sigma values" in order to stress the continuity between them and the meta and para sigma values.

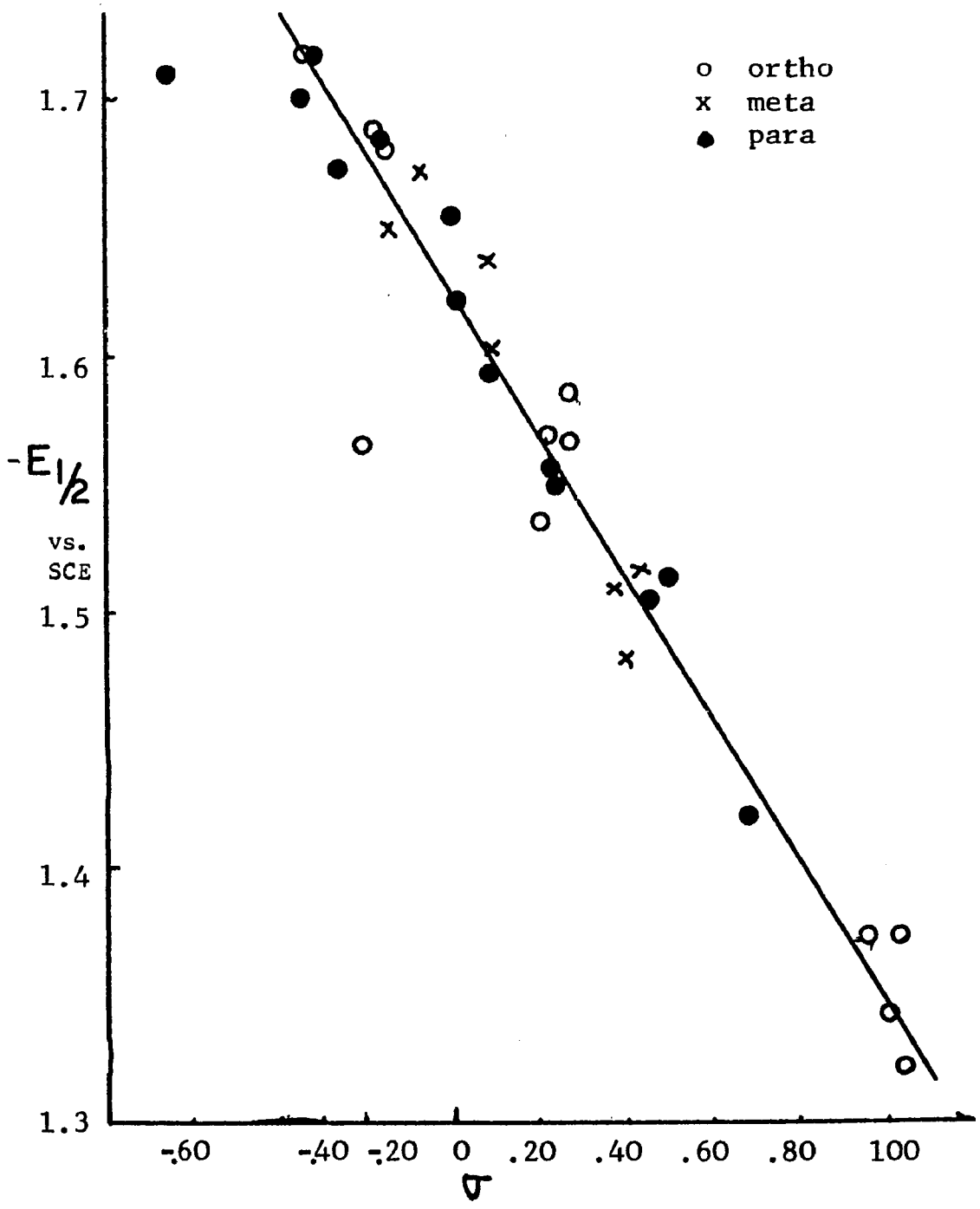
The ortho σ values obtained by using this formula correlated the ortho half-wave potentials with the line formed by the meta and para half-wave potentials versus the linear free energy function for both iodobenzene and bromobenzene (Figures 9 and 10).

TABLE VIII

Calculation of Ortho σ Values for Iodobenzenes

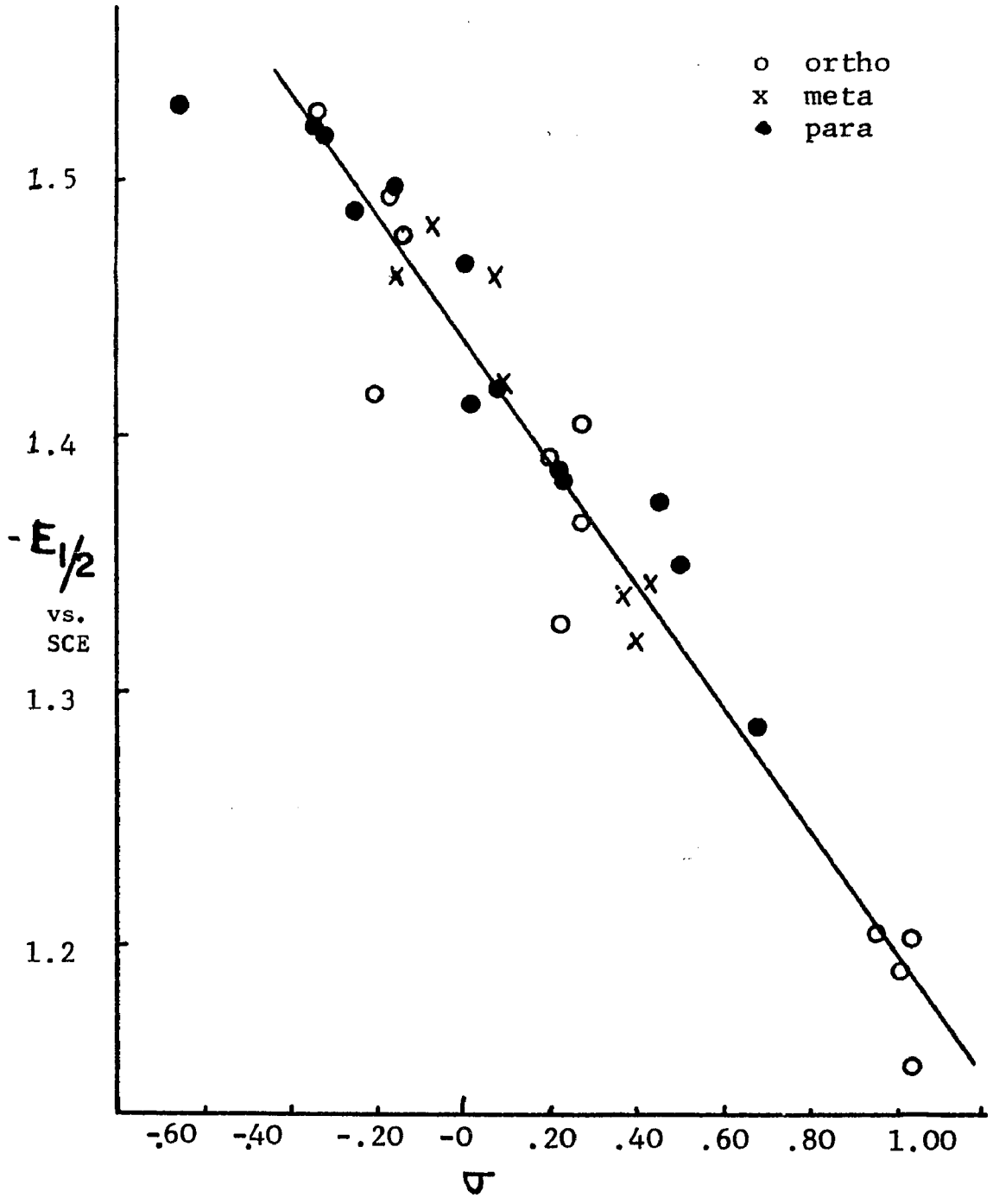
Group	Radius	Steric Factor	(1-S.F.)	$2.4\,\sigma_{I,p}+(1-S.F.)\,\sigma_{R,p}$	σ_o
$-CH_3$	1.73	.52	.48	2.4 (-.05) + .48(-.11)	-.17
$-NH_2$	1.56	.41	.59	2.4 (.10) + .59(-.76)	-.21
$-OH$	1.45	.34	.66	2.4 (.25) + .66(-.60)	.20
$-OCH_3$	1.47	.35	.65	2.4 (.25) + .65(-.51)	.27
$-OC_2H_5$	1.47	.35	.65	2.4 (.25) + .65(-.51)	.27
$-CF_3$	2.15	.78	.22	2.4 (.41) + .22(+.09)	1.00
$-F$	1.39	.31	.69	2.4 (.52) + .69(-.44)	.95
$-Cl$	1.89	.61	.39	2.4 (.47) + .39(-.25)	1.03
$-Br$	2.11	.75	.25	2.4 (.45) + .25(-.22)	1.03
$-C_2H_5$	1.79	.55	.45	2.4 (-.05) + .45(-.10)	-.16
$-C_6H_5$	2.20	.80	.20	2.4 (.10) + .20(+.09)	.22

FIGURE 9



Half-Wave Potentials of Iodobenzenes in $LiClO_4$ vs σ Values

FIGURE 10



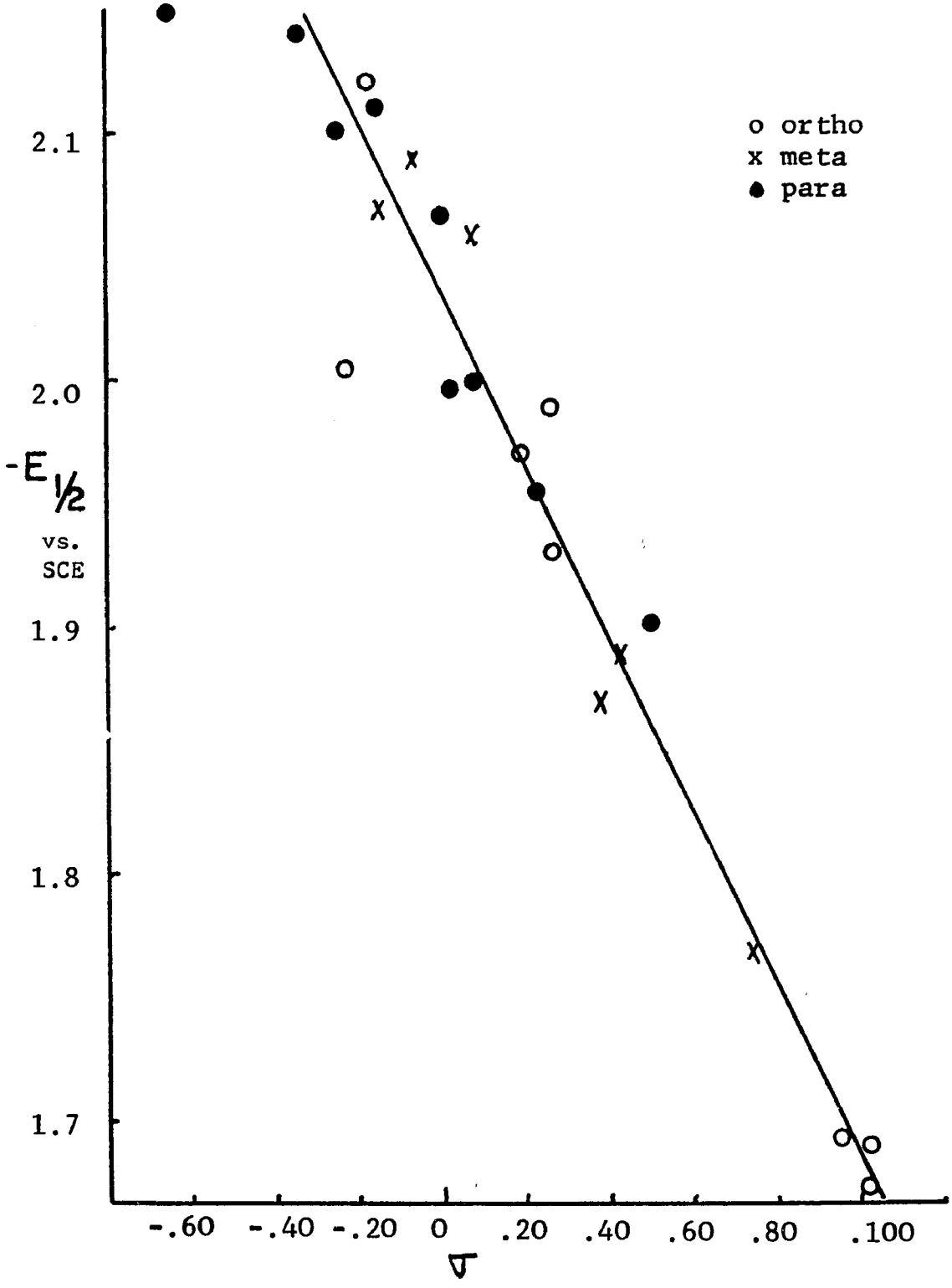
Half-Wave Potentials of Iodobenzene in $(CH_3)_4NCl$ vs σ Values

TABLE IX

Calculation of Ortho σ Values for Bromobenzenes

Group	Radius	Steric Factor	(1-S.F.)	$2.4\sigma_{I,p}+(1-S.F.)\sigma_{R,p}$	σo
$-CH_3$	1.73	.48	.52	2.4 (-.05) + .52(-.11)	-.18
$-NH_2$	1.56	.38	.62	2.4 (.10) + .62(-.76)	-.23
$-OH$	1.45	.32	.68	2.4 (.25) + .68(-.60)	.19
$-OCH_3$	1.47	.33	.67	2.4 (.25) + .67(-.51)	.26
$-OC_2H_5$	1.47	.33	.67	2.4 (.25) + .67(-.51)	.26
$-CF_3$	2.15	.74	.26	2.4 (.41) + .26(+.09)	1.01
$-F$	1.39	.29	.71	2.4 (.52) + .71(-.44)	.94
$-Cl$	1.89	.57	.43	2.4 (.47) + .43(-.25)	1.02
$-Br$	2.11	.71	.29	2.4 (.45) + .29(-.22)	1.02
$-C_2H_5$	1.79	.52	.48	2.4 (-.05) + .48(-.10)	-.17
$-C_6H_5$	2.20	.78	.22	2.4 (.10) + .22(+.09)	.22

FIGURE II



Half-Wave Potentials of Bromobenzenes in $(CH_3)_4NCl$ vs σ Values

The ortho point which is farthest from the line is that for the amino group. This is to be expected since the para value was far from the line and the ortho σ^- value is derived from that of the para. For most of the substituents it can be seen that the ortho effect is largely the result of the increased inductive effect with the decrease in resonance helping. The case of the alkyl groups is one where the two effects cancel each other. The increased inductive effect hinders the reduction in this case, while the decrease in resonance aids the reduction.

In order to confirm this explanation of the ortho effect in polarography, the method should be applied to several other reductions. If correlation of the ortho half-wave potentials with the linear free energy relationship was obtained for several different reductions, it would both support the theory and give more accurate values of the parameters involved. First, however, there should be an examination of the ways in which the parameters might be affected in a different system.

The most important fact is that the ortho σ^- values which were calculated above are not true substituent constants, but can vary with circumstances. It was noted that steric inhibition of resonance would vary with the size of the neighboring group, while the coefficient for the inductive effect was treated as a constant. This constant value of 2.4 was said to be an unknown combination of bond interaction and field effects. However, if the spatial configuration of the ortho substituent and the reaction site was substantially changed it would very probably affect the coefficient for the

inductive effect, especially that portion which is due to increased field effects at the ortho compared to the para position. Thus no system would necessarily have exactly the same parameters unless it was completely analogous to the reduction of the phenyl halides.

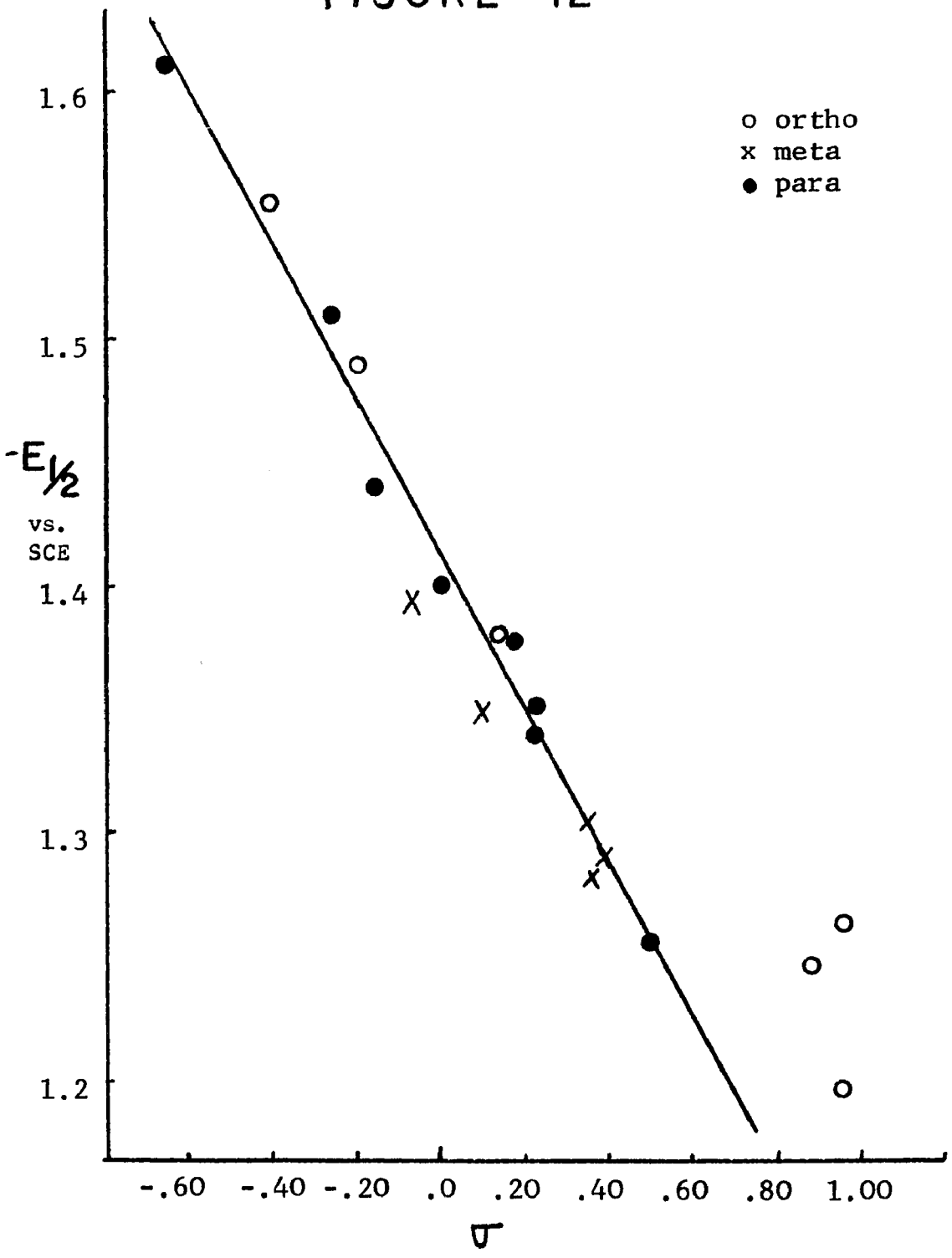
There are many reducible aromatic systems on which substituent effects could be examined. These include unsaturated systems such as styrene and stilbene, carbonyls such as benzaldehyde and benzophenone, α halides such as benzyl bromide and benzyl chloride, and others. In each of these cases, however, the reaction site is one carbon removed from the ring. For example, benzaldehyde is reduced to benzyl alcohol at a pH of more than seven, so that the bond between the aromatic nucleous and the carbonyl carbon is not broken. This is obviously a different situation from the phenyl halides, which are reduced to benzene so that the bond between the aromatic nucleous and the halide atom is broken. Thus there is no reducible group which is completely analogous to the reduction of the phenyl halides.

In spite of this, work on additional systems would be valuable for comparison and to check the generality of the approach taken. However, obtaining meaningful data could be difficult. In the first place, any reduction where the reacting group was seriously affected by steric hindrance of coplanarity would be valueless. Secondly, many organic reductions are subject to pH effects, so that the pH would have to be carefully chosen and controlled. This in turn would require buffers and care must be taken to assure that there is no specific reaction between the buffer system and the

reacting group or the electrode. In addition, a large number of compounds must be commercially available or readily synthesized and purified to that there would be enough data to obtain a meaningful correlation. Finally, the half-wave potentials of the meta and para substituents of the series must correlate well with the Hammett linear free energy function.

Unfortunately, there are no data in the literature which fulfill these conditions. Many studies have involved two or three ortho substituents, which is not enough from which to draw any conclusions. A study of the reduction of 19 substituted benzaldehydes at pH 13 (47) included six ortho substituted compounds and the meta and para substituents correlated well with the Hammett σ^- function. The attempted correlation of the ortho half-wave potentials by the use of the formula derived for the phenyl halides is shown in Figure 12. It is noted that this correlation is not as good as that of the phenyl halides. Since the spatial relationship of the reaction site and the ortho substituent is different from that of the phenyl halides, the lack of correlation could indicate that a different coefficient for the inductive effect is needed. On the other hand, the points which lie furthest from the line formed by the meta and para substituents are those for the three ortho halogen compounds. These are the bulkiest groups of the series, so perhaps this lack of correlation is due to steric hindrance of coplanarity of the carbonyl group by these large ortho substituents. Some authors have noted slight steric hindrance effects in the reduction of ortho substituted benzaldehydes (24), though this conclusion has been

FIGURE 12



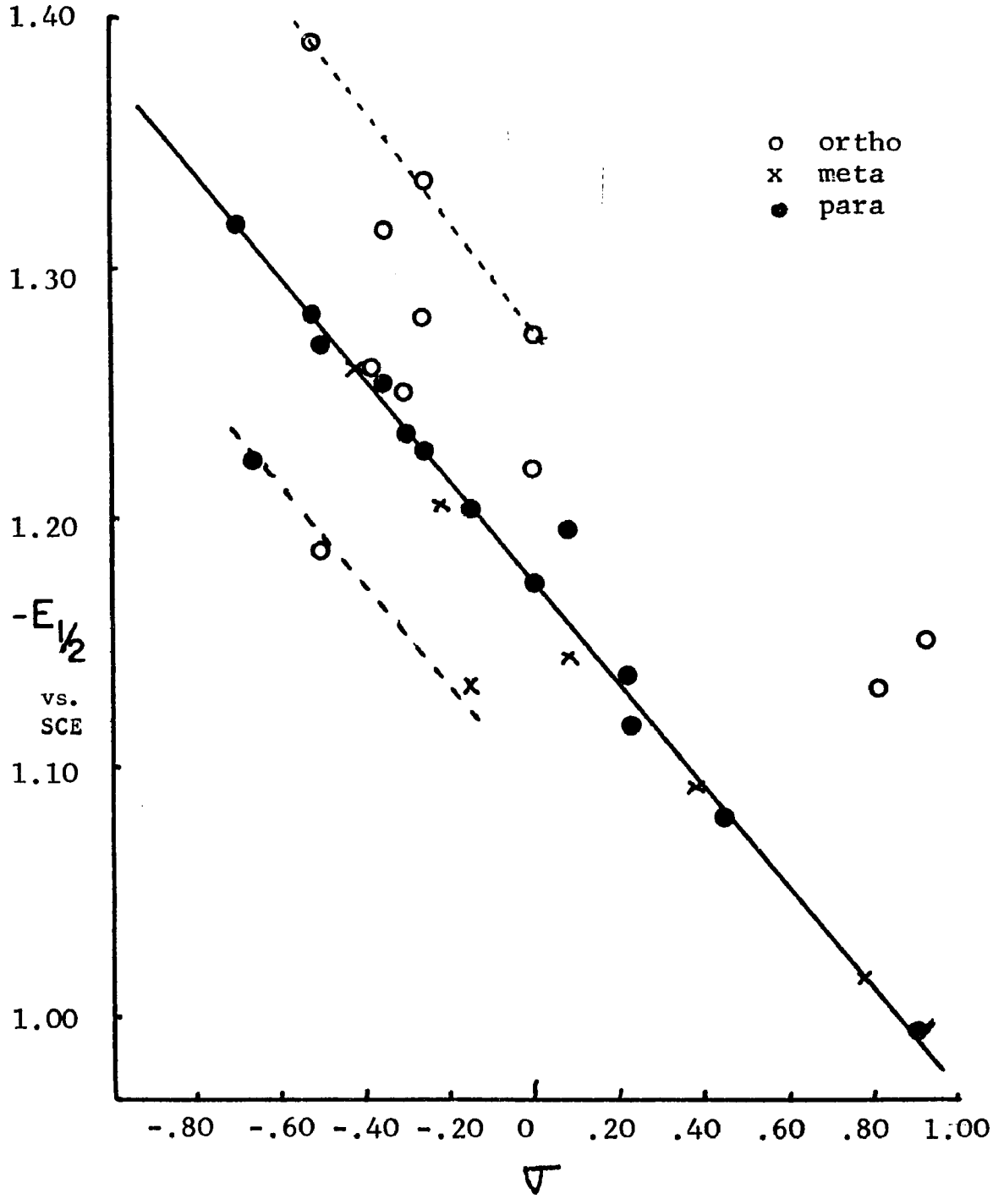
Half-Wave Potentials of Benzaldehydes at pH 13 versus σ^- Values

questioned elsewhere (10). Steric hindrance of the carbonyl group would make reduction more difficult, so the observed deviation of the halo substituted half-wave potentials is in the correct direction. Unfortunately, no transfer coefficients were calculated for these data, so it is not possible to confirm the presence of steric hindrance of the reactive group. It should also be noted that the benzaldehyde data were obtained under somewhat severe conditions at pH 13, so there could be other effects present.

In order to gain further information, a series of thirty substituted benzophenones was reduced in a sodium acetate buffer. Thirteen meta and para substituted benzophenones had been reduced by Brockman and Pearson (3) and an excellent correlation with the linear free energy function was obtained for all substituents except the NH_2 group. An additional advantage of this system is that there are two rings upon which substitution is possible, so that by substituting both rings in the meta or para positions, a much greater range of σ values can be defined.

Unfortunately the results obtained from the benzophenones are inconclusive. Eighteen points lie on a very good straight line while twelve are scattered (Figure 13). All but two of the ortho substituted compounds are in the latter catagory. All of those points which lie on the line have ρ values of .95 $\pm$.05, while the points which are scattered have ρ values of less than .85 or more than 1.15. Thus it is impossible to acertain if the lack of good correlation is due to a change in parameter in the computation of the σ_o values or to a change in the mechanism of the reaction.

FIGURE 13



Half-Wave Potentials of Substituted Benzophenones vs σ Values

Further work on the benzophenone system and perhaps on the simpler benzyl halide system could do much to clarify the situation. Perhaps enough information could be collected to devise new parameters for calculating ortho σ values when the reaction site is one carbon removed from the ortho substituted ring. Then important information about the mechanism of transmission of inductive effects might be obtained by comparing the parameters for the benzyl and phenyl cases.

One factor of this work which should be pointed out is that it is semi-quantitative at best. The spurious effects of the reaction conditions were mentioned earlier as was the semi-quantitative nature of the σ values from which the correlation is obtained. Especially critical is any error in $\sigma_{I,p}$ which would be multiplied by 2.4 to obtain the $\sigma_{I,o}$ values. In addition, the estimation of steric hindrance of resonance is very crude. These limitations are especially severe since further refinement of the treatment by comparison with other reduction series is limited by the factors mentioned above.

However, this treatment does offer an explanation for a previously unexplained phenomenon. The reasoning behind this treatment is supported by literature references from both polarographic and non-polarographic sources. The treatment seems intuitively reasonable and, most importantly, it fits the data. As such, we feel that it offers a contribution to our knowledge of substituent effects in polarography in particular and aromatic organic chemistry in general.

REFERENCES

1. M. Shikata and I. Tachi, J.Chem. Soc. Japan, 53, 834 (1932) Coll. Czech. Chem. Commun., 10, 368 (1938).

2. J.W. Baker, W.C. Davies and M.L. Hemming, J. Chem. Soc., 1940 692.

3. R.W. Brockman and D.E. Pearson, J. Am. Chem. Soc., 74, 4128 (1952).

4. E. Gergely and T. Iredale, J. Chem. Soc., 1953, 3226.

5. P. Zuman, Coll. Czech. Chem. Commun., 25, 3225 (1960).

6. M.J. Astle and W.V. McConnel, J. Am. Chem. Soc., 65, 35 (1943).

7. G. Semerano and V. Capitanio, Gazz. chim. ital., 70, 490 (1940).

8. J. Pearson, Trans. Faraday Soc., 44, 683 (1948).

9. E.L. Colichman and S.K. Liu, J. Am. Chem. Soc., 76, 913 (1954).

10. P. Zuman, Coll. Czech. Chem. Commun., 27, 648 (1962).

11. R.T. Morrison and R.N. Boyd, Organic Chemistry, Allyn and Bacon Boston (1959) p.455.

12. I.M. Kolthoff and J.J. Lingane, Polarography, Vol. I & II, Interscience, New York, 1952.

13. L. Meites, Polarographic Techniques, Interscience, New York, 1955.

14. P.J. Elving and C.S. Tang, J. Am. Chem. Soc., 74, 6109 (1952).

15. H.A. Laitinen, Chemical Analysis, McGraw Hill, New York, 1960, p.306.

16. L.P. Hammett, Physical Organic Chemistry, McGraw Hill, New York 1940, pp 184 f.

17. R.W. Taft Jr., N.C. Deno and P.S. Skell, Ann. Rev. Phys. Chem., 9, 292 (1958).

18. H.H. Jaffe, Chem. Rev., 53, 191 (1953).

19. J. Koutecky, Chem. listy, 47, 323 (1953).

20. J. Duffield, private communication.

21. R.F. Nystrom and W.G. Brown, J. Am. Chem. Soc., 69, 2548 (1947).

22. I. Heilbron, Dictionary of Organic Compounds, Vol. III, Oxford U. Press, New York, 1953, p.22.

23. J. Heyrovsky, Disc. Faraday Soc., 1, 212 (1947).

24. Ch. Prevost, P. Souchay and Ch. Malen, Bull. soc. chim. France, 1953, 78.

25. M. Fields, C. Valle and M. Kane, J. Am. Chem. Soc., 71, 421 (1949).

26. J. Tirouflet, Bull. soc. chim. France, 1956, 274.

27. H. Schmidt and L. Holleck, Z. Electrochem., 59, 531 (1955).

28. R.W. Taft, Jr., Steric Effects in Organic Chemistry, ed. M.S. Newman, Wiley, New York, 1956, chap. 13.

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

30. J. Trotter, Acta. Cryst., 14, 244 (1961).

31. C.K. Ingold, Structure and Mechanism in Organic Chemistry, Cornell U. Press, Ithaca, N.Y. 1953, chap.6.

32. T. Ri and H. Eyring, J. Chem. Phys., 8, 433 (1940).

33. J.G. Kirkwood and F.H. Westheimer, J. Chem. Phys., 6, 506 (1938); ibid. 6, 513 (1938).

34. L.E. Sutton, J. Chem. Soc., 1951, 2820.

35. R.W. Taft, Jr., J. Am. Chem. Soc., 74, 3120 (1952).

36. C.P. Price, J. Am. Chem. Soc., 73, 5833 (1951).

37. L.N. Ferguson, The Modern Structural Theory of Organic Chemistry, Prentice-Hall, Englewood Cliffs, N.J., 1963.

38. E.S. Gould, Mechanism and Structure in Organic Chemistry, Holt, Rinehart and Winston, New York, 1959.

39. J. Hine, Physical Organic Chemistry, McGraw-Hill, New York 1962.

40. G.W. Wheland, Advanced Organic Chemistry, Wiley, New York, 1960.

41. J.D. Roberts, R.A. Clement and J.J. Drysdale, J. Am. Chem. Soc., 73, 2181 (1951).

42. J.D. Roberts, E.A. McElhill and R. Armstrong, J. Am. Chem. Soc., 71, 2923 (1949).

43. P. Sykes, A Guidebook to Mechanism in Organic Chemistry, John Wiley & Sons, New York, 1961, p.114.

44. M.J.S. Dewar, J. Am. Chem. Soc., 74, 3363 (1952).

45. G.E.K. Branch and M. Calvin, The Theory of Organic Chemistry, Prentice-Hall, New York, 1941, p.258.

46. Ref. 36, p.277.

47. L. Holleck and H. Marsen, Z. Electrochem., 57, 944 (1953).

VITA

William W. Hussey was born in Albany, N.Y. on February 8, 1937, the son of Howard and Gladys Hussey. He received his primary and secondary education in the Suffern, N.Y. schools and graduated from Suffern High School in 1955.

In September of 1955, Mr. Hussey entered Middlebury College, majoring in chemistry. He received a degree of Bachelor of Arts in June of 1959.

After serving as a Lieutenant in the U.S. Army Artillery Mr. Hussey entered Bucknell University as a teaching assistant in chemistry. He received a Master of Science degree in chemistry from Bucknell University in 1962.

Mr. Hussey entered Lehigh University in September of 1962 and was awarded the William L. Heim Fellowship. The following June he was awarded a National Science Foundation Cooperative Fellowship which he held for two years. Upon the attainment of his degree, Mr. Hussey will join the faculty of Hartwick College.

In July of 1963, Mr. Hussey married the former Lesley Seaman of Pittsfield, Mass., a graduate of Bucknell University.