A PIONEERING COURSE IN PHYSICAL ORGANIC CHEMISTRY: J. W. BAKER'S 1942 THIRD-YEAR LECTURES TO UNDERGRADUATES

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Introduction

Physical organic chemistry is a creation of the twentieth century in which the techniques used in physical chemistry were introduced to the study of structure, properties and mechanisms of organic molecules. As Tidwell has pointed out (1):

> Thus by 1925 the experimental basis of the subject existed in a form very recognizable today: the major reactive intermediates, namely carbocations, free radicals, carbanions, and carbenes had been formulated, and the first three were even known as long-lived species; kinetic investigations of reaction mechanism were being applied; and the key factors influencing the structure-reactivity relationships were being considered such as stereochemistry, steric effects, and electronic substituent effects.

This new field came to be known as physical organic chemistry with publication of Louis Hammett's book of the same name in 1940 (2). In the five years preceding the publication of Hammett's book several British authors had written works which had a physical organic orientation, which attests to the interest in this newly developing area of investigation in Great Britain. Among these works are ones written by Watson (3) and Waters and Lowry (4). One must also acknowledge the 1934 *Chemical Reviews* article by Ingold, "Principles of an Electronic Theory of Organic Chemistry" (5), which would have been available to many American chemists either directly or in libraries.

These were advanced texts and likely were not used as texts for courses for undergraduates, but rather for reference and for keeping up with the latest developments in this new field of organic chemistry. The emphasis in instruction was still very much oriented to descriptive organic chemistry and its application to synthesis and elucidation of structure of natural products.

The person who had the greatest influence internationally on the development of physical organic chemistry was Christopher Kelk Ingold (1893-1970) (6). His appointment as Professor of Organic Chemistry at Leeds University in 1925 allowed him to initiate a revolution in the way organic chemistry was to be taught. Instead of rote memorization, understanding by examination of structure and mechanism became the emphases of Ingold's revolution. When Ingold left Leeds in 1930 to become professor of organic chemistry at University College London, his former student and collaborator John William Baker (1898-1967) continued the course of lectures given to students in their third and final year of their B.Sc. degree course. In the three ten-week terms in the British academic calendar, third-year students would attend lectures in advanced topics chosen by the lecturers and which reflected generally their interests. Thus it was quite natural for Baker to continue the Ingold course and to continuously update it with new discoveries in the burgeoning field of physical organic chemistry (7).

The new system of Ingold was given the name the "English school" to denote its origins and its difference

from traditional organic chemistry in the period up to 1950. In the United States this new way of connecting structure and mechanism did not make much of an impression. In the preface to his *Electronic Interpretation of Organic Chemistry*, published in 1943, A. E. Remick writes (8):

> Another objective, shared by all advanced courses which are "frontier courses," is to give the student such knowledge as is necessary to follow future developments in the field by reading the research literature. It is partly for this reason that the symbolism and language of the English school have been introduced, despite the fact that they are not popular in this country at the present time.

The basis of this paper is the set of notes taken by Donald Vincent on Baker's course in the second term (mid-January to Easter) of the academic year 1941-1942 at Leeds University (9). Several of the topics covered will be discussed in the context of the work of Ingold as summarized in the 1953 first edition of his *Structure and Mechanism in Organic Chemistry* (10). The opportunity to present the George Fisher Baker Lectures at Cornell University in the fall semester of the academic year 1950-1951 was the incentive to produce the first edition of this book. This book summarized the work of Ingold and his collaborators at University College London and included much research done by other physical organic chemists.

Major Topics Covered in the Lectures

The following is a list of the subject areas covered in the course of lectures at Leeds. Since the course notes do not have dates so as to gauge the amount of time devoted to each topic, they are listed in the chronological order as found in the notes.

•The modern electronic theory of valency (14 pages)

•Application of principles: electrophilic and nucleophilic aromatic substitution (14 pages)

•Tautomerism (24 pages)

•Substitution at saturated carbon (8 pages)

•Elimination reactions and addition reactions (13 pages)

I will discuss in detail three of the subjects that are most associated with Ingold and the so called "English school." These are the modern electronic theory of valency; orientation effects of substituents in electrophilic aromatic substitution; and mechanisms of nucleophilic substitution at saturated carbon as well as elimination reactions. For the three subjects discussed in detail I shall make comparisons with the 1953 first edition of Ingold's *Structure and Mechanism in Organic Chemistry* (henceforth SMOC) to show how advanced this course was for undergraduate instruction in 1942.

The Modern Electronic Theory of Valency

The lectures begin with a review of covalent bond theory and proceed to electronic displacements by the inductive effect and other modes of electron displacement. The terminology used is pure Ingoldian such as inductive, inductomeric, mesomeric, and electromeric, and also + and – signs to note excess and deficiency of charge. In deference to Ingold's longtime rival Robert Robinson
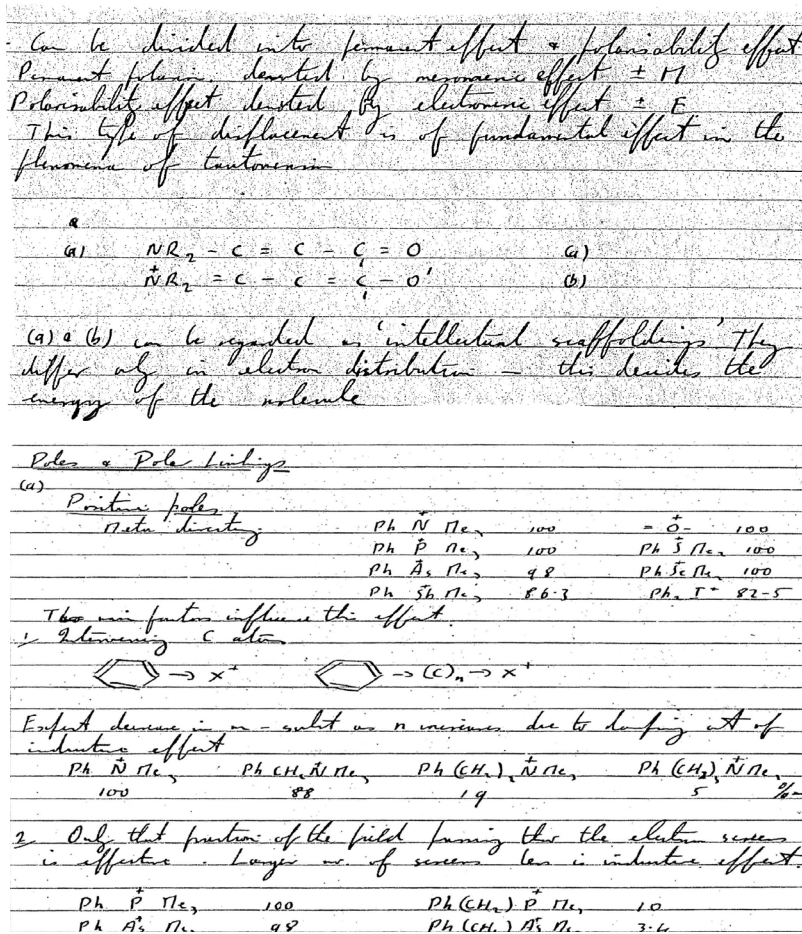

***Figure 1**. Illustrations of the various types of electron displacement*

the curved arrow to show movement of electron pairs is also included. Coupling of these effects is also discussed in terms of where they work in tandem with each other or in opposite directions. Baker's concept of hyperconjugation, for which he is probably best known, is offered as the best explanation for understanding the effect of alkyl groups. The important role played by poles and polar linkages as well as the position of these groups in molecules is illustrated.

Ingold devotes 32 pages in Chapter 2 of SMOC to the material covered in this first section of introductory lectures presented by Baker. Shown below is a typical entry from this first part of the course which illustrates various electron displacement effects as well as the resonance (mesomeric) effect.

Figure 2. Aromatic substitution results from Baker's course (above) and from Ingold's SMOC (below).

TABLE 18-1.—EFFECT OF SIDE-CHAIN LENGTHENING ON PERCENTAGES OF META-DERIVATIVES FORMED IN MONONITRATION OF AROMATIC AMMONIUM IONS.
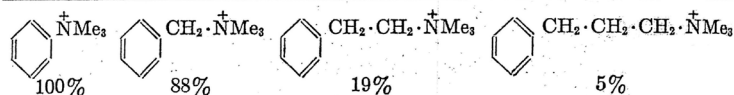
$\overset{+}{N}Me_3$	$CH_2 \cdot \overset{+}{N}Me_3$	$CH_2 \cdot CH_2 \cdot \overset{+}{N}Me_3$	$CH_2 \cdot CH_2 \cdot CH_2 \cdot \overset{+}{N}Me_3$
100%	88%	19%	5%

Substituent Effects in Electrophilic Aromatic Substitution

Orientation effects of substituents in aromatic systems had been the subject of much empirical investigation in the late nineteenth and early twentieth centuries. Experimental results from reactions such as nitration of monosubstituted benzenes had led to tables which gave guidance, by extrapolating back to the collected data, on what might happen to systems that had not been investigated. However a rationale for why certain groups direct ortho and para and others meta was not known. Ingold was a pioneer in this field. He not only used his own insight but relied in the beginning of these investigations on ideas presented by his contemporaries Arthur Lapworth (1872-1941) and Robert Robinson (1886-1975). The explanations given by Ingold are summarized in Baker's lectures and these are the ones that are found in any introductory textbook today.

After reviewing the history of the various structures proposed to explain the properties of benzene and why the Kekule structure was the best, Baker then discusses some of the conclusions that one can reach from experimental observations that had been made by various investigators. These general observations include the effect both electron-donating and electron-withdrawing groups have on orientation. Next specific examples are given concerning the effects of poles and polar linkages. The importance of position and charge in terms of orientation

effects is reviewed. Much of the data presented by Baker can be found on pages on 231-243 in SMOC.

After considering the effects of alkyl groups and the role of hyperconjugation as well as inorganic substituents he then discusses the evidence for his theoretical presentation. Baker discusses the transmission of electrical effects by various classes of substituents using the letters I and T for inductive and tautomeric effects and + and – to signify changes in electron distribution that occur in the course of reaction. Shown below (Figure 3) is an excerpt of the notes from Baker's course as well as the table found on page 247 in SMOC.

Baker then discusses the role of inductive effects in electrophilic aromatic substitution. According to Baker ortho, para substitution may possibly arise from the following:

a) Increase in ortho, para activation with decrease in meta activation;

b) Increase in ortho, para activation leaving the meta activation unchanged;

c) Increase in ortho, para activation with smaller increase in meta activation.
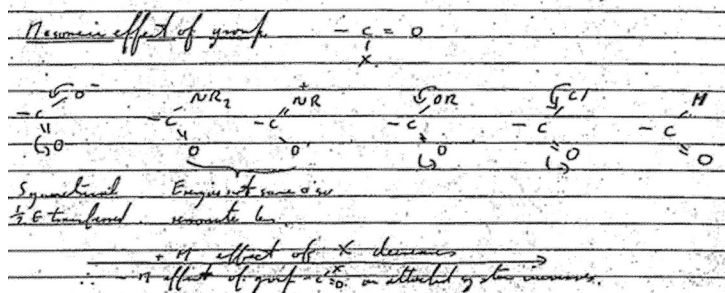
Ingold: Structure and Mechanism in Organic Chemistry 1ˢᵗ Ed.

TABLE 19-3.—CLASSIFICATION OF ORIENTING SUBSTITUENTS.

Type	Electronic mechanism	Examples	Effect on	
			Orientation	Reactivity
(1) $+I$	Ph←R	Ph—CH_3	ortho-para-	Activation
(2) $-I$	Ph→R	Ph—CO_2Et	meta-	Deactivation
(3) $-I+T$	Ph→R	Ph—SMe_2^+	As in (2)	
		Ph—Cl	ortho-para-	Deactivation
		Ph—OMe	As in (4)	
(4) $+I+T$	Ph←R	Ph—O^-	ortho-para-	Activation

Figure 3*. Inductive and tautomeric effects in electrophilic aromatic substitution from Baker notes (above) and SMOC (below).*

Data from experiments involving the competitive nitration of benzene and toluene was used to determine the correct scenario. In this study the ratio is 23 for toluene as compared to benzene and the o : m : p ratios are 58.4 : 4.6 : 37.2. This supports the interpretation that (c) is the best explanation. Continuing in this vein Baker discusses what happens in the case of a combination of inductomeric and electromeric effects and how this leads to a large increase in the activation of the ortho, para substitution. The inductive effect of electron withdrawing groups has the greatest effect at the ortho, para positions and by default increases the amount of meta substitution.

The unusual activity of the halogens is explained in terms of the conflict between resonance displacement and the inductive effect which leads to an overall deactivation of the molecule. This favors meta substitution. The final portion of the lectures in this section deals with the question of how the attack by reagent molecules occurs in aromatic substitution. The conditions for nucleophilic aromatic substitution are discussed by analogy to electrophilic aromatic substitution.

Substitution at Saturated Carbon and Elimination Reactions

The two last topics are nucleophilic substitution reaction at saturated carbon as well as elimination reactions. These two types of reactions are the ones chemists most associate with the so-called Ingold or English school. Most of Baker's lectures deal with the nucleophilic substitution reactions. He introduces the distinction between S_N1 and S_N2 reactions and the two types of elimination reactions are briefly mentioned in the context of how they can compete with S_N processes. An alkyl group that favors the release of electrons will favor the release of X as an anion in alkyl halides.

According to Baker there exists a continuum of substitution reactions depending on the conditions. Five possible ways for changing bimolecular to unimolecular and six for the reverse are presented. Some of these factors are:

•Strong electron affinity of X will favor ionization.

•Weak nucleophiles or low nucleophile concentrations hinder attack on the substrate.

•Factors favoring ionization include having a solvent with a high polarity.

•Temperature changes as they apply to the energy of activation.

Applications of these ideas are discussed with specific examples of reactions that had been investigated. An example of this comes from the work of Hughes, Ingold and Shapiro (11) on the hydrolysis of alkyl halides. This is shown below in the form of a graph which summarizes the arguments in his lecture (Figure 4). A similar graph can be found as Figure 24.1 in SMOC (Figure 5).
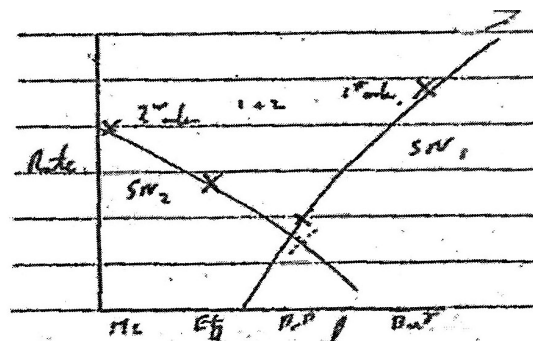

Figure 4. *Schematic illustration of how mechanism, kinetic order, and rates change as shown by Baker (1942).*
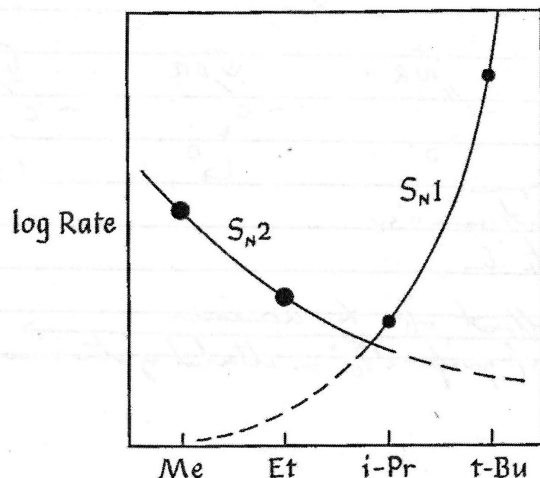
V   NUCLEOPHILIC ALIPHATIC SUBSTITUTION

FIG. 24-1.—Schematic illustration of changes of mechanism, kinetic order, and rate, in a nucleophilic substitution, Y+AlkX=AlkY+X, with variable groups Alk arranged in order of increasing electropositivity.

Figure 5. Schematic illustration of how mechanism, kinetic order, and rates change as shown by Ingold (1953).

A brief section is devoted to the discussion of the mechanisms of elimination reactions and their relationship to substitution reactions. Due to their similarities a duality exists as far as the mechanisms are concerned. Baker points out that the electronic character of the leaving group is not the key factor in the removal of the β hydrogen atom in the E2 mechanism. In the case of the E1 reaction he draws attention to the similarity to the S_N1 reaction in terms of the rate determining ionization step.

Baker's lectures identify actors in the ratio of S_N2 versus E2 in terms of the basicity of the attacking reagent. Using the series Br^-, OAc^-, OPh^-, OH^- as an example, it is shown how the increasing basicity favors the S_N2 over the E2 reaction. This is due to the nature of the attack on carbon versus that on hydrogen. As the basicity decreases the ability to attack carbon increases and causes a rise in S_N2.

The ionizing power of solvents is next considered in elimination versus substitution reactions. The key to the ratios of S_N versus E is the charge distribution in the transition states of these reactions. In the transition state for elimination there is a wider distribution of the charge as compared to substitution. Four scenarios are shown in the diagram below (Figure 6) for bimolecular reactions. In each pair the two transition states are shown and the effect of solvation shown. Table 33-2 on page 457 in SMOC (Figure 7) is more detailed but in many ways similar.

Conclusions

This set of notes offers a unique snapshot in time between leading edge research and its transfer to the advanced undergraduate classroom of the day. These lectures show how advanced undergraduate students in the course discussed in this paper were exposed to a whole new way of thinking about organic reactions. For a student to understand the new insights that Ingold and collaborators brought to the study of mechanism and structure would have required extensive reading of the primary literature. This would have been a daunting task for an undergraduate or post graduate student especially in the United States. As illustrated by the detailed

Figure 6. Solvent effects in substitution and elimination reactions from Baker notes.

Figure 7. Solvent effects in substitution and elimination reactions from SMOC.

examples given above, students in Baker's course were exposed to data and interpretations considered worthy of inclusion in a specialist monograph a decade later. Moreover, the treatment of that material has become standard even in introductory organic chemistry half a century later.

We have previously examined a course in physical organic chemistry given by Paul Bartlett (1907-1997) at Harvard in the spring semester of 1938 (12). This course is much more oriented to the application of physical chemistry in organic chemistry than the approach of Ingold which emphasized structure and mechanism. Baker's course of lectures to advanced undergraduates in this time period may have been possibly unique and we can only answer this question if more material is found from this era.

The significance of the work of Ingold and his collaborators which is discussed by Baker as part of his lectures was so important that Remick devoted a whole chapter to it in his 1943 text (8) which was written for an American audience assumed to be unfamiliar with it. By contrast, the 1953 first edition of SMOC contains many references to the work of a new generation of American chemists. Many of them had spent time in Ingold's laboratory as Fulbright Fellows in the immediate post war era such as J. F. Bunnett (13). American chemists would soon become the leaders in physical organic chemistry in the post war era.

Acknowledgment

References and Notes

1. T. T. Tidwell "The First Century of Physical Organic Chemistry: A Prologue," *Pure Appl. Chem.*, **1997**, *69*, 211-213. See also T. T. Tidwell, "Summary," *Pure Appl. Chem.*, **1997**, *69*, 215-216.

2. L. P. Hammett, *Physical Organic Chemistry: Reaction Rates, Equilibria, and Mechanisms*, McGraw-Hill, New York, 1940.

3. H. B. Watson, *Modern Theories of Organic Chemistry*, Oxford University Press, Oxford, 1937.

4. W. A. Waters and T. M. Lowry, *Physical Aspects of Organic Chemistry,* D. Van Nostrand Company, New York, 1935.

5. C. K. Ingold, "Principles of an Electronic Theory of Organic Chemistry," *Chem. Rev.*, **1934,** *15*, 225-274.

6. There are several major works on the life of and career of Ingold: K. T. Leffek, *Sir Christopher Ingold: A Major Prophet of Organic Chemistry*, Nova Lion Press, Victoria, Canada, 1996. C. W. Shoppee, "Christopher Kelk Ingold, 1893-1970," *Biogr. Mem. Fellows R. Soc.*, **1972**, *18*, 348-411.

7. For more about the career of J. W. Baker see M. D. Saltzman, "John William Baker and the Origin of the Baker-Nathan Effect," *Bull. Hist. Chem.,* **2012**, *37*, 82-90.

8. A. E. Remick, *Electronic Interpretations of Organic Chemistry,* John Wiley & Sons, New York, 1943.

9. Donald Vincent was a third year student in the B.Sc. program in 1942. He later worked at ICI and then became the British equivalent of a patent lawyer. In 2006 he gave his notes to Richard Bushby during a visit to Leeds and these now reside in the archives of Leeds University. I am most grateful to the archives for making a copy of these notes for me.

10. C. K. Ingold, *Structure and Mechanism in Organic Chemistry*, Cornell University Press, Ithaca, NY, 1953.

11. E. D. Hughes, C. K. Ingold and U. G. Shapiro, "Mechanism of substitution at a saturated carbon. Part VI. Hydrolysis of isopropyl bromide," *J. Chem. Soc.,* **1936**, 225-236.

12. L. B. Gortler and M. D. Saltzman, "Paul Bartlett's Chem. 17a: A Pioneering Course in Physical Organic Chemistry," *Bull. Hist. Chem.*, **1998**, *21*, 25-30.

13. Joseph F. Bunnett (1921-2015) was Fulbright Fellow at UCL in the late 1940s shortly after the beginning of the program. Ingold in the Preface acknowledges Bunnett for his contributions to chapter 15 on aromatic nucleophilic substitution.

About the Author

Martin D. Saltzman is Professor of Natural Science at Providence College. He is currently working on a study of the state of chemical knowledge in the United States from 1846-1876 as found in *Scientific American*.