TECHNIQUES OF CHEMISTRY

VOLUME IV

ELUCIDATION OF ORGANIC STRUCTURES BY PHYSICAL AND CHEMICAL METHODS

Second Edition

TECHNIQUES OF CHEMISTRY

VOLUME IV

ELUCIDATION OF ORGANIC STRUCTURES BY PHYSICAL AND CHEMICAL METHODS

Second Edition

Edited by
K. W. BENTLEY
Reckitt & Colman
Hull, England
AND
G. W. KIRBY
Department of Chemistry
Loughborough University of Technology
Loughborough, England

PART II

WILEY-INTERSCIENCE
A DIVISION OF JOHN WILEY & SONS, INC.
New York · London · Sydney · Toronto

Library of Congress Cataloging in Publication Data:

Main entry under title:

Elucidation of organic structures by physical and
chemical methods.

(Techniques of chemistry, v. 4)
1963 ed. published under title: Elucidation of
structures by physical and chemical methods.
Includes bibliographies.
1. Chemistry, Physical organic—Addresses, essays,
lectures. I. Bentley, Kenneth Walter, ed. II. Kirby,
Gordon William, 1934– ed.

QD61.T4 vol. 4 [QD476] 540′.28s [547′.1′22] 72–273

ISBN 0-471-92896-8

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

AUTHORS OF PART II

G. O. ASPINALL
York University, Toronto, Canada
K. W. BENTLEY
Reckitt & Colman, Hull, England
J. P. CANDLIN
Imperial Chemical Industries Ltd., Runcorn, England
ANGELO FONTANA
Institute of Organic Chemistry, University of Padua, Padua, Italy
R. A. C. RENNIE
Imperial Chemical Industries Ltd., Runcorn, England
ERNESTO SCOFFONE
Institute of Organic Chemistry, University of Padua, Padua, Italy
Z. VALENTA
University of New Brunswick, Fredericton, Canada
B. C. L. WEEDON
Queen Mary College, London, England

INTRODUCTION TO THE SERIES

Techniques of Chemistry is the successor to the Technique of Organic Chemistry Series and its companion—Technique of Inorganic Chemistry. Because many of the methods are employed in all branches of chemical science, the division into techniques for organic and inorganic chemistry has become increasingly artificial. Accordingly, the new series reflects the wider application of techniques, and the component volumes for the most part provide complete treatments of the methods covered. Volumes in which limited areas of application are discussed can easily be recognized by their titles.

Like its predecessors, the series is devoted to a comprehensive presentation of the respective techniques. The authors give the theoretical background for an understanding of the various methods and operations and describe the techniques and tools, their modifications, their merits and limitations, and their handling. It is hoped that the series will contribute to a better understanding and a more rational and effective application of the respective techniques.

Authors and editors hope that readers will find the volumes in this series useful and will communicate to them any criticisms and suggestions for improvements.

Research Laboratories
Eastman Kodak Company
Rochester, New York

ARNOLD WEISSBERGER

PREFACE

The elucidation of the structure of unknown compounds and the synthesis of compounds of defined structures rank high among the aims of organic chemistry. The synthesis of complex structures resembles the composing of a jigsaw puzzle whose parts are formed according to certain rules as the composing proceeds. The establishment of the rules and techniques for the formation of bonds and for the transformation of groups and their application constitutes a major part of organic chemistry. The design of successful and elegant syntheses is the crowning accomplishment, but it seems very difficult to formulate general directions for this work. Apprenticeship with the masters—personal or through study of the original literature—remains the initiation.

Similar considerations apply to the elucidation of the structure of unknown compounds, but here the respective compound is at hand as the substrate of the work, rather than being a concept and aim. Some guidance is received from the study of the intact molecule, particularly by physical methods, and elucidation of structure lends itself, therefore, more readily to comprehensive presentation than multistep synthesis. Moreover, the degradative methods used in the elucidation of structure lack documentation in the reviewing literature. The present volumes are designed to fill this gap and to give guidance to the chemist who tries to unravel the structure of unknown organic synthetic or natural products.

In preparing this second edition of a book originally published more than eight years ago almost the whole work has been rewritten by a new team of contributors, thus ensuring properly structured up-to-date surveys of fields that have changed markedly in recent years. The emphasis is on results and interpretation rather than physical principles and manipulative techniques, wherever these are more fully dealt with in other volumes of this series, though no details essential to an understanding of the main text have been omitted. The subjects of some chapters in the first edition are no longer included, as they have received full and detailed treatment elsewhere (e.g., molecular rearrangements and biogenetic theory), and the subjects of other chapters have in some cases been combined to achieve a more rational and uniform treatment. New topics covered in this edition include X-ray crystallography, certain aspects of nuclear magnetic resonance spectroscopy, and stereoselective synthesis.

This rewriting has resulted in a much larger work, which is more conveniently divided into three volumes than two as in the first edition.

Hull, England
Loughborough, England
February 1972

K. W. BENTLEY
G. W. KIRBY

CONTENTS

PART II

Chapter X

DEHYDROGENATION AND ZINC DUST DISTILLATION

Z. Valenta

---

1 INTRODUCTION

Dehydrogenation is a valuable tool in the structure elucidation of natural products and preparation of aromatic substances. The carbon skeletons of a great number of sesqui-, di-, and triterpenes, steroids, and alkaloids were deduced primarily from the conversion of the compounds under investigation into recognizable aromatic substances. It is this "aromatization" reaction that will be the main topic of this chapter. The dehydrogenation of alcohols to ketones, used extensively in industrial processes and in the laboratory, formation of enones from saturated ketones by the action of quinones, catalytic oxidation with molecular oxygen and a metal catalyst [1], and similar processes involving only the oxidation of functional groups will not be included.

The dehydrogenation leading to an aromatization is very often the method of choice in structure elucidations, since the products contain few, if any, asymmetric carbon atoms and their carbon skeleton and often even the position of substituents can be recognized with the help of typical ultraviolet spectra. These aromatic dehydrogenation products can then be synthesized or compared with known compounds, and their identification provides an important clue for the structure elucidation of the more complex compound under investigation. It should be pointed out, however, that this powerful tool of degradative chemistry should be used with caution and regard for established principles of organic chemistry. A consideration of bond energies reveals that a dehydrogenation at elevated temperatures need not be (and in fact very seldom is) a simple removal of hydrogen. Carbon–carbon and carbon–heteroatom bond breakages leading to a loss of substituents and ring openings are often encountered. In addition, other transformations such as retropinacol rearrangement, ring expansion and contraction, formation of new rings, migration of substituents, and even reduction must be anticipated. While these "side reactions" cause the relatively low yields encountered in the dehydrogenation of complex molecules, they are not an unsurmountable obstacle to the correct interpretation of dehydrogenation results and they provide an additional challenge to the investigator's chemical reasoning. It will be one of the main purposes of this chapter to review not only the commonly encountered transformations, but also to point out the more unexpected and sometimes very surprising results obtained in dehydrogenation studies.

Structure elucidation is, of course, not the only field in which dehydrogenation has been applied. Its use in the synthesis of aromatic systems and in studies aimed at the elucidation of dehydrogenation mechanisms is frequently encountered in the chemical literature and will be briefly reviewed here.

The most commonly used methods for dehydrogenation, limited to the "aromatization" reaction as stated above, are *(1)* catalytic action of transition metals, *(2)* action of sulfur or selenium, and *(3)* "hydrogen transfer" to other organic compounds such as quinones without the use of a catalyst.

These processes will first be dealt with separately in a brief way, and some of their characteristics and possible modes of action will be described. Following the survey of the individual dehydrogenation agents, most of the dehydrogenation results are arranged on the basis of the chemical transformation type rather than on the basis of different dehydrogenation agents or reaction conditions. This is done mainly because *the products* of dehydrogenation with different agents are very often the same or at least similar and analogous side reactions are encountered with both metal catalysts and sulfur or selenium (although, of course, *the mechanism* of action may be quite different).

The dehydrogenation with sulfur, selenium, and platinum metals has been extensively reviewed by Plattner [2], his review containing references up to 1946. Earlier results were summarized by Ruzicka in 1928 [3] and Linstead in 1937 [4]. Jackman [5] has reviewed hydrogen transfer reactions in which both the donor and acceptor are organic molecules. An extensive review by Beroza and Coad [6] describes the use of a microreactor connected with a gas chromatograph. Recent articles on selenium dehydrogenation of diterpenes by Carman [7] and of steroids by Shöntube and Janák [8] provide good examples of the use of modern analytical methods in this field.

2 CATALYTIC DEHYDROGENATION

Theoretical Considerations

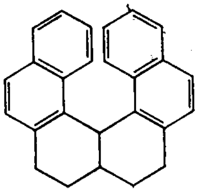
The pioneering work of Sabatier and Senderens [9] on catalytic dehydrogenation in the vapor phase with nickel catalysts and of Zelinsky [10] with platinum metal catalysts initiated an extensive use of metals in the dehydrogenation of organic compounds in the last five decades.

Parallel with the application of the catalytic dehydrogenation as a preparative and degradative method was the thorough investigation of the theoretical aspects of metal catalysis. Although a detailed description of these theoretical studies is clearly outside the scope of this chapter, and although "far too little is known about the mechanism at present" [11], it should be of interest to summarize very briefly some of the results of these investigations.

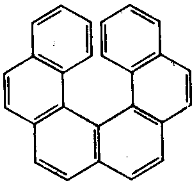
In a review, Trapnell [12] discusses some of the factors responsible for effective catalysis. First of all, a metal must contain the correct lattice spacing in order to catalyze a particular reaction; i.e., the catalyst atoms must be at certain favorable distances, and in a certain geometric pattern, for the most effective adsorption and reaction [13]. Thus, a so-called *geometric* or *lattice spacing factor* is operative in catalysis. Second, an active metal must have orbitals available for surface bonding; i.e., an *electronic factor* is operative. The atomic *d*-orbitals of transition metals are considered responsible for high catalytic activity [14, 15].

Furthermore, in an effective catalysis, the adsorption of the substrate on the metal surface should be rapid and weak; i.e., both the heat and activation energy (in the case of an activated process) of adsorption should be small

[12]. From the geometric standpoint, weak adsorption can be achieved by strain introduced into the molecule when it is adsorbed at more than one point [16]. It is interesting that this reasoning is similar to the "incomplete fit" or "transition state fit" hypothesis of enzyme catalysis.



1

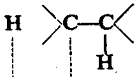


2

From the electronic standpoint, weak adsorption is the consequence of a limited number of *d*-orbitals available for bonding. In a study of adsorption of H_2 and ethylene on different transition metals, Beeck [17] found that the heat of chemisorption decreased with decreasing availability of atomic *d*-orbitals.

It is probably little more than a coincidence that the metals of the platinum and palladium triads have both the most favorable geometry and electronic factor for effective catalysis. While platinum and palladium are the two metals most commonly used in hydrogenations and dehydrogenations, it should be pointed out that rhodium seems to possess the best characteristics [12] and might well be tried when other metals fail. Newman found, for instance, that the dehydrogenation to helicene (**1** → **2**) proceeds best with rhodium on Al_2O_3 in benzene (acting as solvent and H_2 acceptor) at 300°C [18].

While all the mechanisms involving hydrogen in a catalytic reaction are still controversial, detailed work on parahydrogen conversion, deuterium exchange, and similar exchange reactions has led to some clarification in the field [11, 12, 19]. It appears probable that reactions involving addition, exchange, or abstraction of hydrogen proceed through the adsorption of the reacting molecules on the catalytic surface followed by their transformation into a so-called "half-hydrogenated state" of the type:



where each dotted line marks a bonding to the catalyst. Taylor [20] postulated the simultaneous removal of all six hydrogens on dehydrogenation of cyclohexane, and Braude, Linstead, and Mitchell [21] came to a similar conclusion in their study of the disproportionation of cyclohexene. The English authors postulated a termolecular reaction mainly because no detectable amount of cyclohexadiene was formed and because cyclopentene, cycloheptene, and cyclooctene did not disproportionate under similar conditions. Actually, these findings do not prove the simultaneous removal of *all* hydrogens [21], but only indicate that the reacting molecules probably do not desorb at an intermediate stage. A certain support for the theory that cyclohexane is attacked at several points simultaneously comes from the work of Balandin [22, 23] who studied the reaction of six-membered rings on active metal surfaces. He concluded that only metals possessing crystal faces with hexagonal symmetry (i.e., faces capable of forming six metal–carbon bonds) were active as catalysts.

It is likely that all metals act by the same basic mechanism and that differences in reactivity are caused by a different geometric and electronic factor [24].

Experimental Procedure

Catalysts

The most commonly used dehydrogenation catalysts are palladium and platinum, applied mostly with carriers. The preparation of platinized charcoal was described by Packendorff and Leder-Packendorff [25], palladized charcoal by Zelinsky and Turova-Pollak [26] and by Diels and Gädke [27], active palladium by Willstätter and Waldschmidt-Leitz [28], active platinum by Loew [29], platinized and palladized asbestos by Zelinsky and Borisoff [30], and palladium on barium sulfate by Mozingo [31]. Platinum on aluminum oxide has been used by Pines, Ipatieff, and their coworkers [32, 33], and Hernandez and Nord [34] described the preparation of rhodium and other metals on synthetic high polymers.

Zelinsky and his collaborators were the first to show that the method of preparation of the catalyst influences its activity and mode of action upon the substrate [26, 30, 35, 36]. Linstead and his collaborators [37, 38] investigated the effects of the various preparative methods on the activity of the catalysts and came to the following conclusions:

1. The catalysts prepared by the method of Willstätter and Waldschmidt-Leitz [28] are highly active; their activity can be improved by precipitation at higher dilution.
2. Platinum and palladium catalysts made under identical conditions have very similar activities. Palladium seems to have a greater tendency to produce side reactions.
3. The carrier has a considerable influence on activity, the order of activity being metal on charcoal > metal on asbestos > metal "black."
4. The course of the dehydrogenation of substances containing a quaternary cyclic carbon is influenced by the nature of the carrier, but not by the choice of metal.

Palladium on charcoal in combination with sulfur has been used for cyclodehydrogenation [39]. Catalysts and reaction conditions used in industrial dehydrogenation and aromatization processes have been described in summarizing articles [40–42].

Reaction Conditions

The temperature necessary for dehydrogenation varies widely and depends mainly upon the oxidation state of the substrate and the presence of quaternary carbon atoms. While tetralin can be dehydrogenated at 200°C or even lower, decalin requires 300°C [37] and the perhydronaphthalenes containing quaternary carbon atoms require a temperature of 325°C or higher [38, 43].

The duration of dehydrogenation also varies widely, but for workable yields the reaction should in general not be run for more than several hours.

The type of apparatus used for dehydrogenation will depend mainly upon the temperature and the amount of compound available. For degradative studies, it is often possible simply to heat the compound with the catalyst. It is recommended to perform the reaction in an inert atmosphere by sweeping with a slow stream of nitrogen or carbon dioxide. The reaction is thus driven to completion by removal of hydrogen, and side reactions involving hydrogenation are brought down to a minimum [37]. The reaction vessel is usually provided with a sealed-on air- or water-cooled reflux condenser and the low volatile products are collected in appropriate cold traps. This procedure should, of course, be applied only for substances boiling at a sufficiently high temperature. For lower boiling substances and for the dehydrogenation of a very small amount of substance a sealed tube can be used. In order to remove the hydrogen formed, it is often advantageous to use a hydrogen acceptor when the sealed tube technique is applied [18, 44–47].

Microdehydrogenations in a system connected to a gas chromatograph [6] and dehydrogenation of perhydroazulenes and perhydronaphthalenes for only 1–3 min [48] have recently been described.

Solvents

Various solvents have been used for catalytic dehydrogenation, both as hydrogen acceptors and as diluents. Benzene [18, 44–46], acetone [47], and maleic [49, 50], and fumaric and cinnamic acid [51] are the commonly used hydrogen acceptors, and naphthalene, quinoline, mesitylene, *p*-cymene, Dowtherm, *sym*-trichlorobenzene, xylene, triethylbenzene, and diphenyl ether have been used as solvents. The choice of an appropriate solvent makes it possible to perform the dehydrogenation at reflux at a chosen temperature.

Vapor Phase Technique

Günthard, Plattner, and coworkers described an apparatus for quantitative studies of dehydrogenation with palladized charcoal in the vapor