

8202076

ISOTOPIC EXCHANGE
AND THE REPLACEMENT OF HYDROGEN
IN ORGANIC COMPOUNDS

by
A. I. Shatenshtein

0643.14
E701

~~5-1896~~

R
==

8202076

外文

ISOTOPIC EXCHANGE AND THE REPLACEMENT OF HYDROGEN IN ORGANIC COMPOUNDS

by
A. I. Shatenshtein

*Authorized translation from the Russian
by C. Nigel Turton, B.Sc., Ph.D. and Tatiana I. Turton, B.A.*



CONSULTANTS BUREAU
NEW YORK

1962

*The Russian text was published by the USSR
Academy of Sciences Press in Moscow in 1960.*

Александр Исаевич Шатенштейн

**Изотопный обмен и замещение водорода
в органических соединениях**

Library of Congress Catalog Card Number 62-12859

©1962 Consultants Bureau Enterprises, Inc.

227 West 17th St., New York 11, N.Y.

All rights reserved

*No part of this publication may be reproduced in any
form without written permission from the publisher*

Printed in the United States of America

ИЗОТОПНЫЙ ОБМЕН
И ЗАМЕЩЕНИЕ ВОДОРОДА
В ОРГАНИЧЕСКИХ СОЕДИНЕНИЯХ

IZOTOPNYI OBMEN
I ZAMESHCENIE VODORODA
V ORGANICHESKIKH SOEDINENIYAKH

ISOTOPIC EXCHANGE
AND THE REPLACEMENT OF HYDROGEN
IN ORGANIC COMPOUNDS

*I dedicate this book to
the memory of my brother
David Isaevich Shatenshtein*

PREFACE

Hydrogen replacement reactions play an outstanding part in organic chemistry. They include such industrially important processes as halogenation, nitration, sulfonation, alkylation, and direct amination and metallation of organic substances. It is no accident that the data obtained in the investigation of these reactions have been used extensively in the solution of a series of fundamental problems in theoretical organic chemistry and this tendency still exists.

Isotopic exchanges of hydrogen also belong to this group of chemical conversions. They have attracted considerable attention as they are the simplest and, to some extent, models of hydrogen replacement reactions, which are convenient for elucidating the mechanism of hydrogen replacement and the effects of interaction between atoms in organic molecules.

The mechanisms of hydrogen replacement reactions are examined in this monograph and the most space is allocated to hydrogen isotope exchanges. The mechanisms of all the given reactions are interpreted from the point of view of the acid-base properties of the reagents. In this connection, a large section of the book is devoted to a thorough substantiation of the thesis that hydrocarbons participating in the given reactions act as acids or bases. Problems of acid-base catalysis and the mechanism of acid-base interaction are also discussed. Thus, a considerable part of the book is concerned with problems of the theory of acids and bases.

In general, the contents of this book fall within the field of physical organic chemistry, which is evolving very rapidly nowadays. Most of the phenomena described lie at the meeting point of three sections of chemistry: the study of the structure and reactivity of organic compounds, the chemistry of isotopes, and the theory of acids and bases. It is most tempting to bridge the gap between them and thus make it possible to use the conclusions reached in the study of some phenomena for interpreting the nature of others and also to promote a critical attitude toward some existing generalizations from a new point of view.

Definite opinions are put forward on the nature and mechanism of heterolytic hydrogen exchange in solutions and the mechanisms of acid-base reactions as well as hypotheses on the effect of the medium on the reactivity of organic substances and

on the manifestation of the interaction between atoms in their molecules. These hypotheses required a multiplicity of facts for a thorough and objective substantiation. In the hope of stimulating the discussion of the problems considered in the book, the author has tried to group the material in such a way that concrete scientific conclusions evolve from it and these are formulated at the end of each chapter and section.

Soviet literature includes many books on problems in isotope chemistry, the mechanism of organic reactions, and the theory of acids and bases. It is sufficient to mention the valuable works of A. I. Brodskii, "The Chemistry of Isotopes" (1957), S. Z. Roginskii, "Theoretical Bases of Isotopic Methods of Studying Chemical Reactions" (1956), O. A. Reutov, "Theoretical Problems in Organic Chemistry" (1956), and N. A. Izmailov, "Electrochemistry of Solutions" (1959). I should also mention my previous monograph, "Theories of Acids and Bases." It seemed useless to duplicate the contents of these books. The reader can refer to them for further information. The present monograph summarizes and generalizes data obtained by Soviet and foreign authors and published in journals mainly in the decade up to and including 1958. Some work from 1959 is mentioned.*

The book contains numerous cross references, which help to associate the material in the different sections.

The monograph is the final outcome of investigations of the isotopic exchange of hydrogen in nonaqueous solutions under the general direction of the Scientific Council of the "Theory of Chemical Structure, Kinetics, and Reactivity" of the Division of Chemical Sciences of the Academy of Sciences USSR. The author is very grateful to the chairman of the Scientific Council Academician V. N. Kondrat'ev for his interest in these investigations and assistance in the publication of the book. The author considers it his pleasant duty to thank the Responsible Editor M. I. Kabachnik for much valuable advice and fruitful discussion and Academician Acad. Sci. Ukr.SSR A. I. Brodskii and Corresponding Member Acad. Sci. Ukr. SSR N. A. Izmailov for friendly help in the form of a critical review of the manuscript and valuable comments. All remarks as to the shortcomings of the book will be gratefully received.

Moscow,
May, 1959

* The translation includes supplementary material written by the author, which takes into consideration work published in 1959-1961.

THE FOLLOWING SOVIET JOURNALS CITED IN THIS BOOK
ARE AVAILABLE IN COVER-TO-COVER TRANSLATION

Russian Title	English Title	Publisher
Doklady Akademii Nauk SSSR	Proceedings of the Academy of Sciences USSR	Consultants Bureau (chemistry sections)
Kinetika i kataliz	Kinetics and Catalysis	Consultants Bureau
Optika i spektroskopiya	Optics and Spectroscopy	American Institute of Physics
Izvestiya Akademii Nauk SSSR, Otdelenie khimicheskikh nauk	Bulletin of the Academy of Sciences USSR, Division of Chemical Sciences	Consultants Bureau
Zhurnal fizicheskoi khimii	Journal of Physical Chemistry USSR	The Chemical Society (London)
Zhurnal obshchei khimii	Journal of General Chemistry USSR	Consultants Bureau

INTRODUCTION

The history of any science is an absorbing account of the discovery of new phenomena and their generalization, the rise and development of concepts, hypotheses, and theories, and the interaction of ideas.

In chemistry there are many concepts that have occupied the thoughts of scientists for centuries and these include an element, valence, chemical affinity, etc. The concepts of "acid" and "base" have an even longer history as the peculiar properties of fermented grape juice and an infusion of wood ash have been known since remote antiquity. An attempt to follow the successive changes in the ideas on acids and bases was made in the monograph, *Theories of Acids and Bases* [1].

The hydrogen theory of acids originated at the beginning of the last century. Davy, Ampère, and Gay-Lussac discovered that hydrochloric, hydrofluoric, and prussic acids contain hydrogen. The idea that acids must contain hydrogen was expressed particularly clearly by Dulong. An important stage in the history of the hydrogen theory is associated with the name of Liebig. He defined acids as hydrogen compounds in which the hydrogen may be replaced by a metal. This definition is still of some value. The success of Arrhenius' theory of electrolytic dissociation stimulated a re-examination of the definition of acids and alkalis. The acidity and alkalinity of substances were related to their dissociation in aqueous solution to form hydrogen ions (H^+) and hydroxyl ions (OH^-), respectively.

To counterbalance Arrhenius' physical theory of solutions, D. I. Mendeleev put forward a chemical theory of solutions and the Russian physical chemists D. P. Kononov, I. A. Kablukov, and others participated actively in substantiating it.

Hantzsch, Franklin, Kraus, P. I. Walden, V. A. Plotnikov, and many other scientists helped to develop the chemistry and physical chemistry of nonaqueous solutions. The study of nonaqueous solutions showed that the properties and reactions of aqueous solutions of acids and alkalis are similar to those of solutions which not only contain no H^+ and OH^- ions, but do not even conduct an electric current.

In 1923 Brønsted [2] and Lowry [3] simultaneously and independently defined acids and bases as donors and acceptors of protons. The new definition agreed well with all

experimental material. Brønsted's orderly quantitative theory of acid-base equilibrium and catalysis has had a great influence on the investigations of chemists in different countries for several decades. Nonetheless, in the summary of the results achieved during the twenty-five years that Brønsted's theory has existed given in the monograph *Theories of Acids and Bases* [1] it was noted that there were already serious deviations from the theory and its limitations were beginning to be felt, while in the last decade so many facts have accumulated which do not agree with Brønsted's theory that a re-examination of it has become imperative. N. A. Izmailov [4] has established experimentally a theory of the dissociation of acids and bases, which allows for considerably greater complexity of the dissociation process than follows from Brønsted's theory. The equations of Brønsted's qualitative theory were found to be a particular case of N. A. Izmailov's equations.

The transfer of a proton, to which Brønsted reduced the reaction between an acid and a base, is actually only the final stage of an acid-base interaction. It occurs only under favorable conditions.

Brønsted greatly extended the scope of acids and bases, but still did not cover the whole range of acid-base processes. This became evident with the application of methods that were more sensitive than classical ones, namely, potentiometry, conductimetry, and electronic spectrophotometry. Measurements of infrared spectra, dipole moments, and proton magnetic resonance have made it possible to not only detect, but even characterize quantitatively much weaker interactions of the same type as normal acid-base reactions.

One extremely sensitive method utilizes the isotopic exchange of hydrogen in nonaqueous protophilic (basic) and protogenic (acidic) media. This was used in the Isotopic Reactions Laboratory of the L. Ya. Karpov Physicochemical Institute over the last ten years for a systematic study of the acidic and basic properties of various hydrocarbons.

Isotopes play a predominant part in contemporary science. They help investigators to elucidate the details of chemical reaction mechanisms, to obtain much important information on the reactivity and structure of substances, etc. Exchange reactions in which atoms of the same element participate can be followed readily by the use of isotopes. Such reactions were predicted by D. I. Mendeleev [5] in 1886: "In a mass of molecules there must or, at least, there may be exchange movement of the atoms. If we have the molecules AB and AB, then A from the former may transfer to the latter molecule and back."

Among the stable isotopes, the heavy isotope of hydrogen, deuterium, which was discovered by Urey, Brickwedde, and Murphy in 1932 [6], has been of the greatest value in chemical investigations. Gaseous deuterium was obtained by fractionation of liquid hydrogen. Washburn and Urey [7], and Lewis and MacDonald [8] soon proposed a simpler method of separating hydrogen isotopes by electrolysis of water; "heavy water" was obtained in this way. Even in the first work with it, Lewis [9], Hall [10], Bonhöffer [11], Klar [12], and other scientists discovered that it was then possible to make a detailed study of the isotopic exchange of hydrogen for deuterium or, more briefly, deuterium exchange. In the USSR, A. I. Brodskii [13] prepared water enriched in heavy isotopes of hydrogen and oxygen and used it successfully for many valuable studies in isotopic chemistry.

The hydrogen bound by O-H, N-H, S-H, and Hal-H bonds exchanges very rapidly with heavy water, but it is not usually possible to effect this exchange with C-H bonds, which is most promising for the solution of many problems in theoretical organic chemistry. It is readily observed that the exchange of hydrogen for the deuterium of heavy water occurs only with the C-H bonds of substances which are weak acids or weak bases in aqueous solutions and the exchange is catalyzed by strong acids and bases. Ingold [14] was able to replace hydrogen in some hydrocarbons by deuterium by the action of deuteriosulfuric acid. These facts suggest the acid-base nature of hydrogen exchange in solutions and from this it follows that if the acidic or basic properties of hydrocarbons and their derivatives are increased by the use of appropriate solvents and catalysts, hydrogen exchange in C-H bonds becomes a normal phenomenon [15]. Knowledge of the rules of acid-base equilibrium and catalysis in nonaqueous solutions has helped in the search for solvents and catalysts which have made it possible to extend the range of hydrogen exchange reactions considerably. In addition, knowledge of the rules of acid-base interaction has made it possible to predict the factors which must affect hydrogen exchange.

Studies on hydrogen exchange in nonaqueous solutions were begun in the Isotopic Reactions Laboratory of the L. Ya. Karpov Physicochemical Institute on the basis of Brønsted's theory, which was found to be of inestimable help in their development [16]. At the same time, the results of these studies have made the limitations of the theory obvious as was also the case in the development of other aspects of acid-base interaction. The accumulation of knowledge of acids and bases has made it necessary to extend the concept of protolytic reactions and to determine their mechanism more accurately.

The isotopic exchange of hydrogen has much in common with chemical hydrogen replacement reactions.* Ingold was the first to note this when he compared deuterium exchange between aromatic hydrocarbons and sulfuric acid with reactions of the former involving strong acids (nitration and sulfonation). However, isotopic reactions are much simpler as the molecular structure of the substance remains almost unchanged during the replacement of hydrogen by its isotope. If we neglect the small change in free energy caused by the differences in the zero point energies of bonds with tritium, deuterium, and protium, then it may be assumed that there is no thermal effect during isotopic exchange and the reaction is determined solely by kinetic parameters. In most cases the kinetics of isotopic exchange can be described quite accurately by a simple first-order equation. By measuring the rate of the exchange of deuterium for ordinary hydrogen in various monodeutero derivatives of the same compound in different solvents, one can readily evaluate quantitatively the reactivities of nonequivalent atoms in the molecule, examine the fine effects of the interaction of atoms, and observe the active role of the medium.

The book consists of five sections. In the first section the classification of reagents and reactions is described and it is shown that only acids and bases may participate in heterolytic hydrogen exchange reactions. In the second section there is a comparison of data on the catalysis of hydrogen exchange by acids and bases, which demonstrates the nature of this catalysis and provides a key to the understanding

*In this book, hydrogen replacements which differ from isotopic reactions are arbitrarily termed chemical. Isotopic reactions essentially are also chemical.

of the mechanism of exchange reactions. The third section consists of a detailed review of the literature on the properties of hydrocarbons as acids and bases. This material demonstrates the need for extending the field of acids and bases beyond the limits set by Brønsted's theory and provides further proof for the thesis on the acid-base nature of hydrogen exchange in solutions. The fourth section contains a discussion of the mechanism of acid-base interaction and a new definition of acids and bases is formulated. Finally, in the fifth and last section of the book the mechanisms of hydrogen replacement in heterolytic chemical reactions are examined. A knowledge of them, together with an understanding of the mechanism of acid-base reactions, is essential for an accurate appraisal of the mechanism of hydrogen exchange in solutions.

The principles of methods of preparing deuterium compounds are examined in the Appendix.

LITERATURE CITED

1. A. I. Shatenshtein, Theories of Acids and Bases [in Russian] (Goskhimizdat, Moscow, 1949).
2. J. N. Brønsted, *Rec. trav. chim Pays-Bas* 42, 718 (1923).
3. T. M. Lowry, *Chem. and Ind.* 42, 43 (1923); *J. Chem. Soc.* 123, 822 (1923).
4. N. A. Izmailov, *Zhur. Fiz. Khim.* 24, 321 (1950); 30, 2164 (1956).
5. D. I. Mendeleev, *Zhur. Russ. Fiz. Khim. Obshch.* 18, 8 (1886).
6. H. C. Urey, F. G. Brickwedde, and G. M. Murphy, *Phys. Rev.* 39, 164 (1932).
7. E. W. Washburn and H. C. Urey, *Proc. Nat. Acad. Sci. U.S.* 18, 496 (1932).
8. G. N. Lewis and R. MacDonald, *J. Chem. Phys.* 1, 341 (1933).
9. G. N. Lewis, *J. Am. Chem. Soc.* 55, 3502 (1933).
10. N. F. Hall, E. Bowden, and T. Jones, *J. Am. Chem. Soc.* 56, 750 (1934).
11. K. F. Bonhöffer and G. W. Brown, *Z. phys. Chem.* 23B, 171 (1933).
12. R. Klar, *Z. phys. Chem.* 24B, 335 (1934).
13. A. I. Brodskii, *Chemistry of Isotopes* [in Russian] (Izd. AN SSSR, 1957); *Zhur. Fiz. Khim.* 6, 1431, 1437 (1935); 9, 417, 755 (1937).
14. C. K. Ingold and C. L. Wilson, *Z. Elektrochem.* 44, 62 (1938).
15. A. I. Shatenshtein, *Uspekhi Khim.* 21, 914 (1952); 24, 377 (1955); 28, 3 (1959).
16. A. I. Shatenshtein and Yu. P. Vyorskii, *Doklady Akad. Nauk SSSR* 70, 1029 (1950); *Zhur. Fiz. Khim.* 25, 1206 (1951).

CONTENTS

Introduction	xiii
SECTION I. Types of Reagents and Reactions	
1. Oxidizing and Reducing Agents	1
2. Acids and Bases	2
3. Acidlike Substances	4
4. Nucleophilic and Electrophilic Reagents	7
5. Wider Definitions of Acids and Bases	9
6. Relative and Approximate Nature of the Classification of Reagents	10
7. Donor-acceptor Interaction	12
8. Heterolytic and Homolytic Reactions	16
9. Place of Hydrogen Exchange Among Other Reactions	18
10. Summary	19
Literature Cited	19
SECTION II. Acid-Base Catalysis of Hydrogen Exchange	
1. Introduction	21
2. Comparison of the Rates of Hydrogen Exchange with Amphoteric and Protophilic Solvents	22
3. Comparison of the Rates of Hydrogen Exchange with Amphoteric and Protogenic Solvents	25
4. Effect of the Dielectric Constant of the Solvent and the Polarity of Its Molecules on the Hydrogen Exchange Rate.	27
5. Effect of the Substrate and Catalyst Charge on the Hydrogen Exchange Rate	29
6. Effect of Dual Reactivity of a Substance on Hydrogen Exchange	33
A. Acceleration of Acid Exchange by a Base	33
B. Acceleration of Basic Exchange by an Acid	33
C. Inversion of Relative Rates of Hydrogen Exchange with Amphoteric and Protophilic Solvents	35
D. Inhibition of Acid Hydrogen Exchange by an Acid.	36
7. Effect of Steric Hindrance on Hydrogen Exchange	38
8. Decrease in the Activity of a Catalyst on Its Reaction with the Substrate	40
9. Activation of a Catalyst by a Change of Solvent.	41
10. Catalytic Activity of Complexes of Hydrogen Acids with Acidlike Substances in Hydrogen Exchange	42
11. Brønsted's Relation in Hydrogen Exchange	43
A. Rate and Equilibrium of Protolyte Ionization	43
B. Brønsted's Relation in Hydrogen Exchange	46
12. Hammett's Relation in Hydrogen Exchange	48
A. Hammett's Acidity Function	48

B. Reaction Rate and Acidity Function	54
C. Hammett's Relation in Hydrogen Exchange	59
13. Salt Effect in Hydrogen Exchange	64
14. Acid-Base Catalysis of Hydrogen Exchange in H-H, B-H, N-H, As-H, P-H, O-H, and S-H Bonds	66
A. Exchange in H-H Bond	66
B. Exchange in B-H Bond	67
C. Exchange in N-H Bond	67
D. Exchange in P-H Bond	70
E. Exchange in As-H Bond	70
F. Exchange in O-H Bond	71
G. Exchange in S-H Bond	72
15. Heterogeneous Acid-Base Hydrogen Exchange	72
16. Summary	73
Literature Cited	74
SECTION III. Hydrocarbons as Acids and Bases	
Introduction	80
Literature Cited	82
Chapter 1. Hydrocarbons as Acids	82
1. Metallation of Hydrocarbons	83
A. Reactions of Hydrocarbons with Alkali Metals	83
B. Reactions of Hydrocarbons with Bases	84
2. Saltlike Nature of Organoalkali Compounds	86
A. Electrical Conductivity of Solutions	87
B. Ionic Reactions	88
3. Carbanions	88
A. Formation of Carbanions	88
B. Spectra of Carbanions	89
4. Comparison of the Strengths of Carbo Acids by Metallation Reactions	92
A. General Comparison	92
B. Classes of Hydrocarbons	93
5. Isotopic Exchange of Hydrogen	96
A. Amphoteric Solvents	96
B. Liquid Ammonia	98
C. Liquid Exchange Between Hydrocarbons	114
6. Isomerization of Unsaturated Hydrocarbons	116
A. Nature of Reaction	116
B. Isomerization of Hydrocarbons by Bases	117
C. Rules of Isomerization	117
7. Alkylation by Olefins	119
A. Michael and Analogous Reactions	119
B. Alkylation of Amines and Ammonia by Olefins	120
C. Alkylation of Aromatic Hydrocarbons	120
D. Dimerization of Olefins	123
8. Summary	124
Literature Cited	124
Chapter 2. Hydrocarbons as Bases	130

1. Introduction	130
2. Carbonium Ions	130
A. Rupture of a Bond Between Carbon and an Electronegative Atom or Group	131
B. Exchange Between a Carbonium Ion and a Hydrocarbon	133
C. Elimination of a Hydride Ion	133
D. Addition of a Proton to an Unsaturated Hydrocarbon	134
E. Addition of a Carbonium Ion to an Aromatic Hydrocarbon	135
F. Detection of a Carbonium Ion by Deuterium Exchange.	135
3. Equilibrium Reactions of Hydrocarbons with Acids	136
A. Introduction	136
B. Liquid Hydrogen Fluoride	137
C. Sulfuric Acid	149
D. Hydrogen Chloride and Bromide	152
E. Carbonium Salts of Haloaluminic Acids	157
F. Carboxylic Acids	159
4. Equilibrium Reactions of Basic Hydrocarbons with Acidlike Substances. .	161
A. Introduction	161
B. Sulfur Dioxide	161
C. Halogens	162
5. Irreversible Reactions of Basic Hydrocarbons with Acidlike Substances . .	165
6. Isotopic Exchange of Hydrogen Between Hydrocarbons and Acids.	167
A. Introduction	167
B. Aromatic Hydrocarbons	168
C. Unsaturated Aliphatic Hydrocarbons	180
D. Saturated Hydrocarbons.	181
7. Summary	187
Literature Cited	188
Conclusion.	195
SECTION IV. Mechanism of Acid-Base Interaction	
1. Brønsted's Theory of Acids and Bases	197
2. Deviations from Brønsted's Theory and the Need for Development of the Latter.	199
3. Noncoulombic Interaction in Solutions of Acids and Salts	200
4. Acid-Base Reactions in Aprotic Solvents.	202
A. Application of Brønsted's Theory.	202
B. Inadequacy of Brønsted's Theory	202
5. N. A. Izmailov's Theory of the Dissociation of Acids and Bases	203
A. Comparison of the Strengths of Acids in Different Solvents	203
B. Reasons for Deviations from Brønsted's Theory	204
C. N. A. Izmailov's Theory	206
6. The Role of the Hydrogen Bond in Acid-Base Interaction	212
A. Donor-Acceptor Interaction in the Formation of a Hydrogen Bond. .	213
B. Polarity of Molecular Compounds of Acids with Bases	214
C. Displacement of Bond Vibration Frequency in the Infrared Ab- sorption Spectrum on the Formation of a Hydrogen Bond.	220
D. Other Manifestations of a Hydrogen Bond	229

7. Range of Protolytic Reactions	233
8. Definitions of Acids and Bases.	236
9. Summary	237
Literature Cited	238
SECTION V. Mechanisms of Hydrogen Replacement Reactions	
Introduction	242
Chapter 1. Replacement of Hydrogen by Reaction with a Nucleophilic Reagent	244
1. Attack of the Reagent on the Hydrogen Atom of a CH Bond	244
A. Electrophilic Substitution Hypothesis and Criticism of It.	245
B. Metallation - A Protophilic Substitution Reaction	245
2. Attack of the Reagent on the Carbon Atom of a CH Bond	248
A. General Principles	248
B. Chichibabin's Reaction	249
C. Replacement of Hydrogen in Nitro Compounds	251
D. Replacement of Hydrogen in Hydrocarbons	253
3. Summary	253
Literature Cited	253
Chapter 2. Replacement of Hydrogen by Reaction with an Electrophilic Reagent	255
1. Orientation Rules	255
2. Relation of the Reactivity of a Substance to the "Activity" of the Reagent	257
3. Partial Rate Factors of the Replacement of Hydrogen Atoms in an Aromatic Ring	258
A. Definition	258
B. Relation Between the "Activity" of the Reagent and the "Selectivity" of the Replacement	259
C. Change in the Reactivity of a Substance in Catalysis	262
D. Calculation of the Relative Reactivity of Substances from Partial Rate Factors	263
4. Reason for Selectivity of Replacement	264
5. Role of the Steric Factor in the Replacement of Hydrogen	266
6. Participation of Associative and Ionization Processes in Hydrogen Replacement Reactions	269
7. Summary	273
Literature Cited	273
Chapter 3. Mechanisms of Hydrogen Exchange	275
1. Comparison of Rules of Hydrogen Exchange and Other Replacements of Hydrogen in Aromatic Compounds	275
A. Basic Hydrogen Exchange	275
B. Acid Hydrogen Exchange	279
2. Mechanisms of Hydrogen Exchange	283
A. A. I. Brodskii's Classification	283
B. Associative and Ionization Mechanisms of Hydrogen Exchange. . .	286
3. Summary	290
Literature Cited	291
Conclusion	293

CONTENTS

xi

Appendix: Preparation of Deuterated Organic Compounds	295
1. Introduction	295
2. Methods of Preparing Deuterated Organic Compounds.	296
3. Synthesis of Deuterated Organic Compounds.	297
A. Reduction	297
B. Hydration and Hydrolysis.	298
C. Ammonolysis	299
D. Condensation	300
E. Decarboxylation	300
4. Isotopic Exchange of Hydrogen	300
A. Hydrogen Exchange with Heavy Water and Deuteroalcohol	300
B. Hydrogen Exchange with Deuteriosulfuric Acid	301
C. Hydrogen Exchange with $\text{DCl} + \text{AlCl}_3$	301
D. Hydrogen Exchange with Liquefied Gases	302
5. Comparison of Methods of Preparing Deuterium Compounds	304
Literature Cited	306

SECTION I

TYPES OF REAGENTS AND REACTIONS

In order to be clear on the place of hydrogen isotope exchange reactions among other reactions, it is essential to be familiar with the existing classification of reagents and reactions [1-7].

1. OXIDIZING AND REDUCING AGENTS

When an atom is converted into an ion, it donates or adds one or several electrons. A substance whose atoms act as electron donors is called a reducing agent and one whose atoms act as electron acceptors, an oxidizing agent.

An oxidation-reduction process is represented by equations (1) and (2):

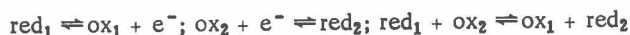


where e^- is an electron.

An oxidation-reduction reaction actually occurs only when an electron donor and an electron acceptor are present at the same time. Summing equations (1) and (2) gives the equation of an oxidation-reduction reaction:



Examples of the reactions are the mutual ionization of sodium and chlorine atoms (4) and the formation of a hydride from atomic sodium and hydrogen (5):



Oxidation-reduction relationships extend to reactions between an atom and an ion (6), between ions (7) and (8), between an atom or an ion and a molecule (9) and (10), and between molecules (11).