THE CHEMISTRY OF HETEROCYCLIC COMPOUNDS

HETEROCYCLIC COMPOUNDS

with

THREE- AND FOUR-MEMBERED RINGS

Part One

Arnold Weissberger, *Editor*

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HETEROCYCLIC COMPOUNDS
WITH THREE- AND FOUR-MEMBERED RINGS

In Two Parts
PART ONE

THE CHEMISTRY OF HETEROCYCLIC COMPOUNDS

A SERIES OF MONOGRAPHS

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The Chemistry of Heterocyclic Compounds

The chemistry of heterocyclic compounds is one of the most complex branches of organic chemistry. It is equally interesting for its theoretical implications, for the diversity of its synthetic procedures, and for the physiological and industrial significance of heterocyclic compounds.

A field of such importance and intrinsic difficulty should be made as readily accessible as possible, and the lack of a modern detailed and comprehensive presentation of heterocyclic chemistry is therefore keenly felt. It is the intention of the present series to fill this gap by expert presentations of the various branches of heterocyclic chemistry. The subdivisions have been designed to cover the field in its entirety by monographs which reflect the importance and the interrelations of the various compounds and accommodate the specific interests of the authors.

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v

Preface

Compounds with three and four ring members play a considerable role in the rapid and still accelerating development of heterocyclic chemistry. There are two closely related aspects of heterocyclic chemistry: the investigation of different derivatives of the respective nuclei, and that chemistry in which the nuclei themselves undergo changes. The latter aspect attains particular importance with the heterocyclic compounds with less than five ring members, some of which belong to the most reactive compounds in organic chemistry. Consequently, these compounds are playing a role of ever increasing importance as intermediates in reactions including polymerizations.

The lack of a comprehensive and reasonably complete presentation of the field was keenly felt, and we hope that the present volume, written by experts in the various branches, will fill a real need.

The three- and four-membered ring compounds have in common the property of bond-angle strain. Dr. Scott Searles, Jr., one of the authors of the present treatise, points out that the high degree of strain in three-membered rings results in many properties of the compounds such as high reactivity in ring cleavage reactions and low electron-donor ability in coordination with electron acceptors. These properties may be associated with different orbital hybridization, for both bonding and non-bonding electrons, in three-membered ring compounds as compared with 'strainless' analogs, as well as with the relief of angle strain in reaction transition states. 'The chemistry of four-membered ring heterocycles is generally quite different from that of their three-membered analogs, as well as of their five- and six-membered ring analogs. Although in many respects the chemical properties of four-membered heterocyclics are intermediate between those of the corresponding three- and five-membered analogs, this situation is by no means always true. For example, the electron-donor ability associated with the four-membered ether ring of oxetanes is definitely greater than that of other ethers, cyclic or non-cyclic. A different combination of geometric, transannular and probably orbital

hybridization factors may lead to somewhat unique results in four-membered ring heterocyclics.'

I want to thank the authors for their efforts which made this volume possible, and the publishers and their staff for their expert and efficient handling of the production of this treatise.

My wife, Dr. Louise Harris Weissberger, took a special part in this volume by translating from the French original the chapters on Thietanes and β-Lactones. I am following Dr. Etienne's request to honor her memory by mentioning her competent and painstaking effort in representing the authors' original thoughts in faultless English. In my life and in my editorial work, she has played an infinitely larger role by encouraging my efforts, by her ability to acquire and to communicate an understanding of complex problems, by her mastery of the English language, by her sincerity and warmth of personality, and by patience, devotion and love.

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Contents

Part One

Part Two

Contents of Part One

CHAPTER I

Ethylene Oxides

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CONTENTS

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1

'. . . This compound exhibits certain of the characteristics of aldehydes and represents the first of a new series of substances possessing with respect to aldehydes proper the most curious isomeric relationships.' It was with these singularly prophetic remarks that the celebrated French chemist Wurtz announced in 1859 the isolation of a new substance isomeric with acetaldehyde, which he called ethylene oxide.[1884] In the 100 years after its discovery, ethylene oxide grew from a mere laboratory curiosity into one of the most widely utilized research and industrial chemicals, and the preparation and investigation of its higher homologs came to constitute a considerable segment of organic chemical literature.[185, 1136, 1717, 1857]

Ethylene oxide itself is the lowest member of a class of substances formally termed 'oxiranes',[864] but more commonly designated 'epoxides' or 'ethylene oxides'. Sometimes encountered also are such variants as 'α-oxides' and '1,2-epoxides', to name but two. In deference to common usage the present chapter will retain the terms

'epoxide' and 'ethylene oxide' to describe any substance incorporating in its structure one or more three-membered rings containing one oxygen and two carbon atoms each.

Epoxides are at present the simplest known oxygen-containing heterocycles. Dioxiranes, three-membered rings containing one carbon and two oxygen atoms, were at one time believed to be among the peroxidic products formed from carbonyl compounds on reaction with oxygen. Reference to such compounds can frequently be encountered in the older literature. It is likely, however, that the dioxiranes in question are in fact dimeric or polymeric peroxides. Walsh has called attention to the improbable nature of the dioxirane molecule on the basis of the molecular-orbital theory.[1798]

Acetylene oxide is likewise unknown at present, although certain of its alkyl derivatives were recently postulated as products of the addition of peroxyacids to the corresponding alkylacetylenes.[1538, 1539] Other investigations have cast doubt on the validity of this postulate.[578] More tangible evidence than is currently available seems necessary before such substances can be included among the three-membered oxygen heterocyclic compounds.

The present chapter will be devoted to the chemistry of epoxides, and will be divided into five principal sections. These will deal respectively with the following topics : I, physical properties ; II, occurrence in nature ; III, synthesis ; IV, chemical reactions ; V, analytical methods.

I. Physical Properties

Ethylene oxides, like other three-membered ring systems, possess many singular features that invite a basis in theory. To satisfy this demand, much effort has been devoted to the task of determining with precision such fundamental properties of the molecule as bond lengths, bond angles, and bond energies. With the advent of modern instrumental methods it has been possible to develop a dependable physical basis for theoretical speculations on the electronic structure of ethylene oxide. The present section is concerned with this aspect of epoxide chemistry.

1. Molecular Geometry

The molecular geometry of ethylene oxide has been studied primarily by means of electron diffraction and microwave spectroscopy, together with classical techniques of dipole-moment measurement.

The dipole moment of ethylene oxide is the result of non-uniform electron distribution in σ-bonds, and is caused by the presence of an

electronegative atom in the ring. In benzene solution ethylene oxide has a dipole moment of approximately 1.8–1.9 debye,[25, 32, 631, 632, 768] and of about 1.9 debye in the gaseous state.[32, 631, 632, 1430, 1664] Substitution of an electron-repelling methyl group, as in propylene oxide, causes a slight elevation in dipole moment to 1.9–2.0 debye.[25,390,768,1481] On the other hand, the electron-attracting vinyl group, as in 1,2-epoxy-3-butene, appears to produce little increase if any.[1481] The dipole moments of cyclopentene oxide and cyclohexene oxide were found by Canals and co-workers to be 1.8 and 1.7 debye respectively, whereas 1-methyl-1,2-epoxycyclohexane gave a value of 1.8 debye.[285]

The group moment for an epoxide function has been taken to be 1.3 debye for calculating the expected dipole moments of 4-bromo-2,3-epoxycyclopentanol and 5-bromo-2,3-epoxycyclopentanol respectively.[982] The dipole moments predicted in this fashion are in accord with experimental values.

Microwave spectroscopy has been an exceedingly useful tool for elucidating the molecular geometry of epoxides.[391, 393, 696, 1578] In addition to confirming the above-mentioned trend of dipole moments
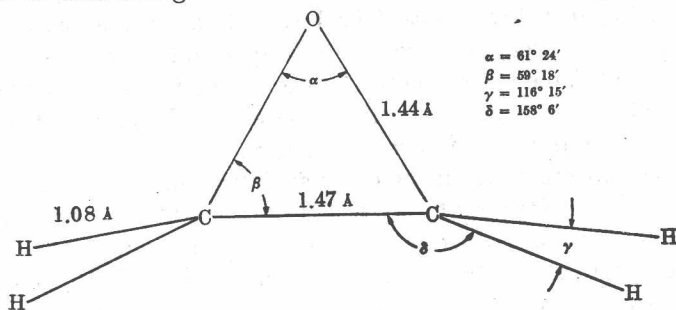
Fig. 1. Detailed structure of ethylene oxide.

for ethylene oxide and propylene oxide, for which values of 1.9 and 2.0 debye respectively were obtained,[392, 1770, 1674] this valuable technique has yielded information concerning bond angles and force constants. Electron-diffraction studies [8, 1836, 850, 851] likewise provide a picture of simple epoxides which is in accordance with other investigations. The results of these various studies are summarized in Fig. 1.

Fig. 1 shows that the plane formed by the carbon and hydrogen atoms is perpendicular to that of the ring. The hydrogens are situated above and below the ring, and the two carbons are raised above the plane formed by the four hydrogens. The C—C bond length is intermediate between that of a normal C—C bond (1.54 Å) and that of a C=C bond (1.33 Å), while the H—C—H bond angle is intermediate

between the tetrahedral (109° 28') and trigonal (120°) configuration. It can thus be imagined that the oxygen atom is somehow 'lifting' the two carbons out of the plane formed by the four hydrogens, the plane in which they would lie if they were genuine olefinic sp^2-hybridized carbons. These geometrical features become more important when theoretical models are considered in a subsequent section.

2. Energetics

Ethylene oxide is a gas at room temperature and atmospheric pressure, its boiling point being only about 10.5°.[1081, 635] Addition of a methyl group, as in propylene oxide, raises the boiling point to 35°, whereas stilbene oxide, because of the combined influences of molecular weight and structural symmetry, is a solid at room temperature. Ethylene oxide is higher-boiling than cyclopropane (b.p. − 32.9°), a fact which is consistent with its more polar character. Similarly, its melting point of − 112.5°[635] is higher than that of cyclopropane (m.p. − 127.5°) for the same reason.
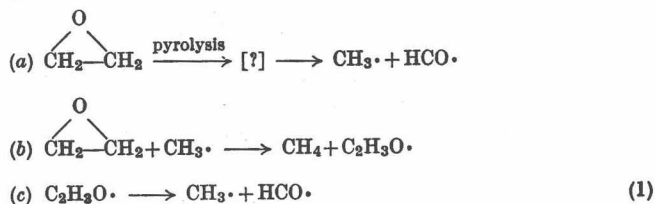
Crog and Hunt[375] found the heat of combustion of ethylene oxide to be 312.55 ± 0.20 kcal./mole. The heats of fusion and vaporization, determined with great precision by Giauque and Gordon,[635] are 1236 and 6101 kcal./mole respectively. An approximate value for the strain energy of ethylene oxide has been computed by Nelson and Jessup.[1229] The experimental heat of formation, derived by combustion calorimetry, was subtracted from the calculated total bond energy, obtained by summation of Pauling C—C, C—H, and C—O bond energies. The difference, 13 kcal./mole was assigned to strain energy. The corresponding values for cyclopropane, ethyleneimine, and ethylene sulfide were estimated to be 25, 14, and 9 kcal./mole respectively.

The enthalpy of ethylene oxide, measured calorimetrically, has been reported[1617] to be 498 kcal./mole. Measurement of the enthalpy of ethylene oxide over a wide range of pressures has been conducted in at least two laboratories,[325, 1166] and entropy calculations have been made from these results. The entropy of ethylene oxide vapor was likewise determined by Giauque and Gordon.[635] Their experimental value of 57.38 cal./degree-mole after a suitable correction for deviation from ideality is not far from the value 57.56 calculated from theory.

The critical temperature above which ethylene oxide gas cannot be liquefied has been listed variously as 192° and 196°.[1081, 1799] The critical pressure is subject to much more disagreement, however, since an early estimate to 49.1 atm.[939] has given way to a later one of 70.9 atm.[1799]

Perhaps of interest at this point are certain studies involving rupture of the ethylene oxide ring by pyrolysis or photolysis.

Thermal decomposition of ethylene oxide is known to yield methyl radicals, together with such products as carbon monoxide, methane, ethylene, and ketene.[1047, 1204, 1205] Lossing, Ingold, and Tickner have studied the course of ethylene oxide pyrolysis at 800–1000°, using mass spectrometry, and found that no CH_2 is formed.[1047] Their finding rendered untenable a previous proposal by Fletcher and Rollefson[549, 550] that this elusive species might be produced. Operating at about 400° Mueller and Walters[1204, 1205] investigated the effect of methyl radicals from dimethylmercury on the product composition, particularly with respect to acetaldehyde and ketene formation. Although suggestions have appeared that ethylene oxide decomposition takes place by way of intermediate species like $\cdot CH_2CH_2O\cdot$ or even $\cdot CH_2OCH_2\cdot$,[1092, 1911] it would seem that further work is required before the details are understood. On the basis of available evidence the most probable course for the pyrolysis of ethylene oxide, as postulated by Mueller and Walters,[1204, 1205] appears to be as shown in Eq. (1).

$$
\begin{aligned}
&(a)\ \overset{\displaystyle O}{\overset{\displaystyle \diagup\!\diagdown}{CH_2\!-\!CH_2}} \xrightarrow{\text{pyrolysis}} [?] \longrightarrow CH_3\cdot + HCO\cdot \\[2ex]
&(b)\ \overset{\displaystyle O}{\overset{\displaystyle \diagup\!\diagdown}{CH_2\!-\!CH_2}} + CH_3\cdot \longrightarrow CH_4 + C_2H_3O\cdot \\[1ex]
&(c)\ C_2H_3O\cdot \longrightarrow CH_3\cdot + HCO\cdot
\end{aligned}
\tag{1}
$$

Ketene could be formed in the above scheme by abstraction of hydrogen from $C_2H_3O\cdot$, whereas acetaldehyde is presumably formed in a separate but still not clarified isomerization step.

Photolysis of ethylene oxide has likewise been studied, both directly[657] and by the mercury-photosensitization technique.[399] In each case the first step is considered to be as shown in Eq. (2).

$$
\overset{\displaystyle O}{\overset{\displaystyle \diagup\!\diagdown}{CH_2\!-\!CH_2}} \xrightarrow{h\nu} CH_3\cdot + HCO\cdot
\tag{2}
$$

The exact order of events leading to these familiar species still remains obscure, however. Cvetanovic has called attention to the similarity between the photolytic decomposition of ethylene oxide and the fate of energy-rich intermediates formed during high-temperature catalytic ethylene oxidation.[400, 401]