146 Topics in Current Chemistry

Physical Organic Chemistry

Physical Organic Chemistry

With Contributions by
G. Boche, G. Kaupp, E. Masimov,
M. Rabinovitz, B. Zaslavsky

With 21 Figures and 27 Tables

Springer-Verlag Berlin Heidelberg NewYork
London Paris Tokyo

This series presents critical reviews of the present position and future trends in modern chemical research. It is addressed to all research and industrial chemists who wish to keep abreast of advances in their subject.

As a rule, contributions are specially commissioned. The editors and publishers will, however, always be pleased to receive suggestions and supplementary information. Papers are accepted for "Topics in Current Chemistry" in English.

ISBN 3-540-18541-0 Springer-Verlag Berlin Heidelberg New York
ISBN 0-387-18541-0 Springer-Verlag New York Heidelberg Berlin

Library of Congress Cataloging-in-Publication Data
Physical organic chemistry.
(Topics in current chemistry; 146)
Includes index.
1. Chemistry, physical organic. I. Boche, Gernot. II. Series.
QD1.F58 vol. 146 540 s 87-28630
[QD476] [547.1'3]
ISBN 0-387-18541-0 (U.S.)

Printed in GDR

Bookbinding: Lüderitz & Bauer, Berlin
2152/3020-543210

Editorial Board

Table of Contents

Rearrangements of "Carbanions"

Gernot Boche

Fachbereich Chemie der Philipps-Universität Marburg, Hans-Meerwein-Straße, D-3550 Marburg, FRG

Table of Contents

Topics in Current Chemistry, Vol. 146

After a brief introduction "carbanion" and "carbanion" radical rearrangements are reviewed with special concern to the literature of the last ten years. Radical "anion" systems are included because of the increasing importance of electron transfer reactions.

The first topic deals with the cyclopropyl-allyl and the intimately related allyl "anion" rearrangement. Next, electron transfer induced rearrangements of cyclopropanes (stereoisomerization and formation of ring-opened derivatives via trimethylene radical "anions") are reviewed. In relation with this subject the question is discussed whether the rearrangement of cyclopropanes in the presence of a base is initiated by proton or electron transfer. Section 3 deals with electron transfer induced rearrangements of the generalized cyclobutene-butadiene radical "anion" system, followed by the cyclization of 5-hexenyl "anions". Because of the widespread use of 5-hexenyl radical cyclizations as a mechanistic tool it is important to separate the radical from the "anion" rearrangement. Section 5 deals with the isomerization of α-substituted vinyllithium compounds. Section 6 describes how the structure of a "carbanion" is strongly influenced by a variation of the gegenion, the solvent, complexing agents and the temperature. Electron transfer valence isomerizations are treated next. The complexity of "carbanion" structures in solution, as shown in sections 6 and 7, is also observed in the solid state as demonstrated by the polymorphism of organolithium compounds. Section 9 is devoted to some results concerning rearrangements of and within alkyllithium aggregates, and the final topic refers to "carbanion"-accelerated rearrangements.

1 Introduction

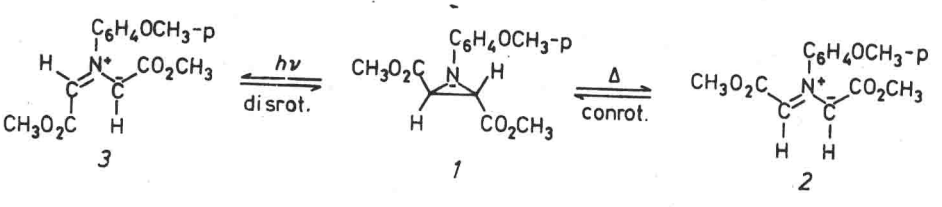
The literature on rearrangements of "carbanions" published up to 1979 has already been reviewed [1-8]. Sigmatropic rearrangements and other migrations of saturated groups (hydrogen, alkyl groups, hetero-atoms), unsaturated carbon (olefins, acetylenes, aromatic compounds) and doubly bonded oxygen species (homoenolization, Favorskii rearrangement, Ramberg-Bäcklund reaction) are treated especially in the articles of Grovenstein [6] and Hunter, Stothers and Warnhoff [8]. Electrocyclic reactions have been extensively reviewed by Staley [5], Buncel [3] and Hunter [4].

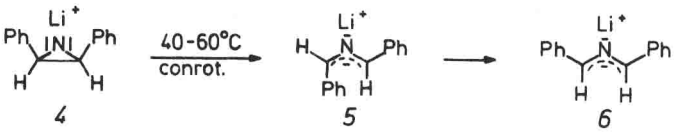
Most of the literature on rearrangements of "carbanions" reviewed in this article has been published since 1979. Since "carbanions" normally neither exist in solution (nor in the solid state), and since the gegenion, the solvent and chelating agents strongly influence the structure and the reactivity of a certain (alkali or alkali earth) organometallic compound, we stress those influences whenever there is information in the literature. Furthermore, since it has been possible in recent years to characterize different aggregates of organolithium species, their *intra-* and *inter-*"molecular" rearrangements and their different reactivities we included these results into this article, too. Thus, we would like to emphasize the importance of non-skeletal rearrangements of "carbanions". Similarly, we have summarized rearrangements of radical "anions" induced by electron transfer reactions because of the increasing importance of this type of reaction lately.

2 Rearrangements Involving Three-Membered Rings

2.1 Cyclopropyl-Allyl-"Anion" Rearrangements

It was only after Woodward and Hoffmann had predicted a conrotatory mode for the thermal cyclopropyl-allyl anion transformation in 1965 [9] that new interest developed in this reaction [10]. But it was first shown by Huisgen and coworkers [11] by means of the iso-π-electronic uncharged aziridine *1* which gives the azomethine ylids *2* and *3*, respectively, that the stereochemistry of the thermal and the photochemical reactions agrees with the prediction.





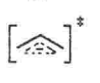
Kauffmann and coworkers [12] studied another hetero-analogous but in this case an "anionic" system, N-lithio-cis-2,3-diphenylaziridine (*4*). *4* transforms thermally into *endo,exo*-1,3-diphenyl-2-azallyllithium (*5*).

The rearrangement of *5* to *6* competes successfully with the trapping of *5* with *trans*-stilbene which established the stereochemistry of *5*. The stereochemistry of *2* and *3* has similarly been determined by 1,3-dipolar cycloaddition reactions.

Why is it that the predicted modes of rearrangement were first confirmed by means of these two systems and not with a "real" cyclopropyl-allyl "anion" system? The long history of the cyclopropyl-allyl "anion" rearrangement shows that this is because of several problems [10b]. The first of these, which is also indicated from the results with *1* and *4*, and which is confirmed by MO calculations, is the *slow* thermal conrotation of a cyclopropyl "anion" to give the corresponding allyl "anion", as compared to the *fast* isomerization of the allyl "anion" to give the most stable isomer.

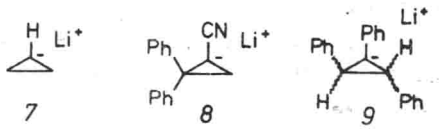
Table 1 gives the results of several MO calculations for the conrotatory ring-opening of the cyclopropyl anion to give the allyl anion, and of the isomerization of the allyl anion [13].

Table 1. Relative energies ($\Delta\Delta H_f$, kcal/mol) with respect to the cyclopropyl anion of the transition state of the conrotatory cyclopropyl-allyl anion rearrangement A, the allyl anion B, and the transition state of the allyl anion isomerization C.

	A 	B 	C 
MINDO/3	31.2	−9.8	—
STO-3G	66.7	−9.7	25.3
4-31G	38.0	−40.0	27.6

It is evident from Table 1 that the "activation energy" for the allyl anion isomerization is much lower than for the conrotation of the cyclopropyl anion to give the allyl anion. Consequently, in order to verify the predicted conrotatory mode one has to trap the first formed allyl "anion" before it isomerizes to give the thermodynamically most stable isomer, e.g., in a cycloaddition reaction. Exactly this was possible with *2*, *3* and *5*. So far, however, a similarly fast reaction has not been found for allyl "anions" [13].

The second problem is concerned with the question of which organometallic compounds behave like cyclopropyl "anions" and undergo such a ring-opening reaction. Interestingly, *no* ring-opening reaction has been observed, e.g., with cyclopropyllithium *7* [14] and 1-cyano-2,2-diphenylcyclopropyllithium *8* [15]. On the other hand, 1,2,3-triphenylcyclopropane reacts with n-butyllithium/tetramethylethylene diamine (TMEDA) to give a mixture of isomers of 1,2,3-triphenylallyllithium which indicates that the intermediately formed 1,2,3-triphenylcyclopropyllithium *9* is able to undergo a ring-opening reaction [16].

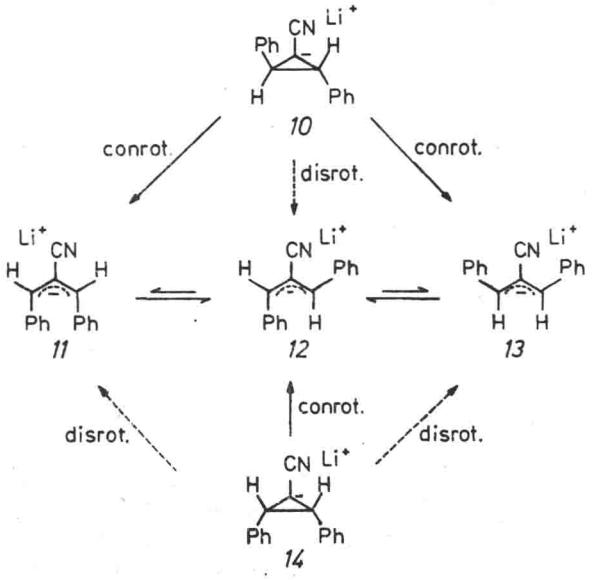


7 8 9

If one compares *7*, *8* and *9* (and many more cyclopropyl "anions") [10b] it turns out that electron acceptor substituents at ***both*** carbon atoms, which become terminal centers of the allyl "anion", facilitate the ring scission. In addition it is necessary that the negative charge of the cyclopropyl "anion" is stabilized by electron withdrawing (!) groups; hydrogen or alkyl groups at C-1 render the ring-opening reaction more difficult or impossible. This, of course, is quite the opposite to what one would expect if a real cyclopropyl *anion* were the ring-opening species. Thus, *ion pair effects* play an essential role in the rearrangement of cyclopropyl "anions".

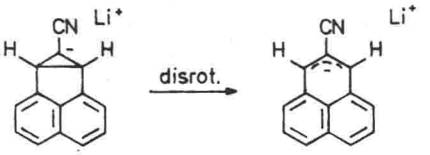
In spite of these difficulties a kinetical criterium has been elaborated for the thermal conrotation of a cyclopropyl "anion". The result of this study has recently been confirmed by a special cyclopropyl-allyl "anion" rearrangement allowing trapping reactions of the allyl "anion".

In their kinetic studies, Boche and coworkers [13,17] first examined the rates of the ring-opening reactions of the isomeric 1-cyano-2,3-diphenylallyllithium compounds *10* and *14*, and of the isomerization reactions of the 1,3-diphenyl-2-cyano-allyllithium species (*11* ⇌ *12* ⇌ *13*).



It was shown that the ring-opening reaction e.g. of *10* to give *13* (and/or *11* which is not clear from the available data) is about 1500 times *slower* than the isomerization of the allyl "anion" *13* (and/or *11*) to give the more stable *12*. A similar situation occurs when one starts from the cyclopropyl "anion" *14* [18]. These experimental data thus nicely confirm the results of the theoretical calculations discussed in connection with Table 1.

The rates of the ring-opening reactions of the cyclopropyl "anions" *10* and *14* have also been compared with the rate of the "forbidden" disrotatory ring-opening reaction of the structurally related cyclopropyl "anion" *15* (to give *16*) which was introduced by Wittig and coworkers [19, 13].



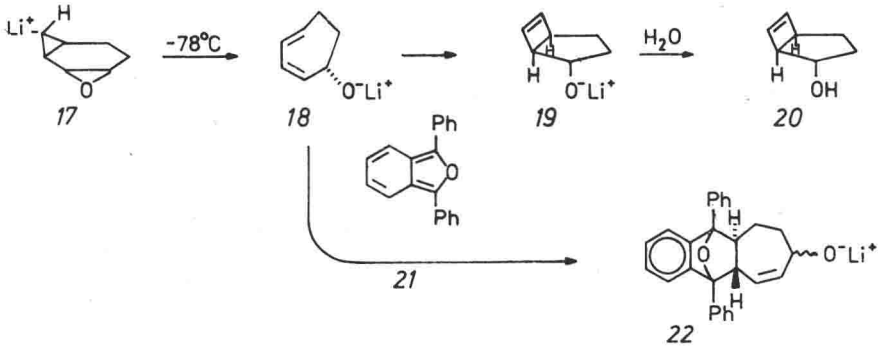
15 *16*

At 20 °C the following ratios of rate constants are measured:

$$\frac{k_{10}}{k_{15}} = 5500\ ; \qquad \frac{k_{14}}{k_{15}} = 740$$

These data demonstrate that the "forbidden" disrotatory ring opening of *15* is much slower than the ring-opening reactions of the cyclopropyl "anions" *10* and *14* which are not prevented from occurring in the predicted conrotatory mode. This kinetical criterium for the thermal conrotatory cyclopropylallyl "anion" transformation has been published independently by Ford and coworkers [20].

Similarly, a thermal conrotation has been observed in the case of the tricyclic cyclopropyllithium species *17* [21].



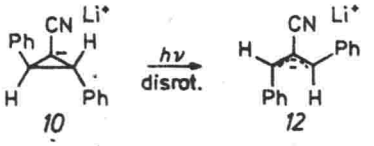
17 *18* *19* *20* *21* *22*

The conrotatory mode of ring opening of the β-lithiocyclopropyloxirane *17* is suggested first by the isolation of the *cis*-fused cyclobutene *20*; conclusive evidence for the intermediate *18* (the precursor of *19* and *20*) is provided by trapping the diene *18* in a Diels-Alder reaction with *21* to give the *trans*-fused adduct *22*.

The ring opening of *17* is in strong contrast to the normally unreactive cyclopropyllithium compounds with hydrogen at C-1 and alkyl substituents at C-2 and C-3 as mentioned earlier. Therefore, in this rather special cyclopropyl "anion", electrocyclic transformation combined with a Grob-type fragmentation the ring-opening reactions of *both* three-membered rings must be *concerned*. Furthermore the reaction should profit from the formation of a lithium-oxygen bond in *18*.

It is thus unambigously proven that the thermal cyclopropylallyl "anion" rearrangement follows the predicted conrotatory mode.

Photochemical cyclopropyl-allyl "anion" transformations have been observed by Newcomb and Ford [20c] and by Fox [22]; for example, the photochemical disrotation of *10* to give *12*.

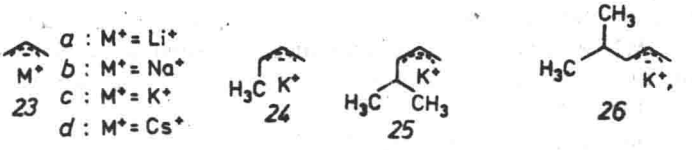


10 *12*

It is not clear, however, whether a photochemical "anion" or a thermal cyclopropyl radical ring-opening — the latter caused by photochemical electron ejection — took place.

2.2 Allyl-"Anion" Isomerizations

Thompson and Ford determined the rotational barriers of allyllithium *23a*, allylpotassium *23c*, allylcesium *23d*, (Z)-1-methylallylpotassium *24*, (Z)-1-isopropylallylpotassium *25* and (E)-1-isopropylallylpotassium *26* [23].



The results of their NMR lineshape measurements are summarized together with those of allylsodium *23b* [24] in Table 2.

Table 2. Exchange barriers of the allyl "anions" *23–26* in THF-D_8 [23]; a: Ref. 24 ($\Delta H^{\neq}$ value)

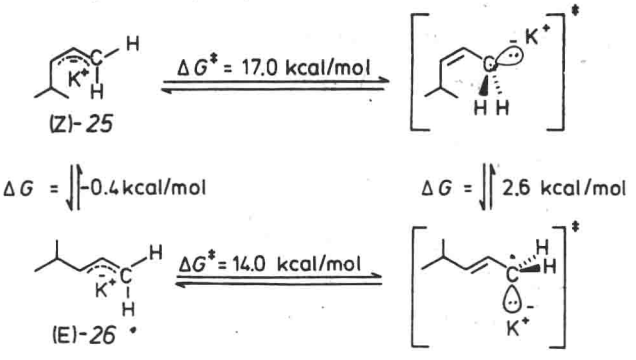
	$\Delta G_T^{\neq}$ [kcal/mol]	T [°C]
allyllithium *23a*	10.7 ± 0.2	−51
allylsodium *23b*	11.5	—[a]
allylpotassium *23c*	16.7 ± 0.2	68
allylcesium *23d*	18.0 ± 0.3	68
(Z)-1-methylallylpotassium *24*		
C_1–C_2	18–22	
C_2–C_3	17.0 ± 0.3	68
(Z)-1-isopropylallylpotassium *25*		
C_1–C_2	>19.3	68
C_2–C_3	17.0 ± 0.3	47
(E)-1-isopropylallylpotassium *26*		
C_2–C_3	<14.0	28

The result with allyllithium *23a* differs only insignificantly from that of an earlier report (10.5 kcal/mol) [25]. Complexation of *23a* with TMEDA does not influence the rate of exchange. Hexamethylphosphoric triamide (HMPT), 15-crown-5 ether and [2.1.1]cryptand in tetrahydrofuran (THF) led to rapid decomposition of *23a*. Addition of n-butyllithium had essentially no effect on the barrier. Since the ^{13}C NMR chemical shifts of *23a* are independent of the solvent, it is assumed that *23a* exists as a contact ion pair or higher aggregate in the NMR experiments. (The other alkali metals should also form contact ion pairs with the allyl anion because of their well-known tendency to form contact ion pairs even more readily than the lithium cation [26]).

Concerning the aggregation, it has been reported that allyllithium *23a* in *THF* is predominantly monomeric possibly with some dimers [27]. Since *23a*, on the other hand, is highly aggregated in *diethyl ether* [25, 28], but the barriers are the same in both solvents [25], it is believed [23] that the state of aggregation of allyllithium *23a* does not affect its rotational barrier.

The earlier determinations of the aggregation state and the discussions of its influence on the rotational barrier have recently been questioned [29]. Cryoscopic measurements show conclusively that allyl*lithium* is a *dimer* in THF at −108 °C. Furthermore, the *ab initio* rotational barrier computed for isolated allyl*sodium 23b* (11.5 kcal/mol) [30] is the same as the experimentally observed value (11.5 kcal/mol) [24] though the latter value must refer to a *solvated* species. It is hence concluded that the discrepancy between the *ab initio* calculated barrier for isolated allyl*lithium* (17.7 kcal/mol) and the experimental value in THF solution (10.7 kcal/mol, see Table 2) is due to *dimerization*. MNDO calculations indeed indicate an asymmetric dimer structure of allyl*lithium*. The asymmetric structure is consistent both with earlier [32] and more recent [29] NMR results.

The rotational barriers of allylpotassium *23c* (16.7 kcal/mol) and allylcesium *23d* (18.0 kcal/mol) are much higher than those of *23a* and *23b*. This observation and the question of whether aggregates are involved in the rotational process, clearly emphasize once more the important influence of the gegenion in "carbanion" reactions. The experimental results with *23a–d* thus lead only to a lower limit (18.0 kcal/mol) for the rotational barrier of the allyl *anion* in solution. Incidently, this value comes close to the lowest calculated (MP2/4-31 + G//4-31 + G) value of the allyl *anion* rotational barrier (22.2 kcal/mol) [33].

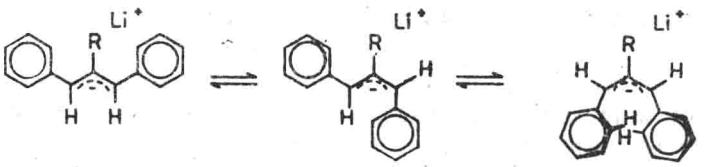


Scheme 1

In the case of the *alkyl*-substituted allylpotassium compounds *24*, *25* and *26* the anticipated effects of a C-1 alkyl group are to increase electron density at C-3 of the allyl "anion", to increase the C-1–C-2 bond order, and to decrease the C-2–C-3 bond order. Exactly this is found in the NMR experiments (Table 2). Interestingly, the rotational barrier of the CH_2-group in (Z)-*25* is higher than in (E)-*26*. This is not due to lowering of the ground-state energy of (Z)-*25* relative to (E)-*26* because the isomer ratio (Z)-*25*:(E)-*26* = 65:35 accounts for an energy difference of only 0.4 kcal/mol. The difference of 3.0 kcal/mol in the free enthalpies of activation consequently means that the (Z)-*25* transition state is 2.6 kcal/mol *less* stable than the (E)-*26* transition state (Scheme 1).

It has been proposed [23] that the CH_2 group of the isomer (Z)-*25* rotates in such a way that the cation migrates through the *anti*-face of the allyl plane, away from the isopropyl group (Scheme 1). On the other hand, the (E)-1-isopropyl substituent in (E)-*26* permits the *syn*-location of the cation in the transition state (Scheme 1). Calculations show a significant preference for *syn*-transition states in such rearrangements [30].

Rotational barriers and conformational equilibria of 1,3-diphenylallyl lithium and a series of 2-substituted 1,3-diphenylallyl lithium compounds have been determined by Boche and coworkers [18]. Table 3 summarizes the amounts of *endo,endo*-, *endo,exo*- and *exo,exo*-conformers *27* and the free energies of activation of their mutual transformations.



exo,exo-*27* *endo,exo*-*27* *endo,endo*-*27*

The different equilibria essentially result from the steric interactions of the phenyl group(s) and the substituent R in the *endo,exo*- and *exo,exo*-conformations, and the two phenyl groups in the *endo,endo*-conformation. The *endo,endo*-conformer is favored as the ν-value [35] of R increases. Thus, the decrease of the $\Delta G^{\neq}$ values on going

Table 3. *Exo,exo*-, *endo,exo*- and *endo,endo*-conformers (%) and free energies of activation ($\Delta G^{\neq}_{273\,°C}$ [kcal/mol]) for rearrangements in THF starting from the *endo,exo*-isomers of the 2-substituted 1,3-diphenylallyl lithium compounds *27a–g* [18]

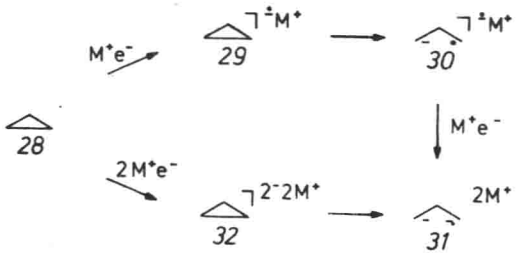
27	R	*exo, exo*-*27*	$\overset{\Delta G^{\neq}}{\longleftarrow}$	*endo, exo*-*27*	$\overset{\Delta G^{\neq}}{\longrightarrow}$	*endo, endo*-*27*
a	H	92	$\overset{17.8}{\longleftarrow}$	8		–
b	CH_3	8	$\overset{14.2}{\longleftarrow}$	92		–
c	CN	4.5	$\overset{16.4}{\longleftarrow}$	91	$\overset{16.4}{\longrightarrow}$	4.5
d	C_2H_5	15	$\overset{13.8}{\longleftarrow}$	68	$\overset{13.8}{\longrightarrow}$	17
e	C_6H_5	–		56	$\overset{14.3}{\longrightarrow}$	44
f	$CH(CH_3)_2$	–		38	$\overset{12.5}{\longrightarrow}$	62
g	$C(CH_3)_3$	–		–		100

from *27a* to *27f* should clearly result from an increasing destabilization of the ground states. Transition-state effects, if at all, should play a minor role.

Ion-pair effects, as in the case of the unsubstituted allyl alkali metal compounds *23a–d*, do not markedly influence the rotational barriers of the 1,3-diphenylallyllithium species *27a–f*, although the reason is different: *27a–f* are solvent-separated ion pairs [36]. Addition of HMPT to the THF solution of *27a* raises the $\Delta G^{\ddagger}_{38\,°C}$ value by 0.9 kcal/mol which corresponds to a rate retardation of 5–6 times. In the case of the methyl-substituted allyl "anion" *27b* HMPT slows down the rate by a factor of only 2–3. With the 2-cyano "anion" *27c* the $\Delta G^{\ddagger}$ values of the Li^+ compound in THF and the Li^+, Na^+ and K^+ species in dimethyl sulfoxide (DMSO) are the same [18]. In the case of *27e* and *27f* the rate of the rearrangement is not affected if HMPT or TMEDA are added to the THF solutions. The observations of some solvent dependence in the case of the sterically less hindered *27a* and *b*, but of no effect with the more crowded *27e* and *f*, are in line with the general observation that solvent-separated ion pairs are favored with respect to contact ions pairs by increasing steric hindrance [25]. Hence, these experimental results could be interpreted to mean that in the case of *27a* and *b* contact ion pairs participate in the allyl "anion" rearrangement reaction.

2.3 Electron Transfer Induced Rearrangements of Cyclopropanes and Consecutive Reactions [37]

Electron transfer to cyclopropane *28* should lead to the cyclopropane radical "anion" *29*, which, in principle, can rearrange to give the ring-opened trimethylene radical "anion" *30*. Further reduction of the trimethylene radical "anion" should give a 1,3-"dianion" (*31*). A less likely pathway to give *31* is conceivable via the cyclopropane "dianion" *32* (Scheme 2).

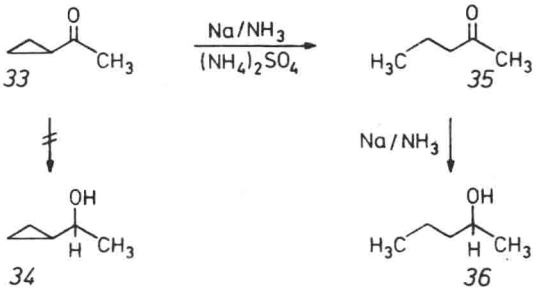


Scheme 2

The preparation of *29* was reported in 1963 [38]. Three years later, however, these results were shown to be false [39,40]. Cyclopropanes with *electrophoric* substituents (e.g. π-electron systems like carbonyl or aromatic groups), on the other hand, easily accept electrons. In many cases this leads to skeletal rearrangements and further reactions.

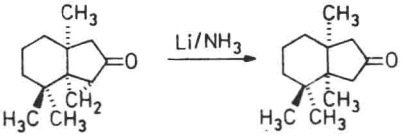
2.3.1 Cyclopropanes Substituted with Carbonyl Groups

The first report on what turned out to be a reduction of a carbonyl substituted cyclopropane was published in 1949 [41]. Reaction of methyl cyclopropyl ketone *33* with sodium in liquid ammonia in the presence of ammonium sulfate yielded instead of the expected methyl cyclopropylcarbinol *34* a mixture of 2-pentanone *35* and 2-pentanol *36*.



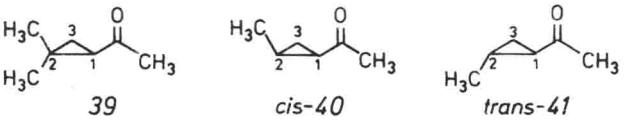
33 *35* *34* *36*

From an investigation of several conjugated cyclopropyl ketones, as e.g. *37*, Norin discovered [42] that the steric course of the reaction depends on the configuration of the cyclopropyl ketone in such a way that the cyclopropyl bond which is cleaved is the one possessing maximum overlap of the Walsh orbitals with the π-orbitals of the carbonyl group. *37* thus leads to *38*.



37 *38*

By means of the cyclopropyl ketones *39*, *cis-40* and *trans-41*, in which the two bonds of the cyclopropane ring, C-1–C-2 and C-1–C-3, are free to overlap with the carbonyl π-system, Dauben evaluated the importance of stereoelectronic versus steric factors [43].

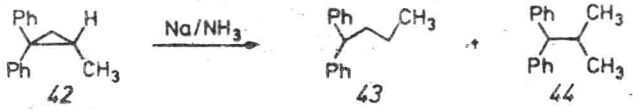


39 *cis-40* *trans-41*

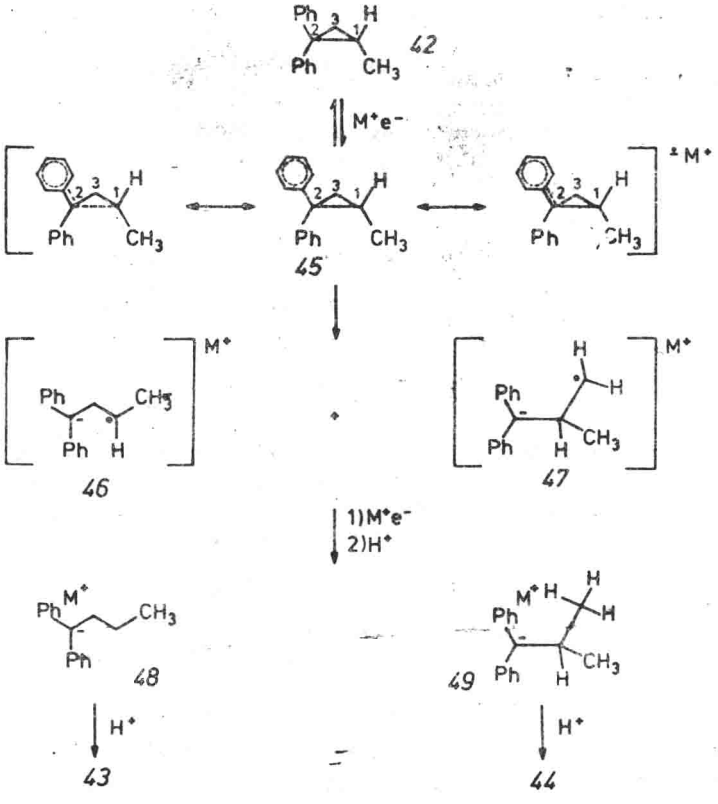
The main products in the reaction mixtures of the 2,2-dimethylcyclopropyl ketone *39* and the *cis*-2-methylcyclopropyl ketone *cis-40*, respectively, result from C-1–C-2 bond breaking. In contrast, the *trans*-2-methylcyclopropyl ketone *trans-41* breaks the C-1–C-3 bond. This strongly suggests that steric factors control the direction of cleavage, presumably through asymmetric overlap of the carbonyl π-system with one of the cyclopropane bonds [43]. In the absence of these steric effects, as in *trans-41*, the bond that cleaves is the one to give the more thermodynamically stable (= less substituted) "carbanion" intermediate.

2.3.2 Cyclopropanes Substituted with Phenyl(Aryl) Groups

The reduction of 1-methyl-2,2-diphenylcyclopropane *42* and one of its enantiomers, (+)-(R)-*42*, with Na/NH_3 to give 1,1-diphenylbutane *43* and 1,1-diphenyl-2-methylpropane *44* in a ~5.5:1 ratio over a wide concentration range has been studied by Walborsky and Pierce [46].



From the well-known ability of the phenyl group to accept electrons from sodium in NH_3 [47] the following mechanism (Scheme 3) [46] was proposed for the opening of the cyclopropane ring in *42* (and other phenyl(aryl)-substituted cyclopropanes).



Scheme 3

The role of the phenyl groups (and similarly of the carbonyl groups in *33*, *37*, *39*, *cis-40* and *trans-41*) is to accept an electron to give the short-lived radical "anion" *45*. ESR experiments have so far failed to demonstrate the existence of *45* [48], and of the