J. Serb. Chem. Soc. 70 (3) 287–318 (2005)
JSCS–3273

UDC 546.26.027*14:542.9
Review paper

REVIEW

Reactions of carbon radicals generated by 1,5-transposition of reactive centers

ŽIVORAD ČEKOVIĆ[#]

Faculty of Chemistry, Studentski trg 16, P.O. Box 158, 11000 Belgrade, Serbia and Montenegro

(Received 6 November 2004)

Abstract: Radical intermediates can undergo specific reactions, such as intramolecular rearrangements, *i.e.*, the transpositions of radical centers, which are not known in classical ionic organic reactions. 1,5-Transposition of a radical center to a non-activated carbon atom are of great synthetic importance. It can be successfully applied for the introduction of different functional groups (oxygen, nitrogen, sulfur, halogens) onto a carbon atom remote from the present functional group. In addition to functionalization of a remote non-activated carbon atom, the formation of new C–C bonds on the δ-carbon atom have also been achieved. 1,5-Transposition of the radical centers takes place from alkoxyl, aminyl and carbon radicals to a remote carbon atom. Relocation of the radical centers preferentially involves 1,5-transfer of a hydrogen atom, although migrations of some other groups are known. The reactions of the carbon radical generated by 1,5-relocation of the radical center are presented and their synthetic applications are reviewed.

Keywords: radical reactions, 1,5-transposition of radicals, hydrogen transfer, groups migration, intramolecular functionalization, C_δ–C bond formation.

CONTENTS

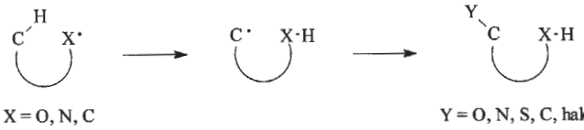
1. Introduction
2. 1,5-Transposition of a radical center by hydrogen atom abstraction. General remarks.
3. Radical transpositions from an oxygen to a carbon atom involving a 1,5-hydrogen transfer
   3.1. Formation of alkoxyl radicals
   3.2. Lead tetraacetate oxidation of alcohols
   3.3. Reactions of alkyl hypohalites
      3.3.1. Alkyl hypoiodites
      3.3.2. Alkyl hypobromites
      3.3.3. Alkyl hypochlorites
   3.4. Photolysis of alkyl nitrites
   3.5. Photolysis of alkyl benzene(arene)sulfenates
   3.6. Reductive decomposition of alkyl hydroperoxides
   3.7. Epoxides as precursors of alkoxyl radicals
   3.8. Other precursors of alkoxyl radicals

Serbian Chemical Society active member

4. Radical transpositions from a nitrogen to a carbon atom involving a 1,5-hydrogen transfer
4.1. Protonated aminyl radicals (Hofmann-Löffler-Freytag reaction)
4.2. Unprotonated nitrogen centered radicals
5. Radical transpositions from a carbon to a carbon atom involving a 1,5-hydrogen transfer
5.1. 1,5-Transposition of vinyl to alkyl radicals
5.2. Transposition of aryl to alkyl radicals
5.3. Transposition of alkyl to other alkyl radicals
6. Radical transpositions involving an intramolecular 1,4(5)-group transfer
6.1. 1,4-Transposition of the cyano group
6.2. 1,4-Transposition of aryl groups
6.3. Transposition of silyl groups
7. Closing remarks

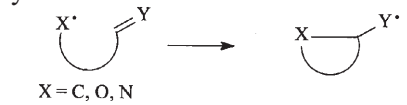
1. INTRODUCTION

In organic synthesis, radical reactions represent a very valuable tool for the introduction of functional groups onto non-activated carbon atoms[1a–d] and the formation of carbon–carbon bonds.[2] The advantages of radical reactions over ionic processes are milder reaction conditions and tolerance of many functional groups in the substrates. An additional aspect contributing to the development of synthetic radical reactions is the possibility of carrying out rearrangements, *i.e.*, *transpositions*, of radical center that are specific and have no classical counterpart in ionic reactions. The term "*radical transpositions"* is applied either to the intramolecular abstraction of a hydrogen atom or the rearrangement of a group (phenyl, silyl, cyano) by alkoxyl, aminyl and carbon radicals resulting in a repositioning of the site of the unpaired electron, *i.e.*, radical center. 1,5-Transposition of a radical center involving hydrogen abstraction from a δ-C–H group by radical species is particularly attractive for the functionalization or alkylation of such a position, which is considered as unreactive in classical ionic reactions (Eq.(1)).[3]

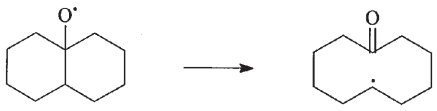


(1)

In addition to this type of radical transpositions, other reactions such as intramolecular additions of carbon[2b,4a] or hetero radical[4b] onto unsaturated bonds (Eq. (2)), and fragmentations of cycloalkoxyl (Eq. (3)), oxyranylcarbinyl and cyclopropylcarbinyl radicals,[5] also proceed with the transposition of radical centers in the same molecule, but they will not be described in this review.



(2)



(3)

2. 1,5-TRANSPOSITION OF A RADICAL CENTER BY HYDROGEN ATOM ABSTRACTION. GENERAL REMARKS

All of the reactions involving a 1,5-repositioning of a radical site proceed through a common step of intramolecular transfer of a hydrogen atom, resulting in the formation of relatively strong bonds (*e.g.*, OH, NH, ArH), compared to those which were broken (*e.g.*, non-activated C–H), as well as the generation of a new more stable radical center on the δ-carbon atom.[1a,b]

Independent of whether an initial oxygen, nitrogen or carbon centered radical is involved, 1,5-hydrogen atom (or group) transfer is the most common reaction (Scheme 1), although abstraction from an other position (1,4-, 1,6- or 1,7-migration) can be exploited when 1,5-hydrogen transfer is precluded by the lack of an abstractable hydrogen atom (or group) or by steric inaccessibility.

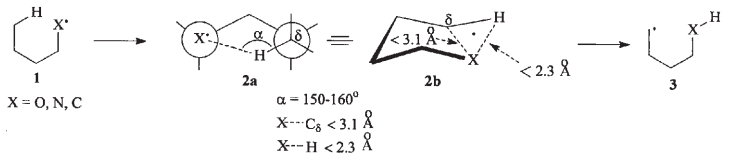
Two groups of factors control the intramolecular hydrogen transfer to the initial oxygen, nitrogen and carbon radicals: *i*) energy factors, which are related to energy values such as bond dissociation energy and enthalpy of reaction and *ii*) structural factors, which depend on steric, conformational and polar effects.

Enthalpy control is the most important, because the bond dissociation energy of RO–H is considerably higher than those of most C–H bonds and therefore hydrogen transfer to an alkoxy radical is an exothermic reaction ($\Delta H = -12.3$ kJ/mol for the formation of a primary carbon radical, –21 kJ/mol for a secondary and –37 kJ/mol for a tertiary carbon radical). The formation of a more stable carbon radical requires a smaller enthalpy of activation (ΔH^*).

In intramolecular 1,5-hydrogen abstraction by alkoxyl radicals, entropy factors dominate and the rate constant is 2.7×10^7 dm^3 mol^{-1} s^{-1},[6] whilst the rate constant for intermolecular hydrogen abstraction is about $10^5 - 10^7$ dm^3 mol^{-1} s^{-1}.[7] It was found that the rate constants for intramolecular 1,5-hydrogen transfer by aryl radicals (>5×10^8 dm^3 mol^{-1} s^{-1}) are remarkably higher than for intermolecular hydrogen transfer (about 10^5 dm^3 mol^{-1} s^{-1}).[8]

1,5-Transposition of the radical center from the oxygen, nitrogen or carbon atoms **1** to the δ-carbon atom **3** involves 1,5-hydrogen transfer, passing through a chair-like six-membered cyclic transition state (Scheme 1).[9] The six-membered transition state (**2a** and **2b**) resembles a flattened chair arrangement with a coplanar radical center, the δ-carbon atom and the two carbon atoms adjacent to it. In the optimal conformation of the transition state, the migrating hydrogen atom is slightly out of plane with the $C_\delta \cdots H \cdots X^\bullet$ angle being greater than 153°. All other geometries of the transition states are higher in energy. The entropy factor and proximity effects favour the intramolecular 1,5-hydrogen rearrangement. 1,5-Hydrogen transfer is mostly favoured when both reactive centers (the radicalic center and the proactivated carbon atom) possess a fixed stereochemistry resembling a quasi-six-membered cyclic transition state.[10]

An intramolecular hydrogen abstraction also occurs in the cases when one or both reactive centers are flexible and constitutionally remote non-activated carbon atoms

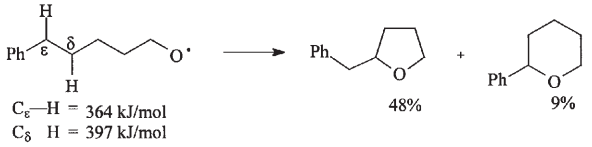


Scheme 1.

must be conformationally suitably oriented with respect to the attacking radicalic center in the transition state controlling this process. Such an orientation is attained with minimal interactions and distortions when the intramolecular distance between the attacking radicalic center and the proactivated δ-carbon atom reaches the optimal distance 2.5 – 2.7 Å, indicating that the recognition of a particular hydrogen atom to be abstracted, in a molecule possessing another energetically similar non-activated carbon–hydrogen bond is mainly controlled by stereochemical factors.[1,9]

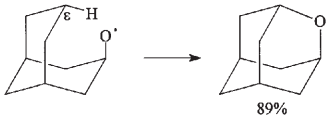
The predominance of intramolecular 1,5-hydrogen transfer over 1,6-hydrogen rearrangement comes mainly from entropy control. The ratio of the rate constants for 1,5-/1,6-hydrogen transfer is 10 : 1. 1,6-Hydrogen migrations, involving a seven-membered cyclic transition state, were observed as a side reaction, but this may be the main reaction only when favourable conformational factors exist or when there are no hydrogen atoms at the δ-carbon atom.[9,10]

1,6-Hydrogen atom abstractions in open chain molecules, involving a quasi-seven-membered cyclic transition state, is not, however, favourable because angle strain and non-bonding interactions require more activation energy, even when the ε-hydrogen atoms are energetically activated by benzylic or allylic interactions (Eq. (4)).[11]



(4)

On the other hand, in rigid bicyclic or polycyclic systems in which, due to structural and stereochemical factors, the ε-carbon atom and oxygen radical assume the optimal distance of 2.5 – 2.7 Å, 1,6-hydrogen transfer is the favoured reaction (Eq. (5)).[12]



(5)

1,4-Hydrogen migration, involving a five membered cyclic transition state, is rare and was only theoretically considered.

Intramolecular 1,5-hydrogen transfer resulting in the 1,5-transposition of a radical center is an efficient method for the introduction of a variety of functional groups and forming new carbon–carbon bonds on the δ-carbon atom. As a result of these possibilities, radical reactions on the unreactive carbon atom have become a

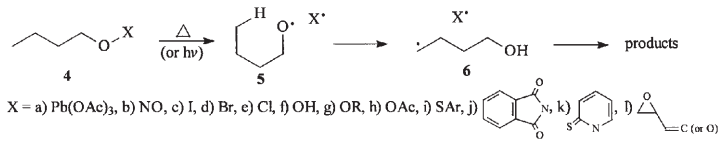
very valuable tool in organic synthesis. In this review, intramolecular 1,5-hydrogen abstraction from the C_δ–H bond by alkoxyl, aminyl and carbon (vinyl, aryl and alkyl) radicals and the formation of δ-carbon radicals will be considered. The synthetic potential of these reactons, the reactivity of the translocated carbon radicals and the dependence of the reaction products on the precursors of the initial radical, reagents and reaction conditions are reviewed.

3. RADICAL TRANSPOSITIONS FROM AN OXYGEN TO CARBON ATOM INVOLVING A 1,5-HYDROGEN TRANSFER

Alkoxyl radicals undergo a variety of reactions but, from the synthetic point of view, intramolecular 1,5-hydrogen transfer from a non-activated C–H bond is the most important reaction. The diversity of this type of reactions offers several possibilities for the introduction of different oxygen, nitrogen, halogen, and sulfur functional groups (Eq. (1)), as well as an olefinic bond onto non-activated carbon atoms.[1,3] The formation of carbon–carbon bonds on non-activated δ-carbon atoms have also been discovered, but they have not been realized in polar reactions.

3.1. Formation of alkoxyl radicals

Various classes of oxygen-containing compounds can be used as appropriate precursors of alkoxyl radicals undergoing a 1,5-hydrogen rearrangement and a variety of reagents and reaction conditions can be applied.[1] Transposition of a radical center can only take place at alkoxyl radicals possessing at least one hydrogen on conformationally close carbon atoms at the δ-position. The formation of an alkoxyl radical involves the homolysis of a weak oxygen–hetero atom bond in **4** (RO–X, < 292 kJ/mol) (Scheme 2). The alkoxyl radical **5** cannot be directly generated from alcohols by homolysis of an O–H bond (435 kJ/mol). Numerous reagents are, however, available for the conversion of alcohols to suitable precursors **4** of alkoxyl radical intermediates.[1,3]



Scheme 2.

Alcohols are formally used as substrates for the oxidative formation of reactive intermediates **4** *in situ* which undergo thermally or photolytically induced homolytic cleavage of the O–X bond. Thus, in the lead tetraacetate (LTA) oxidation of alcohols in non-polar solvents,[3b,d] in alkoxyl radical precursor **4a** X is $Pb(OAc)_3$, in hypoiodite reaction (LTA + I_2 or $PhI(OAc)_2$ + I_2)[3a] X is iodine (RO–I, 234 kJ/mol) and in the hypobromite reaction[13] X = Br (RO–Br, 251 kJ/mol). All of these presursors of alkoxyl radicals, formed *in situ* from the corresponding alcohols and oxidant, are unstable and have not been isolated. Alkyl hypochlorites (X = Cl), however, are good precur-

sors of alkoxyl radicals, and can be prepared in a separate reaction and then subjected to photolytic decomposition.[14] Among the most convenient and easily available precursors of alkoxyl radicals are the alkyl nitrites **4b** (RO–NO, 222, kJ/mol), prepared by the esterification of alcohols with nitrous acid or nitrosyl chloride. The intramolecular reaction of alkyl nitrites is known as the Barton reaction.[3c,15]

Peroxy compounds (alkyl hydroperoxides, dialkyl peroxides and peroxy acetates (RO–OY, Y = H, R, Ac, >142 kJ/mol) form alkoxyl radical by reduction with metal salts (Fe^{2+}, Co^{2+} *etc*), and by thermal or photolytic decomposition.[16]

Photolysis of alkyl benzenesulfenates **4i** (RO–SPh) in the presence of a radical initiator generates the alkoxyl radical intermediates **5** (alkyl benzenesulfenates are prepared by the reaction of alcohols with benzenesulfenyl chloride in the presence of triethylamine as a base).[17]

Several new precursors of alkoxyl radicals, such as *N*-alkoxypyridine-2-(1*H*)-thiones **4k**[18] and *N*-alkoxyphthalimides **4j**,[19] prepared from the corresponding alcohols, react with the $Bu_3Sn^{\bullet}$ radical, under photolytical conditions, to generate the alkoxyl radicals **5**. Epoxides possesssing potential for radical generation at the α-carbon atom have been used as convenient precursors for the generation of alkoxyl radicals.[20]

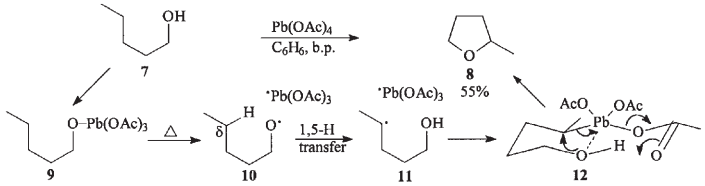
Irrespective of $X^{\bullet}$, the transposition of the alkoxyl radical **5** takes place to produce the intermediary δ-carbon radicals **6** (Scheme 2).

3.2. Lead tetraacetate oxidation of alcohols

The lead tetraacetate oxidation of saturated alcohols **7** (possessing an appropriate carbon skeleton) in non-polar solvents, such as benzene or cyclohexane, under thermal or photolytic conditions, results in oxidative cyclization to five-membered cyclic ethers **8** (Scheme 3).[3b,d] Tetrahydrofuran ring formation involves the alkoxyl radical **10** and translocated δ-carbon radical **11** as intermediates. The formation of the alkoxyl radical involves the homolytic decomposition of the intermediary lead(IV) alkoxides **9**. Transposition of the radical center, *i.e.*, an internal 1,5-hydrogen transfer, is a characteristic reaction of alkoxy radicals **10**, resulting in the generation of the corresponding δ-carbon radicals **11**. The carbon radical **11**, however, exists as a tight radical pair with its $^{\bullet}Pb(OAc)_3$ radical counterpart and undergoes concerted intramolecular ligand transfer oxidation involving a transition state such as **12** (Scheme 3).[3b] Oxidation of the carbon radical **11** involves a Pb–C bond formation and, in the subsequent intramolecular ligand transfer-like reaction a five-membered cyclic ether ring closure takes place, affording the final product **8**.[1b]

When an intramolecular ligand transfer reaction is not favourable, an electron transfer oxidation of carbon radical by Pb(III) or Pb(IV) salts occurs and the products derived from the carbocation intermediate are formed as side products.[11a,21]

The structural environment of the C_{δ}–H bond may influence, by operation of various factors, the efficiency of the 1,5-transposition of the radical center, *i.e.*, the relative yields of the cyclic ether products in the LTA oxidations of alcohols. Thus an ether oxygen enhances the reactivity of an adjacent C_{δ}–H bond towards intramo-

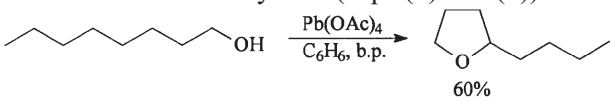


Scheme 3.

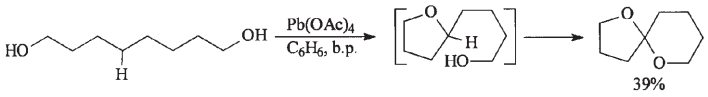
lecular hydrogen abstraction, resulting in an increasing rate of the reactions.[22] On the other hand an aromatic ring adjacent to a δ-methylene group does not noticeably affect the yield of tetrahydrofuran products.[11b,c]

In the lead tetraacetate oxidation of alcohols involving alkoxyl radicals, reactions which have been described as carbonyl-forming fragmentation reactions may accompany transposition of the radical center. In particular, β-fragmentations which give rise to allyl or benzyl radicals, or a radical adjacent to an oxygen function are strongly favoured and, in such cases, δ-hydrogen abstraction may be completely suppressed.[3b,23]

The LTA oxidation of conformationally mobile primary and secondary acyclic alcohols, containing a δ-methylene group, afford the corresponding, five-membered cyclic ethers in about 30 – 60 % yields (Eqs. (6) and (7)).[23a,24]

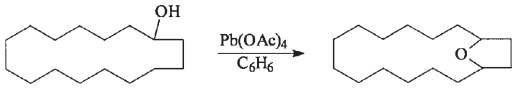


(6)

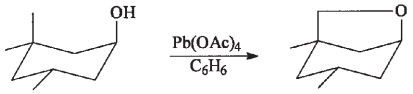


(7)

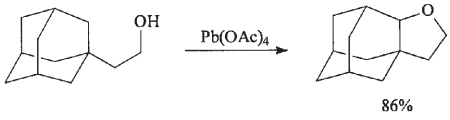
However, in the LTA oxidation of conformationally semimobile and rigid monocyclic and polycyclic alcohols, possessing an appropriately oriented hydrogen at the δ-carbon atom, the yields of cyclic ethers may range from 40 to 90 % (Eqs. (8 – 11)).[25–28]



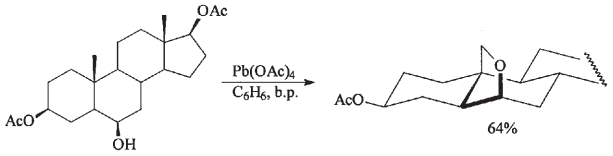
(8)



(9)

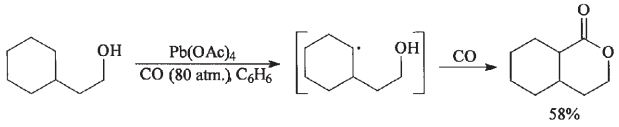


(10)



(11)

The interception of the translocated δ-carbon radicals formed in the LTA oxidations of alcohols by some other reagents was only achieved with carbon monoxide, when the oxidations were performed under a high pressure of carbon monoxide (80 atm, 72 h) and the corresponding δ-lactones are obtained (Eq. (12)).[29] Car-



(12)

bonylation of δ-carbon radicals involves the reaction of the radical with carbon monoxide to give the corresponding acyl radical, which by subsequent oxidation reaction, leads to the δ-lactone ring closure.

3.3. Reactions of alkyl hypohalites

Alkyl hypohalites are good precursors of alkoxyl radicals which in a subsequent 1,5-hydrogen abstraction reaction give the translocated δ-hydroxyalkyl radicals.[1b,d] Alkyl hypochlorites, hypobromites and hypoiodites can conveniently be prepared from the corresponding alcohols. Alkyl hypochlorites are stable compounds in the absence of light at room temperature, whereas alkyl hypobromites and hypoiodites are not stable at room temperature and they are prepared *in situ* as intermediates in the oxidations of alcohols with the corresponding halogen and oxidants. The homolytic cleavage of the RO–X bond in alkyl hypochlorites and hypoiodites proceeds under irradiation conditions while the generation of alkoxyl radicals from alkyl hypobromites requires a metallic oxidant. Although the formation of alkoxyl radicals from alkyl hypohalites takes place with different reagents and under different reaction conditions, a 1,5-transposition of radical center and formation of the δ-carbon radical is a common reaction step, however different reaction products are furnished.

3.3.1. Alkyl hypoiodites

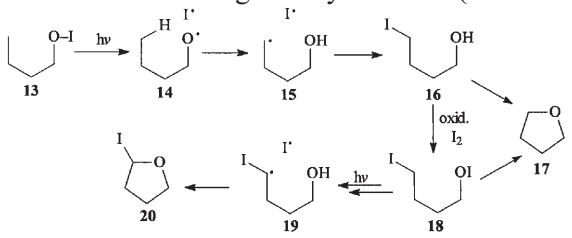
Alkyl hypoiodites are prepared *in situ* in the reaction of alcohols with iodine and an oxidant such as LTA,[3a,30] HgO,[31] $PhI(OAc)_2$,[32] and $Ph_2Se(OH)OAc$[32b,33] (Eq. (13)) under irradiation conditions.

$$RCH_2OH \xrightarrow[C_6H_{12},\ h\nu]{I_2,\ \text{oxidant}} RCH_2O\text{–}I \xrightarrow{h\nu} RCH_2O^{\bullet} \qquad (13)$$

oxidant = $Pb(OAc)_4$, HgO, $PhI(OAc)_2$, $Ph_2Se(OH)OAc$

The alkoxyl radicals **14** are generated by homolysis of the O–I bond induced by photolysis of the alkyl hypoidites **13**. The thus formed alkoxyl radicals **14** undergo 1,5-transposition of the radical center and the formation of δ-hydroxy carbon radicals **15** which are captured by iodine or by the abstraction of iodine from the alkyl hypoidites **13**, resulting in the formation of intermediary 1,4-iodohydrins **16** (Scheme 4).[3a,34] In the presence of an excess of the metallic oxidant and pro-

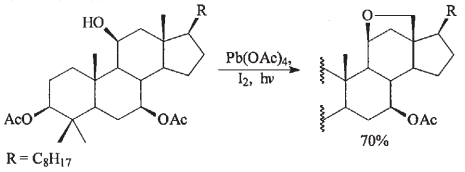
longed reaction time, 1,4-iodohydrins **16** undergo intramolecular reaction affording the tetrahydrofuran derivatives **17**. However, in the presence of large excesses of lead tetraacetate and iodine, further oxidation of the 1,4-iodohydrins occurs, involving the formation of new 4-iodoalkyl hypoiodites **18** and, by subsequent generation of an alkoxyl radical and translocation of the radical center, α-iodotetrahydrofuran derivatives **20** are obtained as the final reaction products. It was suggested that the alkoxyl radical formed from the 4-iodoalkyl hypoiodite may undergo intramolecular substitution to give a cyclic ether (Scheme 4).[34]



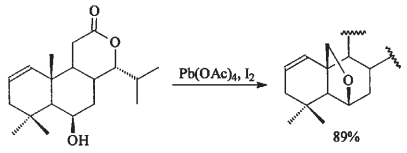
Scheme 4.

In the hypoiodite reaction, the δ-carbon radical **15** is in a tight radical pair with an iodine radical or metallic species from the oxidants and cannot be intercepted by some other reagents and only an ether oxygen and/or iodine are introduced at the non-activated δ-carbon.[3a]

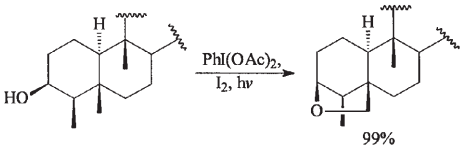
Several versions of the hypoiodite reaction were successfully used for the functionalization of the non-activated carbon atoms of alcohols with simple acyclic, complex cyclic and polycyclic structures, which are illustrated by the following examples (Eq. (14) – (17)).[3a,b,32a,35]



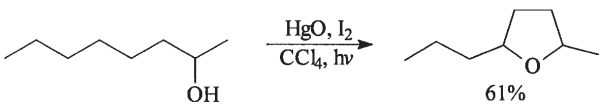
(14)



(15)



(16)

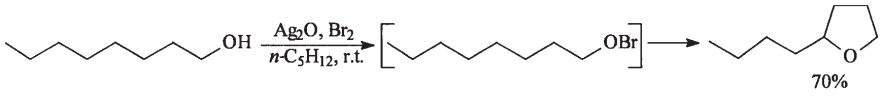


(17)

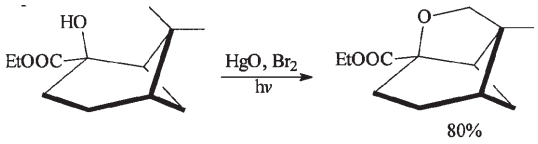
In the hypoiodite reaction of cyanohydrins derived from steroid ketones, an interesting radical transposition takes place involving a 1,4-cyano group migration (see 6.1).

3.3.2. Alkyl hypobromites

Alkyl hypobromites appear as intermediates in the reaction of alcohols with bromine and silver oxide (or acetate) or mercury oxide.[13] Alkyl hypobromites are very unstable and their decomposition occurs in daylight. On homolysis of the O–Br bond, an alkoxy radical is formed and a subsequent 1,5-transposition of the radical center occurs, thereby generating a δ-carbon radical which is intercepted by bromine, thus forming a 1,4-bromohydrin. The intermediary bromohydrin rapidly undegroes an intramolecular cyclization affording the corresponding tetrahydrofuran (Eq. (18)).[13a] In the hypobromite reactions, no noticeable amounts of side reaction products were obtained even in the case when tertiary alkoxyl radicals were involved as intermediates, *i.e.* a β-fragmentation does not occur (Eq. (19)).[13a,37]



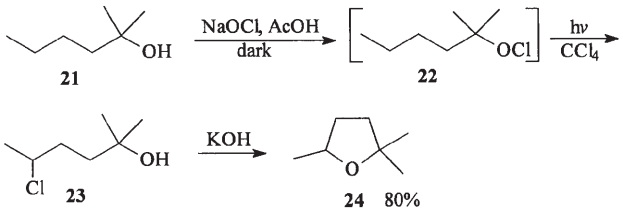
(18)



(19)

3.3.3. Alkyl hypochlorites

The photolysis of tertiary alkyl hypochlorites **22**, derived from tertiary alcohols **21**, were carried out without special precautions during the preparation of the alkyl hypochlorites from the alcohols and hypochlorous acid (from sodium or calcium hypochlorite and acetic acid) in dim light and at room temperature, whilst primary and secondary alkyl hypochlorites must be prepared in the dark at r.t.[14a] In the photolysis of alkyl hypochlorites 1,4-chlorohydrins **23** were obtained as the products of 1,5-transposition of the radical center from the oxygen to the δ-carbon atom. Chlorination of the δ-carbon radical involves abstraction of the chlorine from the starting alkyl hypochlorite, rather than coupling with a chlorine radical. Only when the concentration of the alkyl hypochlorite becomes very low, is coupling of the δ-carbon radical with a chlorine atom a possible reaction. 1,4-Chloro-



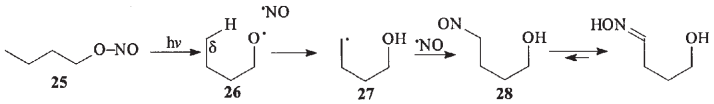
Scheme 5.

hydrins are unstable and smoothly cyclize under basic conditions and the corresponding tetrahydrofuran derivatives **24** were obtained (Scheme 5).[14a,38]

The decomposition of primary and secondary alkyl hypochlorites in the dark was carried out by ferrous salts and a mixture of 1,4-chlorohydrins and tetrahydrofuran derivatives was obtained.[14c]

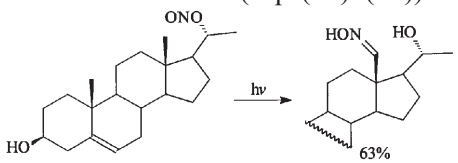
3.4. Photolysis of alkyl nitrites (Barton reaction)

Alkyl nitrites are among the most convenient precursors of alkoxyl radicals to perform a 1,5-transposition of the radical center and an intramolecular functionalization of the non-activated carbon atom with a nitrogen-containing group.[3c,15] Irradiation of alkyl nitrites **25** involves homolysis of the RO–NO bond thereby generating an alkoxyl radical **26** and, by a subsequent 1,5-hydrogen migration, the relocated δ-carbon radical **27** is created. Coupling of the carbon radical with a nitroso radical affords a δ-nitrosoalcohol **28** as the final product of the intramolecular reaction (Scheme 6). This type of reaction is known as a Barton reaction.[15,39]

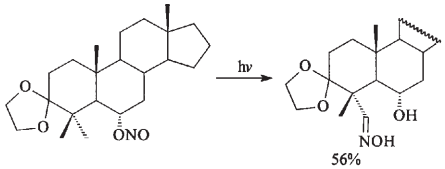


Scheme 6.

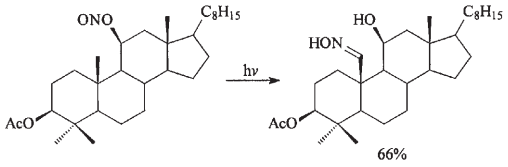
The Barton reaction was successfully applied for the introduction of a nitrogen functional group onto an inaccessible non-activated δ-carbon atom, such as the angular methyl groups in steroid molecules. The following examples illustrate the synthetic potential of the Barton reaction (Eqs.(20)–(23)).[40–43]



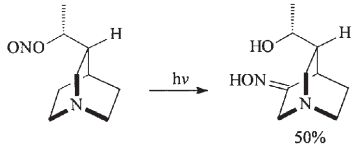
(20)



(21)

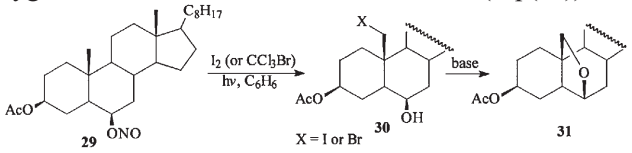


(22)

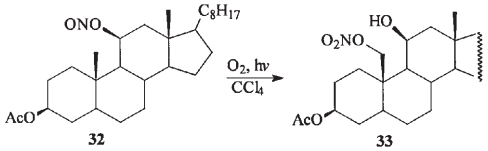


(23)

It was proved that in the photolysis of alkyl nitrites, the alkoxyl radicals as well as the δ-carbon radicals, arising from radical relocation, are not in a tight radical pair with the nitroso radical which enables the δ-carbon radicals to be captured by an added reagent. Thus, in the photolysis of alkyl nitrite **29** in the presence of iodine (or other halogen donors), the δ-carbon radical reacts with the iodine to give the corresponding δ-iodohydrin **30** which is converted by base to the 5β,19-cyclic ether **31** (Eq. (24)),[44] while in the reaction of alkyl nitrite **32**, in the presence of oxygen, the δ-carbon radical is quenched by oxygen and the δ-nitrate ester **33** is obtained (Eq.(25)).[45]

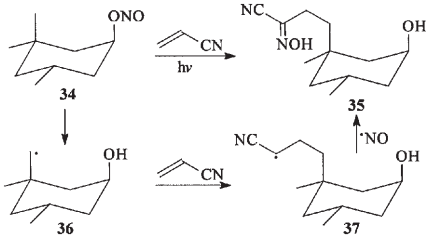


(24)



(25)

Carbon radical addition onto an electron-deficient olefinic bond is well known and is a synthetically valuable reaction. It was found that the δ-carbon radical **36** generated in the photolysis of the alkyl nitrite **34**, in the presence of an excess of an activated olefin, undergoes an intermolecular addition to radicophilic olefins, thus generating a new carbon radical **37** which then reacts with a nitroso radical to give the δ-alkylated product **35**, possessing both an electron-withdrawing group and an α-oximino group in the alkylating chain (Scheme 7).[17]



Scheme 7.

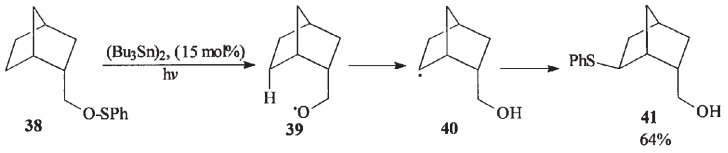
Possessing an olefinic bond at the 5-position, the δ-carbon radicals undergo 5-*exo*-cyclization affording cyclic nitroso alcohols.[46] The δ-carbon radicals generated by the photolysis of alkyl nitrites were oxidized by cupric acetate to give the corresponding unsaturated alcohols.[47]

3.5. Photolysis of alkyl benzene(arene)sulfenates

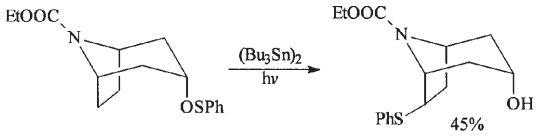
The RO–SPh bond of alkyl benzenesulfenates undergoes homolytic cleavage in a reaction with the tributyltin radical or by laser flash photolysis, and alkoxyl radical intermediates are formed (Eq. (26)).[17,48]

$$RO{-}SPh(Ar) \xrightarrow{Bu_3Sn^{\bullet}} RO^{\bullet} + Bu_3SnSPh(Ar) \quad (26)$$

Independently of the precursors of the alkoxyl radical, the reagents used and the applied reaction conditions, the 1,5-transposition of the radical center from the oxygen to the δ-carbon atom is usually the main reaction with the formation of a δ-carbon radical. When an alkoxyl radical **39** is formed by the photolysis of alkyl benzenesulfenates **38** in the presence of 15 mol% of hexabutylditin, the relocated δ-carbon radical **40** abstracts the phenylthio group from the starting alkyl benzenesulfenate **38**, giving the δ-phenylthio alcohol **41** and generating a new alkoxyl radical which continues the radical chain reaction (Scheme 8, Eq. (27)).[49,50]

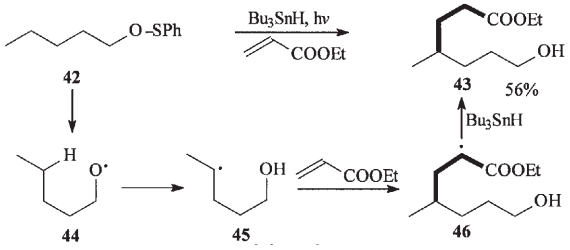


Scheme 8

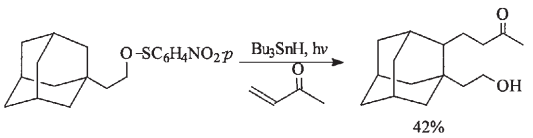


(27)

However, when an alkoxyl radical is generated by the photolysis of an alkyl benzenesulfenate, *e.g.*, **42**, in the presence of an equal amount of tributyltin hydride and a 50 molar equivalent excess of an electron-deficient olefinic compound, the relocated δ-carbon radical **45**, formed by 1,5-transposition of the radical center of an alkoxyl radical **44**, is converted to the carbon radical **46** by intermolecular addition to the olefinic bond (Scheme 9).[17] The final reaction product **43** is formed by the reaction of the radical **46** with Bu_3SnH. In this sequence of radical reactions, alkylation of the remote carbon atom was achieved and a functionalized alkyl chain was introduced on the non-activated δ-carbon atom (Eq. (28)).[17,51]

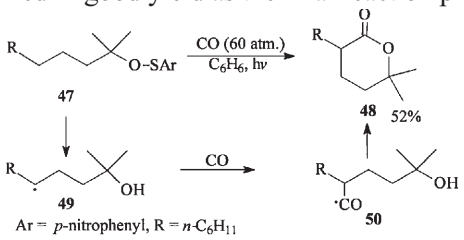


Scheme 9.



(28)

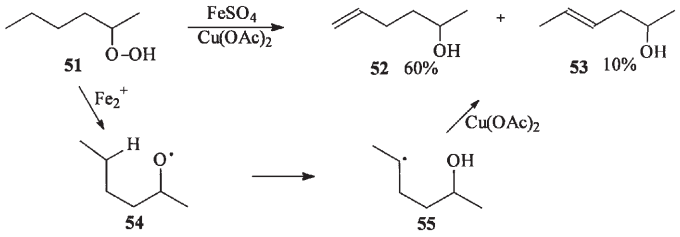
The δ-carbon radical **49** arising from alkyl *p*-nitrobenzenesulfenate **47**, after 1,5-hydrogen shift in the intermediary alkoxyl radical, was quenched by carbon monoxide when the reaction was performed under a high pressure (60 atm) of carbon monoxide. The intermediary acyl radical **50** reacts with the starting sulfenate ester to give an arylthio ester as the intermediate. In the subsequent thiophenol elimination, the δ-lactone **48** was obtained in good yield as the final reaction product (Scheme 10).[29]



Scheme 10.

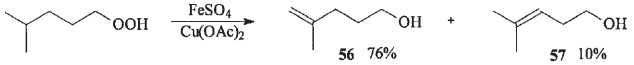
3.6. Reductive decomposition of alkyl hydroperoxides

In the reductive decomposition of alkyl hydroperoxides, *e.g.*, **51** and dialkyl peroxides, induced by ferrous ion or other oxidizable metal ions, alkoxyl radical intermediates **54** are involved. 1,5-Transposition of the radical centers is the main subsequent reaction of the alkoxyl radicals, resulting in the formation of δ-carbon radicals **55**. Carbon radicals formed under these conditions can undergo either electron transfer or ligand transfer oxidations.[16] In the ferrous ion-induced decomposition of alkyl hydroperoxide **51**, in the presence of cupric acetate as an electron transfer oxidative reagent of alkyl radicals, the δ-unsaturated alcohol **52** was obtained as the main reaction product, in addition to a small amount of the isomeric γ-unsaturated alcohol **53** (Scheme 11, Eq. (29)).[16,52]



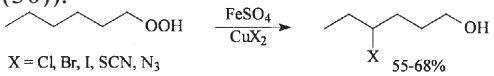
Scheme 11.

It is of interest to note that the unsaturated alcohol **56**, with the double bond in the δ-position to the hydroxyl group is the main reaction product, and not necessarily the thermodynamically more stable γ-olelfinic alcohol **57**. This is possible due to a directive effect of the hydroxyl group exerted through the cyclic transition state leading rather to the *exo*-elimination of a hydrogen from the more remote ε-carbon atom than the *endo*-elimination affording a γ-unsaturated alcohol **57** (Eq. (29)).[52]



(29)

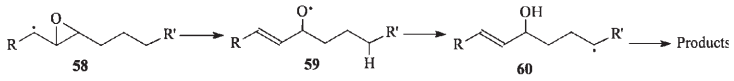
However, when the decomposition of alkyl hydroperoxides and dialkyl peroxides was carried out by ferrous ions in the presence of a ligand transfer oxidant, such as cupric halides or pseudohalides, a ligand transfer oxidation of the δ-carbon radical occurred and a halide atom or pseudohalide group was introduced at the δ-carbon atom (Eq. (30)).[53]



(30)

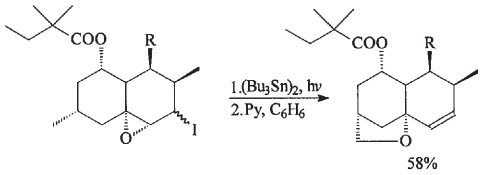
3.7. Epoxides as precursors of alkoxyl radicals

Oxiranylmethyl radicals **58** undergo rapid ring opening by homolytic cleavage of the C–O bond and allyloxy radical intermediates **59** are generated. Irrespective of the nature of the original functional group attached to the proradicalic α-carbon atom of the epoxide ring, these alkoxyl radicals can also undergo 1,5-transposition of the radical center to give carbon centered radicals **60** (Scheme 12).[20,54]



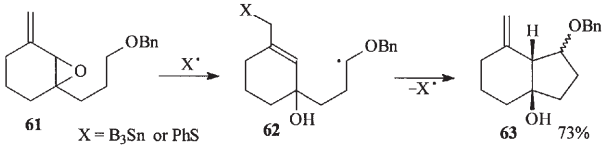
Scheme 12.

The oxiranylmethyl radical, formed as an intermediate in the reaction of α-iodoepoxide with hexabutylditin, undergoes the following sequence of reactions: epoxide ring opening with alkoxyl radical formation, 1,5-transposition of the radical center and the generation of an alkyl radical and then iodo transfer to give the 1,4-iodohydrin, which is converted to the tetrahydrofuran derivative under basic conditions (Eq. (31)).[55]



(31)

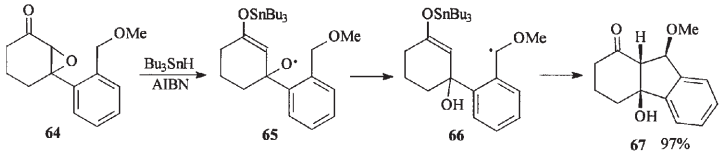
The addition of a tributyltin or phenylthio radical onto the olefinic bond of vinyl epoxides **61** results in the generation of an oxiranylmethyl radical which, in the subsequent sequence of radical reactions (alkoxyl radical formation, 1,5-hydrogen transfer, 5-*exo*-cyclization and elimination of the initial, *e.g.*, tributyltin radical), affords a bicyclic product **63** (Eq. (32)).[56]



(32)

1,5-Transposition of a radical center is very successful when the δ-carbon radical bears stabilising functional groups (aryl, alkoxy, alkenes, *etc.*). In the reaction of keto-epoxide **64** with tributyltin hydride, a considerable reconstruction of the carbon skeleton occurs involving the following sequence of radical reactions: the concerted addition of tributyltin radical onto the keto group and the opening of the epoxide ring

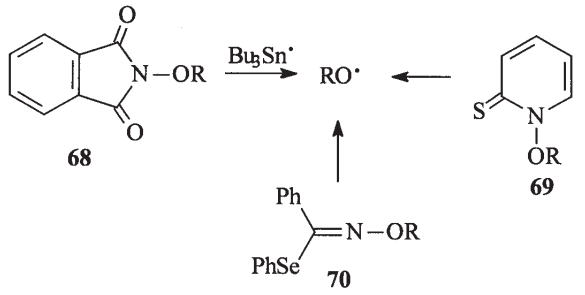
to form an alkoxyl radical **65**, 1,5-translocation of the radical center, 5-*exo*-addition of the carbon radical **66** onto the olefinic bond with the expulsion of a tributyltin radical. Thereby the tricyclic ketone **67** is afforded (Scheme 13).[57]



Scheme 13.

3.8. Other precursors of alkoxyl radicals

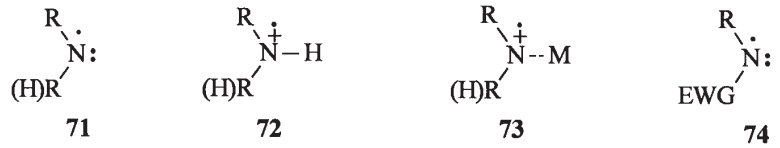
In addition to the previously described precusors of alkoxyl radical undergoing 1,5-transposition of the radical center, the following substrates may also be good precursors for this type of radical reaction: *N*-(alkoxy)pyridine-2-(1*H*)-thiones **69**,[18] *N*-alkoxyphthalimides **68**[19,58] and Se-phenyl benzeneselenohydroxamates **70**.[59] In all of these substrates, the cleavage of the N–O bonds and the generation of alkoxyl radicals are induced by tributyltin radicals. However, these substrates were applied for kinetics studies only and not for synthetic purposes.



4. RADICAL TRANSPOSITIONS FROM A NITROGEN TO A CARBON ATOM INVOLVING A 1,5-HYDROGEN TRANSFER

The most important reactions of nitrogen centered radicals are inter- and intramolecular hydrogen abstraction involving an alkane C–H σ-bond cleavage.[1a,60] The reactivity of amino radicals **71** depends on the extent to which the lone electron pair is associated with a proton **72**, with a Lewis acid **73** or with an electron withdrawing group **74**.[60]

Intramolecular hydrogen abstraction occurs regioselectively resulting in the 1,5-transposition of the radical center from a nitrogen to a carbon atom. Higher reactivity towards the hydrogen abstraction reaction as well as a greater synthetic utility was observed when the electrophilic character of the N-centered radicals was increased. Intramolecular translocation of an aminyl radical is energetically favourble by about 21–33 kJ/mol, because a strong N–H bond (431 kJ/mol) is formed.[61]

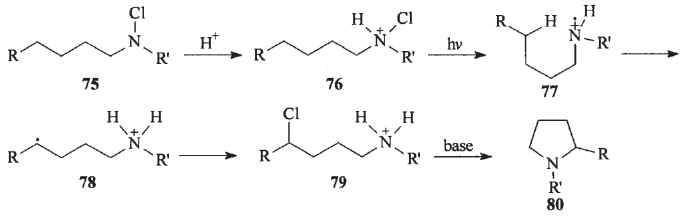


71 72 73 74

Nitrogen radicals are readily generated from the corresponding *N*-haloamines by photolytically, thermally or ferrous ion induced homolysis of the N–X bond. 1,5-Transpositions of the radical center from a nitrogen to a non-activated carbon atom have been widely investigated and applied in the synthesis of numerous pyrrolidine derivatives and alkaloids. Here reactions of protonated aminyl radicals (radical cation) and neutral aminyl radicals will be described.[1d,62]

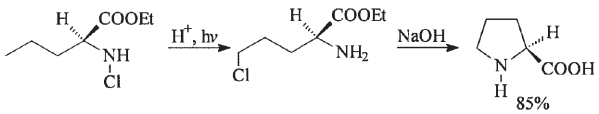
4.1. Protonated aminyl radicals (Hofmann-Löffler-Freytag reaction)

The oldest synthetic reaction of aminyl radicals which involves 1,5-transposition of the radical center is the Hofmann-Löffler-Freytag reaction (HLF).[63] Thus, when *N*-chloroamines **75** are heated or irradiated in strong acidic solution, δ-chloroamines **79** are formed and upon treatment with bases pyrrolidines **80** are obtained as the final reaction products.[64] The first step in this reaction is the formation of chloroammonium salts **76** and by irradiation they are converted to the corresponding nitrogen radical cation intermediates **77** which are reactive species for the abstraction of a hydrogen atom from a non-activated δ-carbon atom. The thus generated δ-alkyl radical cation **78** abstracts a chlorine from the starting *N*-chloroamine to give the δ-chloroamine **79** and a new nitrogen radical cation **77** (Scheme 14).

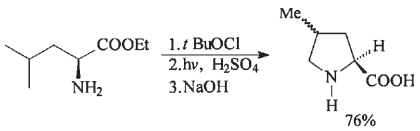


Scheme 14.

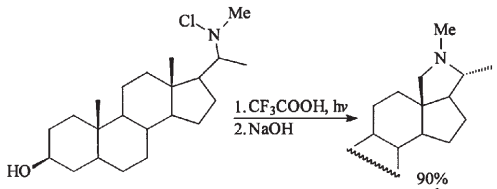
The Hofmann-Löffler-Freytag reaction has been successfuly applied in the synthesis of various substituted pyrrolidine derivatives as well as of numerous alkaloids which are illustrated in Eqs. (33) – (36).[65–67]



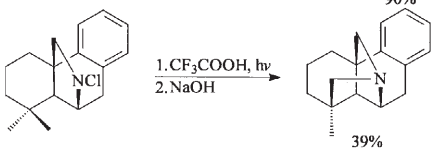
(33)



(34)



(35)

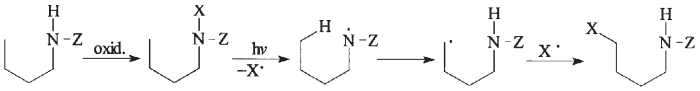


(36)

The strong acidic conditions required in the traditional Hofmann-Löffler-Freytag reaction considerably limit its synthetic applications and several modifications of the basic reaction have been developed that facilitate the pyrrolidine formation under milder reaction conditions.

4.2. Unprotonated nitrogen centered radicals

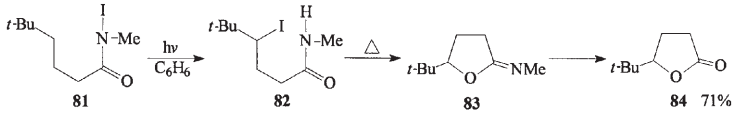
Several modifications of the HLF reaction for performing a 1,5-transposition of a radical center from a nitrogen to a carbon atom under neutral conditions have been discovered.[60] In order to maintain a higher reactivity of the N-radical towards hydrogen abstraction, it was necessary to make the aminyl radicals more electrophilic by attachment of an electron withdrawing group to the nitrogen atom.[68] Thus, *N*-haloamides possess a C=O group, which increases the electrophilicity of the aminyl radicals and also *N*-halo derivatives of nitroamines, cyanamides, phosphoramides and sulfonamides are good precusors of neutral nitrogen radicals possessing sufficient reactivity for hydrogen abstraction from a non-activated C–H bond (Scheme 15).[69]



Z = COR, CN, NO_2, $PO(OR)_2$, SO_2R
X = I, Br, Cl

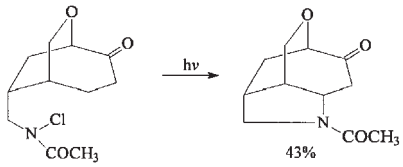
Scheme 15.

Thus, in the photolysis of the *N*-iodoamide **81**, the γ-lactone **84** is obtained as the final reaction product, involving the γ-iodoamide **82** and iminolactone **83** as intermediates (Scheme 16).[69]



81 **82** **83** **84** 71%

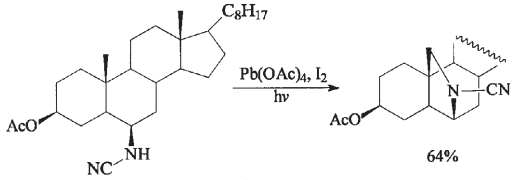
Scheme 16.



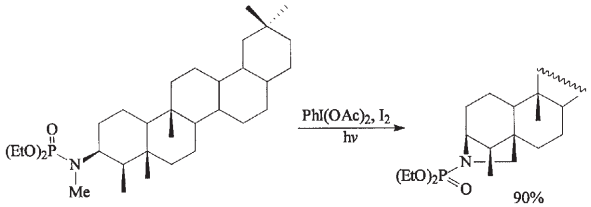
(37)

This modification of the HLF reaction was applied, as the key step, in the synthesis of alkaloids and an example is presented in Eq. (37).[70]

N-Iodoamides and *N*-iodoamines containing an electron witdrawing group attached to the nitrogen are easily prepared *in situ* in the reaction with iodine and an oxidant, such as $Pb(OAc)_4$ and $PhI(OAc)_2$, and then irradiation induced the formation of the nitrogen radicals resulting in the formation of a pyrrolidine derivative as the final reaction product (Eqs. (38) and (39)).[71,72]

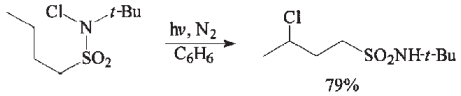


(38)



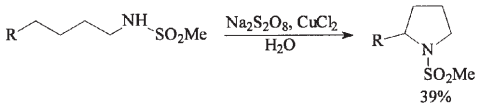
(39)

N-*t*-Butyl-*N*-haloalkane sulfonamides can also undergo intramolecular radical hydrogen abstraction with transposition of the radical center from the nitrogen to the γ-carbon atom, whereby γ-haloalkane sulfonamides are obtained (Eq. (40)). The mechanism of this type reactions is same as the basic HLF reaction.[69,73]



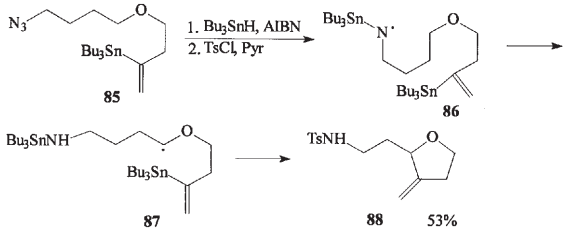
(40)

When *N*-alkylmethanesulfonamides are used as the precursors of nitrogen radicals on oxidation with $Na_2S_2O_8$ in the presence of cupric ions, *N*-sulfopyrrolidine derivatives are obtained (Eq. (41)).[73]



(41)

Nitrogen radicals can be generated under reducing conditions using alkyl azides, *e.g.,* **85**, as the substrates and tributyltin hydride as the reducing agent. In



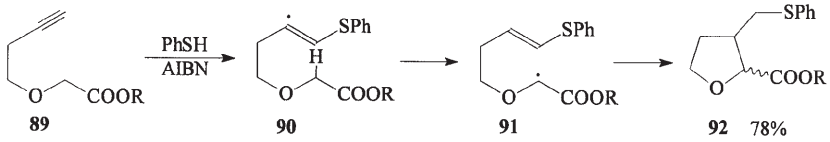
Scheme 17.

this reaction, *N*-tributylstanyl radicals **86** are the reactive intermediates, which are more reactive than ordinary aminyl radicals towards hydrogen abstraction. The translocated carbon radical **87** undergoes the 5-*exo*-cyclization/elimination sequence of reactions to give the cyclic product **88** (Scheme 17).[74]

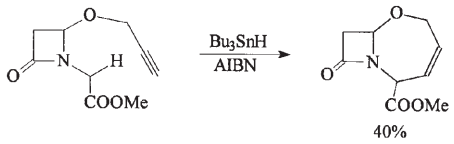
5. RADICAL TRANSPOSITIONS FROM CARBON TO CARBON INVOLVING A 1,5-HYDROGEN TRANSFER

5.1. 1,5-Transposition of vinyl to alkyl radicals

A vinyl radical is more reactive than a saturated carbon radical. Thus, vinyl radicals **90**, generated by the addition of a phenylthio or tributyltin radical to an acetylenic bond **89**, undergo 1,5- or 1,6-hydrogen transfer from the saturated carbon atom to give the more stable carbon radical **91**. This hydrogen migration from the sturated carbon atom to the vinyl radical is energetically favored by about 42 kJ/mol. The further reactions of the relocated carbon radical depend on the structure of the substrate and the rection conditions. In the example given, the relocated radical **91** undergoes a cyclization reaction to give the cyclic product **92** (Scheme 18, Eq. (42)).[75,76]

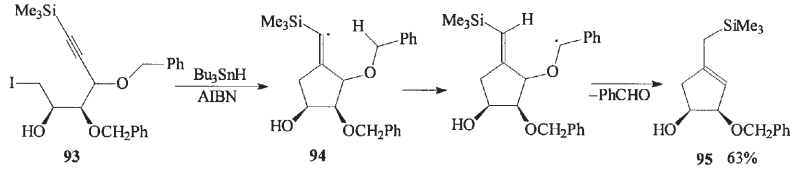


Scheme 18.



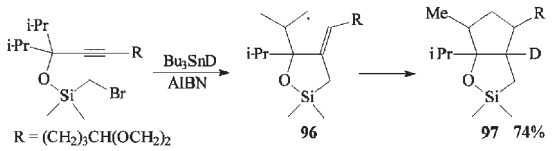
(42)

The vinyl radical **94**, formed by 5-*exo-dig*-cyclization (of the radical derived from the precursor **93**), abstracts an energetically and stereochemically favourable hydrogen atom to give a new, relocated, carbon radical. Fragmentation of the radical adjacent to the ether oxygen atom affords the final reaction product **95** and benzaldehyde (Scheme 19).[77]



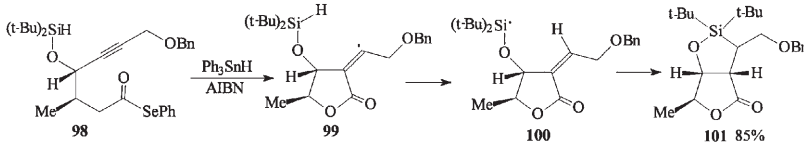
Scheme 19.

The carbon radical **96** is formed in a sequence of radical reactions involving a 5-*exo-dig*-cyclization and subsequent 1,5-hydrogen transfer from the isopropyl group. The thus translocated radical undergoes another 5-*exo*-cyclization to give the bicyclic product **97** (Scheme 20).[78]



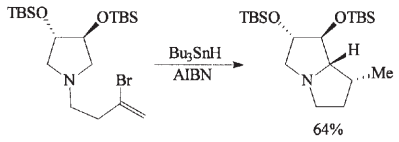
Scheme 20.

In a similar sequence of radical reactions involving the cyclization of an acyl radical (derived from **98**) and subsequent intramolecular 1,5-hydrogen transfer from the Si–H bond to the sp^2 carbon atom, the transposition of the radical center from the vinyl radical **99** to the siloxane **100** occured. The translocated silicon radical **100** undergoes 5-*endo-trig*-cyclization to give the biyclic product **101** (Scheme 21).[79]



Scheme 21.

A highly reactive vinyl radical can also be formed as an intermediate by reduction of vinyl halides with tributyltin hydride or similar regents. The thus formed vinyl radical (derived from a vinyl bromide) abstracts the energetically favourable hydrogen and a translocated carbon radical is formed which undergoes a cyclization reaction to give the final rection product. Interesting bicyclic compounds were prepared by the sequence: vinyl/activated carbon (adjacent to a nitrogen atom) 1,5-radical transposition and a 5-*exo-trig*-cyclization reaction (Eq. (43)).[80]



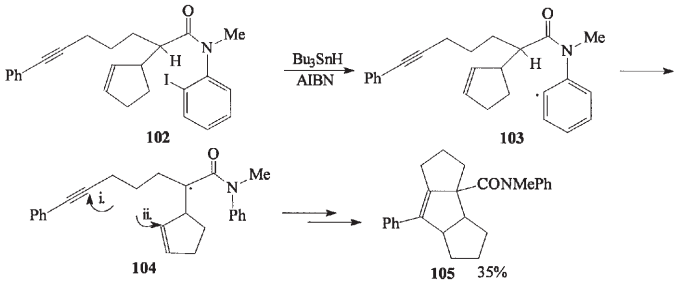
(43)

5.2. Transposition of aryl to alkyl radicals

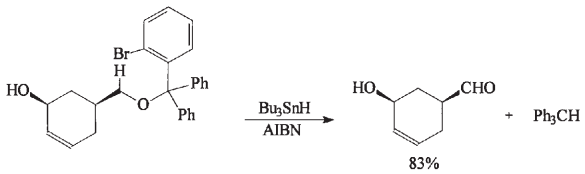
Hydrogen abstraction from a saturated carbon atom by aryl radicals is energetically very favoured process (Ar–H is about 460 kJ/mol), particularly when the abstraction of an activated hydrogen takes place. Therefore, due to the ease of preparation of aryl radical precursors and the wide range of conditions which can be used for their generation, this radical transposition method has been widely used in organic synthesis.

Thus, *ortho*-iodoanilides **102** are the direct precursor of α-carbonyl radicals **104** which could enter into a synthetically useful sequence of cyclization reactions (*i*. 5-*exo-dig*- and *ii*. 5-*exo-trig*-, Scheme 22) to give the triquinane product **105**.[81]

The synthetically useful methodology of a "self-oxidizing protective radical group" involves an aryl radical, derived from the corresponding aryl bromide, which undergoes 1,5-transfer of the hydrogen next to an ether functional group. In the subsequent β-fragmentation of the translocated carbon radical an aldehyde group is released (Eq. (44)).[82]

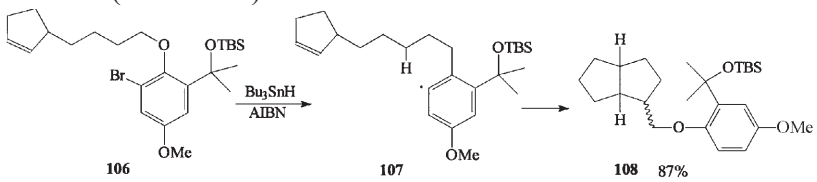


Scheme 22.



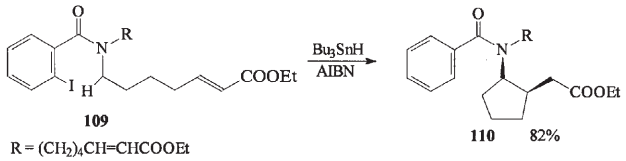
(44)

The *ortho*-bromo-*para*-methoxyphenyl group has been used as a protecting group as well as a precursor of aryl radicals which can be relocated to an alkyl chain by 1,5-hydrogen migration. Thus, an aryl radical **107** generated from the corresponding aryl bromide **106** by 1,5-hydrogen transfer gives an alkyl radical which in a subsequent cyclization reaction, affords the bicyclic compound **108**. Deprotection of the methoxyphenyl ether group is possible under standard oxidative conditions (Scheme 23).[83]



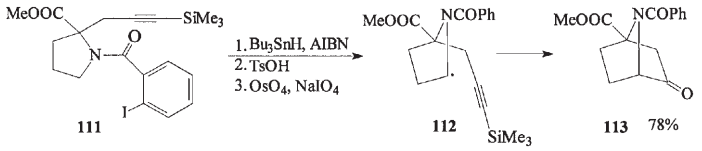
Scheme 23.

α-Amino carbon radicals are conveniently generated when an *ortho*-halobenzoyl group is used as a protective/radical translocating group. Thus, the aryl radicals formed from the *ortho*-iodobenzamide **109** abstract the hydrogen from the α-amino methylene group and the thus formed alkyl radical undergoes cyclization to give the cyclopentane derivative **110** (Eq. (45)).[84]



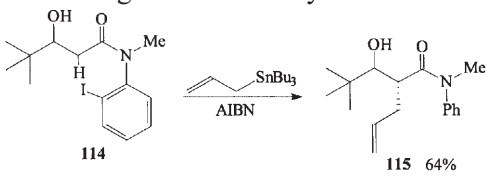
(45)

Sequential reactions involving 1,5 hydrogen abstraction resulting in the translocation of an aryl radical (derived from the aryl iodide **111**) to the alkyl radical **112**, and 5-*exo*-*dig*-cyclization led to an additional ring being closed **113**. This methodology was successfully applied in the synthesis of epibatidine (Scheme 24).[85]



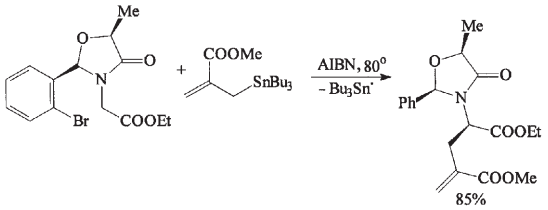
Scheme 24.

The methodology of radical translocation has also been applied in the stereoselective α-alkylation of carboxylic acids under very mild reaction conditions. In this method, the *ortho*-iodoanilide group was used as a protective/radical translocating group for carboxylic acids. Thus, in the reaction of *ortho*-iodoanilide **114** with allyl-tributyltin, an α-carboxyl radical (generated by 1,5-hydrogen migration) undergoes intermolecular addition to give an α-carboxylic acid derivative **115** (Eq. (46)).[86]



(46)

Aryl radical transposition to a saturated carbon atom, involving 1,5-hydrogen atom transfer from an α-amino position, was successfully used for stereoselective synthesis. Thus, the alkyl radical, formed in a 1,5-hydrogen abstraction by an aryl radical, undergoes intermolecular addition onto an activated olefinic bond to give an alkylated product, which can be elaborated to non-proteinogenic α-amino acids (Eq. (47)).[87]

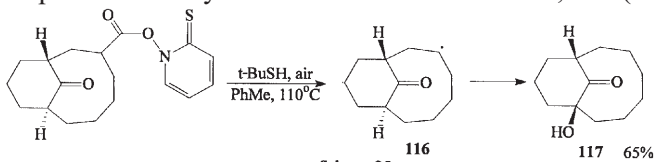


(47)

5.3. Transposition of alkyl to other alkyl radicals

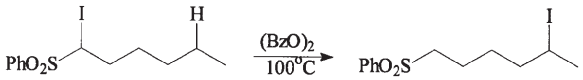
Intramolecular abstraction of a hydrogen atom by an alkyl radical, involving an exchange of one sp^3 centered radical for another carbon radical, is energetically not favoured. Since for hydrogen abstraction it is necessary to establish a six-membered cyclic transition state around a mobile alkyl chain, the entropic components are also unfavourable. Transposition of alkyl radicals are often unintentional and, in some situations radical transposition can direct the pathway away from its intended course. In some cases, in which an alkyl radical has a fixed conformation and possesses a hydrogen atom at the optimal distance (2.3 – 2.5 Å), a translocation of the radical center can take place, as it is illustrated in the following example (Scheme 25). In this case, 1,5-transposition of the secondary radical **116** to the tertiary carbon radical occurs, resulting in the stereo isomerisation of the bicyclic

molecule and, when the reaction is performed in the presence of oxygen, a hydroxylic group at the tertiary δ-carbon atom is introduced, **117** (Scheme 25).[88]



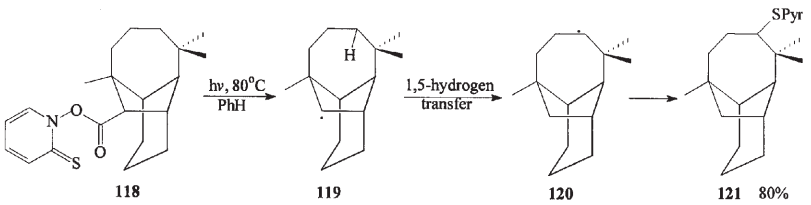
Scheme 25.

Repositioning of the radical center from one to another remote carbon atom in an alkyl chain was realised under iodine atom transfer conditions. An α-iodo sulfone reacts with benzoyl peroxide affording the ω-iodide (Eq. (48)). In this relocation of the radical center, a hydrogen migration from the ε- to the α-position takes place and the thus generated carbon radical abstracts iodine to give the reaction product.[89]



(48)

Transannular repositioning of carbon radicals, involving 1,5-hydrogen transfer, was applied for highly selective and efficient remote functionalization. Thus, by Barton decarboxylation of isolongifolic acid **118**, a transannular 1,5-hydrogen migration occurs (**119** → **120** resulting in the δ-functionalization in the longifolene structure **121** (Scheme 26).[90]



Scheme 26.

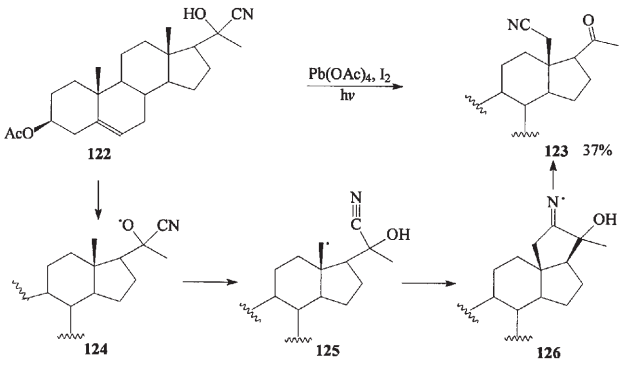
6. RADICAL TRANSPOSITIONS INVOLVING AN INTRAMOLECULAR 1,4(5)-GROUP TRANSFER

1,5-Transposition of a radical center traditionally refers to reactions involving an intramolecular hydrogen atom abstraction by alkoxyl and aminyl, and to a considerably less extent, carbon radicals. However 1,5-transfer of other atoms or groups, resulting also in the transposition of a radical site, are also possible but of less importance. Here the 1,5-transfer of cyano, aryl and trimethylsilyl groups, resulting in the relocation of the radical center, will be discussed.

6.1. 1,4-Transposition of the cyano group

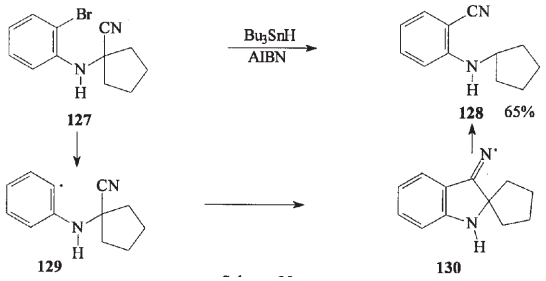
The first reaction of this type was observed in the hypoiodite reaction of steroidal cyanohydrins with lead tetraacetate in the presence of iodine, under irradiation conditions.[91] The reaction proceeds with a formal 1,4-transfer of the cyano group from the

α-hydroxy carbon atom to the δ-carbon radical **125** (Scheme 27). The key steps in this cascade of radical reactions are 1,5-transfer of the hydrogen from the angular methyl group to the alkoxyl radical **124** and subsequent addition of the δ-carbon radical **125** to the cyano group giving an imino radical **126** as an intermediate. The cleavage of the C–C bond in the cyclic intermediate **126** leads to the formation of δ-cyano ketones **123**. The double transposition of the radical centers, involving 1,4-cyano group migration, was observed only when both reactive centers were fixed and fails with flexible open-chain cyanohydrins. The 1,4-migration of the cyano group and the formation of δ-cyano ketones was also observed when alkoxyl radicals **124** were generated from the corresponding perester of cyanohydrins.[92]



Scheme 27.

A 1,4-cyano group transfer from a saturated carbon atom to the aryl radical **129** involving the transposition of the aryl radical center to the saturated carbon atom, was also found when aryl radicals **129** are generated from the corresponding aryl halides **127** by the tributyltin hydride method (Scheme 28).[93] The migration of the cyano group also involves the imino radical **130**, which rather undergoes cleavage of C_{sp^2}–C_{sp^3} bonds and the generation of the tertiary carbon radical than the formation of the aryl radical **129**.



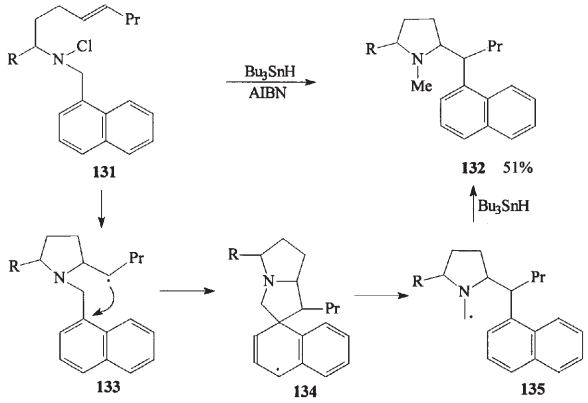
Scheme 28.

6.2. 1,4-Transposition of aryl groups

Radical species (electrophilic or nucleophilic) are very reactive and attack aromatic rings. In the case of intramolecular radical reaction, the transposition of the radi-

cal center can occur. This type of rearrangement involving a 1,4- or 1,5-aryl group migration from a carbon atom to a carbon radical,[94] from nitrogen to a carbon radical,[95] from sulfur to a carbon radical,[96] from silicon to a carbon radical[97] and from an oxygen atom to a carbon radical[98] have been described. Some of these rearrangement reactions may have synthetic importance. Radical migration of aryl groups involves an intramolecular *ipso* attack of the radical at the aryl group proceeding through spiro cyclohexadienyl radicals[99] and results in 1,4- or 1,5-aryl group transfer.

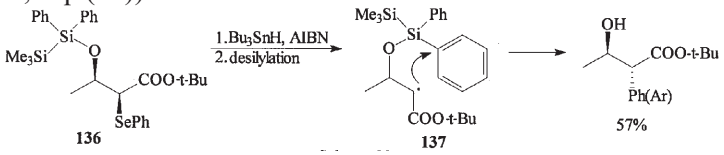
Thus, in the sequential reaction the alkyl radical **133**, formed by intramolecular 5-*exo*-addition of an amino radical (derived from the corresponding *N*-chloro amine **131**) onto the olefinic bond, undergoes the 1,4-transfer of the aryl group (*via* the spiro cyclohexadienyl radical **134**) and a new relocated carbon radical **135** is formed, leading to the final reaction product **132** (Scheme 29).[100]



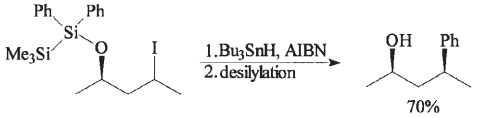
Scheme 29.

1,5-Aryl group migration from a carbon atom to a carbon radical with translocation of the radical center has been reported and used for the preparation of various biaryl systems.[94b,101]

Transposition of a radical center, involving a 1,4- or 1,5-aryl group migration from silicon to a carbon radical was also discovered. Migration (1,4- or 1,5-) of an aryl group from the sterically crowded diphenylsilyl ether group **136** to the carbon radical **137** in 4- (or 5-) position proceeds with excellent levels of stereocontrol (Scheme 30, Eq. (49)).[102]

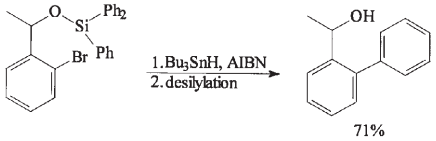


Scheme 30



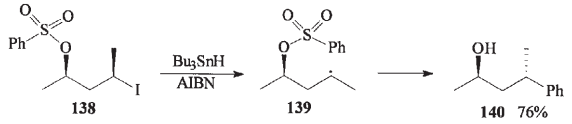
(49)

Stereoselective intramolecular 1,5-aryl migrations from silicon to a carbon radical have been used for the preparations of various biaryl systems. In these processes the transposition of a radical center from the aromatic ring to silicon is an irreversible process and the corresponding diaryl derivatives were obtained in good yields (Eq. (50)).[103]



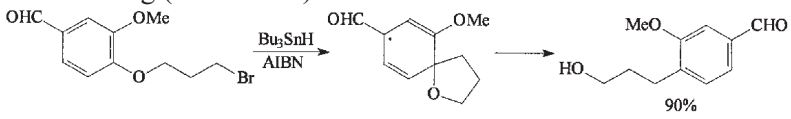
(50)

It was found that the transposition of a radical center, involving a 1,5-aryl group migration from sulfur to a carbon radical, is a convenient method for stereo-controlled arylation. Thus 1,5-aryl group migration in the sulfonate **138** to the secondary carbon radical **139** proceeds with the stereoselective formation of the C–C bond in **140** (Scheme 31).[104]



Scheme 31.

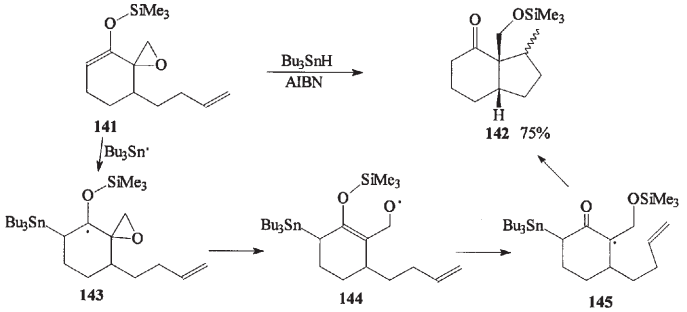
1,4-Transposition of radical from a carbon to an oxygen atom involves an aryl group migration from an ether oxygen to carbon radical. This type of aryl group transfer was found to occur when captodatively stabilized substituents are present on the aromatic ring (Scheme 32).[98]



Scheme 32.

6.3. Transposition of silyl groups

1,5-Transposition of a radical center from an ether oxygen to an alkoxyl radical was realised involving the transfer of trialkylsilyl (or -stannyl) group. Thus, by addition of a tributylstannyl radical onto the silyl enol double bond **141** and the

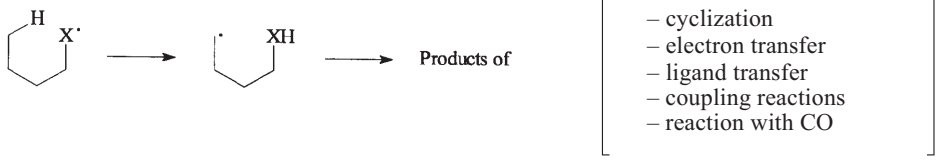


Scheme 33.

subsequent fragmentation of the epoxide ring the alkoxyl radical **144** is generated. Possessing appropriate structural and stereochemical conditions the alkoxyl radical **144** undergoes 1,5-migration of the trialkylsilyl group and the enoxyl (α-carbonyl) radical **145** is formed, which cyclizes to give the fused bicyclic product **142** in good yield (Scheme 33).[105]

7. CLOSING REMARKS

1,5-Transposition of radical centers represents a remarkable and powerful method for the introduction of functional groups at non-activated carbon atoms. δ-Carbon–carbon bond forming reactions can also be carried out on the relocated carbon radical center. The introduction of appropriate functionality by 1,5-hydrogen atom abstraction then allows the rich chemistry of both carbanions and carbocations to be pursued. A number of examples and reactions have been illustrated which prove the generality and synthetic usefulness of reactions involving a 1,5-hydrogen atom transfer. Some of the key pathways for the evolution of the relocated carbon centered radical which have thereby been developed are shown in Scheme 34. Bearing in the mind the diversity of this type of reactions, it is possible to incorporate radical translocation methodology into useful synthetic strategy.



Scheme 34.

Transposition of a radical center from alkoxyl and aminyl radicals to saturated, non-activated, carbon atoms are the favoured processes and reactions of this type have a large number of synthetic applications. While relocations of radical centers from one to another carbon atom are possible when the stability of the radicals are considerably different, however these reactions are of less synthetic importance.

ИЗВОД

РЕАКЦИЈЕ УГЉЕНИКОВИХ РАДИКАЛА НАСТАЛИХ 1,5-РЕЛОКАЦИЈОМ РЕАКТИВНОГ ЦЕНТРА

ЖИВОРАД ЧЕКОВИЋ

Хемијски факултет, Студентски трг 16, п.пр. 158, 11000 Београд

Радикалски интермедијери подлежу неким специфичним реакцијама, као што су интрамолекулска премештања односно релокације радикалског центра, које нису познате код класичних јонских органских реакција. 1,5-Релокације радикалског центра на

неактивирани угљеников атом су од великог синтетичког значаја јер омогућавају увођење разних функционалних група (кисеоничних, азотних, сумпорних, халогена) на угљеников атом удаљен од присутне функционалне групе. Поред функционализације удаљених неактивираних угљеникових атома могу се извршити и реакције при којима се стварају нове C–C везе на δ-угљенику. 1,5-Релокације радикалског центра врше се са алкокси, аминил или угљеникових радикала на удаљени угљеников атом. Релокације радикала најчешће обухватају 1,5-трансфер водониковог атома, мада су познате и миграције неких група. Приказане су реакције угљеникових радикала насталих 1,5-релокацијом радикалског центра и дат је преглед синтетичких примена ових реакција.

(Примљено 6. новембра 2004)

REFERENCES

1. For recent leading references see: a) L. Feray, N. Kuznetsov, P. Renaud, in *Radicals in Organic Synthesis*, P. Renaud, M. B. Sibi, Eds., Wiley-VCH, Weinheim, 2001, Vol. 2, p. 246, Ch. 3.6; b) Ž. Čeković, *Tetrahedron* (Report No 653). **59** (2003) 8073; c) J. Robertson, J. Pillai, R. K. Lush, *Chem. Soc. Rev.* **30** (2001) 94; d) G. Majetich, K. Wheless, *Tetrahedron* (Report No 375) **51** (1995) 7095
2. a) D. P. Curran in *Comprehensive Orgnaic Synthesis*, B. M. Trost, I. Fleming, Eds., Pergamon Press, New York, 1991, Vol .4. pp. 715 and 779; b) B. Giese, B. Kopping, T. Göbel, J. Dickhaut, G. Thoma, K. J. Kulicke, F. Trach, *Org. Reactions.* **48** (1996) 301; c) D. P. Curran, N. A. Porter, B. Giese, *Stereochemistry of Radical Reactions – Concepts, Guidelines* and *Synthetic Application,* VCH Publishers, Weinheim, New York, 1996; d) M. Ramaiah, *Tetrahedron* **43** (1987) 3541; e) C. P. Jasperse, D. P. Curran, T. L. Fevig, *Chem. Rev.* **91** (1991) 1237
3. a) J. Kalvoda, K. Heusler, *Synthesis* (**1971**) 501; b) M. Lj. Mihailović, Ž. Čeković, *Synthesis* (**1970)** 209; c) R. H. Hesse, *Advan. Free Radical Chem.* **3** (1969) 83; d) M. Lj. Mihailović, Ž. Čeković, Lj. Lorenc, *Oxidations with Lead Tetraacetate* in *Organic Synthesis by Oxidation with Metal Compounds*, W. J. Mijs, C. R. H. I. De Jonge, Eds., Plenum Press, New York, 1986, p. 758
4. a) A. Srikrishna, in *Radicals in Organic Synthesis*, P. Renaud, M. B. Sibi, Eds., Wiley-VCH, Weihneim, 2001, Vol. 2, pp. 151; b) J. Hartung in *Radicals in Organic Synthesis*, P. Renaud, M. B. Sibi, Eds., Wiley-VCH: Weinheim, 2001, Vol. 2, p. 427
5. a) E. Suárez, in *Radicals in Organic Synthesis*, P. Renaud, M. B. Sibi, Eds., Wiley-VCH, Weinheim, 2001, Vol. 2, p. 440; b) A. Gansäuer, M. Pierobon in *Radicals in Organic Synthesis*, P. Renaud, M. B. Sibi, Eds., Wiley-VCH, Weinheim, 2001, Vol. 2, p. 207
6. J. H. Honer, S.-Y. Choi, M. Newcomb, *Org. Lett*. **2** (2000) 3369
7. a) V. Malatesta, K. U. Ingold., *J. Am. Chem. Soc.* **103** (1981) 609; b) V. Malatesta, J. S. Scaiano, *J. Org. Chem.* **47** (1982) 1455
8. a) D. P. Curran, H. S. Yu. H. T. Liu, *Tetrahedron* **50** (1994) 7343; b) D. P. Curran, A. C. Abraham, *Tetrahedron* **49** (1993) 4821
9. a) A. E. Dorigo, K. N. Houk, *J. Org. Chem*. **53** (1988) 1650; b) R. T. Weavers, *J. Org. Chem*. **66** (2000) 6453
10. G. Petrović, R. N. Saičić, Lj. Došen-Mićović, Ž. Čeković, *J. Serb. Chem. Soc.,* **69** (2004) 737
11. a) M. Lj. Mihailović, Ž. Čeković, D. Jeremić, *Tetrahedron* **21** (1965) 2813; b) M. Lj. Mihailović, R. Matić, S. Orbović, Ž. Čeković, *Bull. Soc. Chim. Beograd* **36** (1971) 363; c) M. Lj. Mihailović, L. Živković, Z. Maksimović, D. Jeremić, Ž. Čeković, R. Matić, *Tetrahedron* **23** (1967) 3095
12. M. Fish, S. Smallcombe, J. C. Gramain, M. A. McKervey, J. A. Anderson, *J. Org. Chem.* **35** (1970) 1886; b) W. A. Ayer, D. A. Law, K. Piers, *Tetrahedron Lett.* (1964) 2952
13. a) M. Lj. Mihailović, Ž. Čeković, J. Stanković, *J. Chem. Soc., Chem. Comm.* (1969) 981; b) R. A. Sneen, N. P. Matheny, *J. Am .Chem. Soc.* **86** (1969) 3905, see also 5503

14. a) C. Walling, A. Padwa, *J. Am. Chem. Soc.* **83** (1961) 2207 and **85** (1963) 1597; b) C. Walling, D. Bristol, *J. Org. Chem.* **37** (1972) 3514; c) Ž. Čeković, G. Djokić, *Tetrahedron* **37** (1981) 4263
15. a) D. H. R. Barton, *Pure Appl. Chem.* **16** (1968) 1; b) D. H. R. Barton, S. I. Parakh, *Half Century of Free Radical Chemistry*, Cambridge University Press, Cambridge, 1993
16. a) Ž. Čeković, M. M. Green, *J. Am. Chem. Soc.* **96** (1974) 3000; b) B. Acott, A. L. J. Beckwith, *Aust. J. Chem.* **17** (1964) 1342
17. G. Petrović, Ž. Čeković, *Tetrahedron Lett.* **38** (1997) 627 and *Tetrahedron* **55** (1999) 1377
18. a) J. Hartung, F. Gallou, *J. Org .Chem.* **60** (1995) 6706; b) A. L. J. Beckwith, B. P. Hay, *J. Am. Chem. Soc.* **110** (1988) 4415
19. S. Kim, T. A. Lee, Y. Song, *Synlett* (**1998**) 471
20. a) D. H. R. Barton, H. R. S. Motherwell, W. B. Motherwell, *J. Chem. Soc. Perkin Trans. 1* (1981) 2363; b) V. H. Rawal, R. C. Newton, V. Krishnamurtz, *J. Org. Chem.* **55** (1990) 5181
21. a) M. Lj. Mihailović, G. Milošević, A. Milovanović, Ž. Čeković, *Bull. Soc. Chim. Beograd* **43** (1978) 361; b) M. Lj. Mihailović, G. Milošević, A. Milovanović, *Tetrahedron*, **34** (1978) 2587
22. M. Lj. Mihailović, M. Miloradović, *Tetrahedron* **22** (1966) 723
23. a) M. Lj. Mihailović, Ž. Čeković, Z. Maksimović, D. Jeremić, Lj. Lorenc, R. I. Mamuzić, *Tetrahedron* **21** (1965) 2799; b) M. Lj. Mihailović, M. Jakovljević, V. Trifunović, R. Vukov, Ž. Čeković, *Tetrahedron* **24** (1968) 6959
24. V. M. Mićović, S. Stojčić, M. Bralović, S. Mladenović, D. Jeremić, M. Stefanović, *Tetrahedron* **25** (1969) 985
25. M. Lj. Mihailović, Ž. Čeković, V. Andrejević, R. Matić, D. Jeremić, *Tetrahedron* **24** (1968) 4947
26. J. Bošnjak, V. Andrejević, Ž. Čeković, M. Lj. Mihailović, *Tetrahedron* **28** (1972) 6031
27. W. H. W. Lunn, W. D. Podmore, S. S. Szinai, *J. Chem. Soc. (C)* (**1968)** 1657
28. A. Bowers, E. Denot, L. C. Ibannez, M. E. Cabezas, H. J. Ringold, *J. Org. Chem.* **27** (1962) 1862
29. S. Tsunoi, I. Ryu, T. Okuda, M. Tanaka, M. Komatsu, N. Sonoda, *J. Am. Chem. Soc.* **120** (1998) 8692
30. a) C. Meystre, K. Heusler, J. Kalvoda, P. Wieland, G. Anner, A. Wettstein, *Helv. Chim. Acta* **45** (1962) 1317; b) K. Heusler, J. Kalvoda C. Meystre, G. Anner, A. Wettstein, *Helv. Chim. Acta* **45** (1962) 2161
31. a) A. L. Brachet-Cota, G. Burton, *Z. Naturforsch.B*. **43** (1988) 491; b) S. J. Danishefsky, D. M. Armistead, F. E. Wincott, H. G. Selnick, R. Hungate, *J. Am. Chem. Soc.* **109** (1987) 8117
32. a) A. G. Gonzalez, R. L. Dorta, A. G. Rovelo, J. G. Luis, *J. Chem. Res. S* (1988) 150; b) R. Hernandez, S. M. Velazquez, E. Suarez, M. S. Rodriguez, *J. Org. Chem.* **59** (1994) 6395
33. R. L. Dorta, C. G. Francisco, R. Freire, E. Suarez, *Tetrahedron Lett*. **29** (1988) 5429
34. K. Heusler, J. Kalvoda, *Angew. Chem., Int. Ed. Engl.* **3** (1964) 525
35. G. Habermehle, J. Reibstein, *Liebigs Ann. Chem.* (**1978**) 411
36. a) M. Akhtar, P. Hunt, P. B. Dewhurst, *J. Am. Chem. Soc.* **87** (1965) 1807; b) V. Boido, O. E. Edwards, *Can. J. Chem.* **49** (1971) 2664; c) A. Deluzarche, A. Maillard, P. Rimmelin, F. Schue, J. M. Sommer, *J. Chem. Soc. Chem. Comm.* (**1970**) 976
37. T. W. Gibson ,W. F. Erman, *J. Am. Chem. Soc.* **91** (1969) 4771
38. F. D. Grene, M. L. Savitz, F. D. Osterholtz, h. H. Lau, W. Smith, P. M. Zanet, *J. Org. Chem.* **28** (1963) 55
39. a) D. H. R. Barton, J. M. Beaton, *J. Am. Chem. Soc.* **82** (1960) 2641 and **83** (1961) 4083; b) D. H. R. Barton, M. J. Akhtar, *J. Am. Chem. Soc.* **84** (1962) 1496 and **86** (1964) 1528
40. H. Suginome, Y. Nakayama, H. Senboku, *J. Chem. Soc., Perkin Trans.* (1992) 1837
41. J. M. Midgley, J. E. Parkin, W. B. Whalley, *J. Chem. Soc., Chem. Comm.* (1970) 789
42. D. H. R. Barton, R. P. Budhiraja, J. F. McGhie, *J. Chem. Soc., Part C* (1969) 336
43. P. L. Stotter, K. A. Hill, M. D. Friedman, *Heterocycles* **25** (1987) 259
44. M. Akhtar, D. H. R. Barton, P. G. Sames, *J. Am. Chem. Soc.* **87** (1965) 4601

45. a) J. Allen, R. B. Boar, J. F. McGhie, D. H. R. Barton, *J. Chem. Soc., Perkin Trans.* (1973) 2402; b) D. H. R. Barton, M. J. Day, R. H. Hesse, M. M. Pechet, *J. Chem. Soc., Perkin Trans*. (1975) 2252
46. Ž. Čeković, D. Ilijev, *Tetrhedron Lett.* **29** (1988) 1441
47. a) Ž. Čeković, T. Srnić, *Tetrahedron Lett*. (1976) 561; b) Ž. Čeković, *Rad. Jugosl. akad. znan. i umjet. kem.* **2** (1983) 21
48. A. L. J. Beckwith, B. P. Hay, G. M. Williams, *J. Chem. Soc., Chem. Comm*. (1989) 1202
49. a) G. Petrović, R. N. Saičić, Ž. Čeković, *Tetrahedron Lett.,* **38** (1997) 7107; b) G. Petrović, R. N. Saičić, Ž. Čeković, *Tetrahedron* **59** (2003) 187
50. G. Petrović, R. N. Saičić, Ž. Čeković, *Synlett* (1999) 635; b) G. Petrović, R. N. Saičić, Ž. Čeković, *Helv. Chim. Acta* **86** (2003) 3179
51. a) G. Petrović, Ž. Čeković, *Org. Lett.* **2** (2000) 3769; b) G. Petrović, Ž. Čeković, *Synthesis* (**2004**) 1671
52. Ž. Čeković, Lj. Dimitrijević, G. Djokić, T. Srnić, *Tetrahedron* **35** (1979) 2021
53. Ž. Čeković, M. Cvetković,*Tetrahedron Lett.* **23** (1982) 3791
54. M. J. Begley, N. Housden, A. Johns, J. A. Murphy, *Tetrahedron* **47** (1991) 8417
55. T.-J. Lee, W. F. Hoffman, W. J. Holtz, R. L. Smith, *J. Org. Chem.* **57** (1992) 1966
56. S. Kim, S. Lee, J. C. Koh, *J. Am. Chem. Soc.* **113** (1991) 5106
57. a) V. H. Rawal, V. Krishnamurthy, A. Fabre, *Tetrahedron Lett.* **34** (1993) 2899; b) V. H. Rawal, V. Krishnamurthy, *Tetrahedron Lett.* **33** (1992) 3439
58. D. Crich, X. Huang, M. Newcomb, *Org. Lett.* **1** (1999) 225
59. S. Kim, T. A. Lee, *Synlett* (1997) 950
60. L. Stella, in *Radicals in Organic Synthesis*, P. Renaud, M. B. Sibi, Eds., Wiley-VCH, Weinheim, 2001, Vol. 2, p. 407
61. B. J. Maxwell, J. Tsanaktsidis, in *N-Centered Radicals*, Z. B. Alfasi, Ed., Wiley, Chichester, 1998
62. M. E. Wolf, *Chem. Rev.* **63** (1963) 55
63. a) A. W. Hofmann, *Chem. Ber.* **16** (1883) 558; b) K. Loeffler, C. Freytag, *Chem. Ber.,* **42** (1909) 3427
64. E. J. Corey, W. R. Hertler, *J. Am. Chem. Soc.* **82** (1960) 1657
65. S. L. Titouani, J. P. Levergne, P. Viallefont, R. Jacquier, *Tetrahedron* **36** (1980) 2961
66. Y. Shibanuma, T. Okamoto, *Chem. Pharm. Bull.,* **33** (1985) 3187
67. G. van de Woude, L. van Hove, *Bull. Soc. Chim. Belg.* 82 (1973) 49 and **84** (1975) 911
68. a) D. H. R. Barton, A. L. J. Beckwith, A. Gossen, *J. Chem. Soc.* (1965) 181; b) C. Betancor, J. I. Concepcion, R. Hernandez, J. A. Salazar, E. Suarez, *J. Org. Chem.* **48** (1983) 4430
69. R. S. Neale, *Synthesis* (1971) 1
70. S. W. Baldwin, R. J. Doll, *Tetrahedron Lett*. (1979) 3275
71. R. Carrau, R. Hernandez ,E. Suarez, C. Betancor, *J. Chem. Soc., Perkin Trans. 1* (1987) 937
72. P. De Adams, C. G. Francisco, R. Hernandez, J. A. Salazar, E. Surez, *J. Chem. Soc., Perkin Trans. 1* (1988) 3255
73. G. I. Nikishin, F. Troyansky, M. I. Lazareva, *Tetrahedron Lett.* **26** (1985) 1877 and 3743
74. S. Kim, K. M. Yeon, K. S. Yoon, *Tetrahedron Lett*. **38** (1997) 3919
75. a) S. D. Burke, K. W. Jung, *Tetrahedron Lett.* **35** (1994) 5837; b) S. D. Burke, K. E. Jung, R. E. Perri, *Tetrahedron Lett.* **35** (1994) 5841
76. E. Bosch, M. D. Bachi, *J. Org. Chem.* **58** (1993) 5581
77. a) I. Rochigneux, M.-L. Fontanel, J.-C. Malanda, A. Doutheau, *Tetrahedron Lett.* **32** (1991) 2017; b) J.-C. Malanda, A. Doutheau, *J. Carbohydr. Chem.,* **12** (1993) 999
78. S. Bogen, M. Gulea, L. Fensterbank, M. Malacria, *J. Org. Chem.* **64** (1999) 4920
79. D. L. J. Clive, W. Yong, *J. Chem. Soc., Chem. Comm.* (1996) 1605
80. J. Robertson, M. A. Peplow, J. Pillai, *Tetrahedron Lett.* **37** (1996) 5825

81. D. P. Curran, A. C. Abraham, H. Liu, *J. Org. Chem.* **56** (1991) 4335
82. D. P. Curran, H. Yu, *Synthesis* (1992) 123
83. D. P. Curran, J. Y. Xu, *J. Am. Chem. Soc.* **118** (1996) 3142
84. V. Snieckus, J.-C. Cuevas, C. P. Sloan, H. Liu, D. P. Curran, *J. Am. Chem. Soc.,* **112** (1990) 896
85. M. Ikeda, Y. Kugo, Y. Kondo, T. Yamazaki ,T. Sato, *J. Chem. Soc., Perkin Trans 1* (**1997**) 3339
86. D. P. Curran, A. C. Abraham, *Tetrahedron* **49** (1993) 4821
87. L. Girand, P. Renaud, *J. Org. Chem.* **63** (1998) 9162
88. a) J. D. Winkler, B.-C. Hong, *Tetrahedron Lett.* **36** (1995) 683; b) J. D. Winkler, V. Sridar, L. Rubo, J. P. Hey, N. Haddad, *J. Org. Chem.* **54** (1989) 3004
89. a) L. Boiteau, J. Boivin, B. Quicletsire, J. B. Saunier, S. Z. Zard, *Tetrahedron* **54** (1998) 2087; b) M. Masnyk, *Tetrahedron Lett.* **38** (1997) 879
90. J. Boivin, E. Da Silva, G. Ourisson, S. Z. Zard, *Tetrahedron Lett.* **31** (1990) 2501
91. a) J. Kalvoda, C. Meystre, G. Anner, *Helv. Chim. Acta* **49** (1966) 424; b) J. Kalvoda, L. Botta, *Helv. Chim. Acta* **55** (1972) 356
92. R. W. Freerkksen, W. E. Pabst, M. L. Raggio, S. A. Sherman, R. R. Worble, D. S. Watt, *J. Am. Chem. Soc.* **99** (1977) 1536
93. J. Cossy, C. Poitevin, D. G. Pardo, J. L. Peglion, *Synthesis* (1995) 1368
94. a) K. A. Parker, D. M. Spero, K. C. Inman, *Tetrahedron Lett*. **27** (1986) 2833; b) A. N. Abeywickrema, A. L. J. Beckwith, S. Gerba, *J. Org. Chem.* **52** (1987) 4072; c) L. Giraud, E. Lacôte, P. Renaud, *Helv. Chim. Acta* **80** (1997) 2148
95. a) J. Grimshaw, R. Hamilton, J. Trocha-Grimshaw, *J. Chem. Soc., Perkin 1* (1982) 229; b) E. Lee, H. S. Whang, C. K. Chung, *Tetrahedron Lett.* **36** (1995) 913
96. a) J. J. Köhler, W. N. Speckamp, *Tetrahedron Lett.* (**1977**) 631 and 635; b) M. L. E. N. Da Mata, W. B. Motherwell, F. Ujjainwalla, *Tetrahedron Lett.* **38** (1997) 137 and 141
97. J. W. Wilt, C. F. Dockus, *J. Am. Chem. Soc.* **92** (1970) 5813
98. a) E. Lee, C. Lee, J. S. Tae, H. S. Wang, K. S. Li, *Tetrahedron Lett.* **34** (1993) 2343; b) D. Crich, J.-T. Hwang, *J. Org. Chem.,* **63** (1998) 2765
99. M. Julia, B. Malassine, *Tetrahedron Lett.* (1971) 987
100. H. Senboku, H. Hasegawa, K. Orito, M. Tokuda, *Tetrahedron Lett.* **41** (2000) 5699
101. B. Alcaide, A. Rodriguez-Vicente, *Tetrahedron Lett.* **39** (1998) 6589
102. S. Amrein, M. Bossart, T. Vasella, A. Studer, *J. Org. Chem.* **65** (2000) 4281
103. A. Studer, N. Bossart, T. Vasella, *Org. Lett.* **2** (2000) 985
104. A. Studer, M. Bossart, *J. Chem. Soc., Chem. Comm.* (1998) 2127
105. S. Kim, J. Y. Do, K. M. Lim, *J. Chem. Soc., Perkin Trans 1* (1994) 2517.