ELECTROCHEMICAL REDUCTION OF ALLYL ETHERS IN THE PRESENCE OF NICKEL COMPLEXES: A REVIEW OF SYNTHETIC APPLICATIONS

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Received October 13, 1999
Accepted April 7, 2000

Presented at the 32nd Heyrovský Discussion on Organic Electrochemistry, Třešť, June 6–10, 1999.

This review deals with the electrochemical reactivity of a family of organic compounds, namely allyl ether derivatives, in the presence of various catalytic systems. Essentially, nickel complexes associated with various ligands have been described for such reactions. The electrochemical reduction of allyl aryl ethers has been reported to be very dependent on the nature of the catalytic system. Ni(II) complexes with 2,2′-bipyridine ligands selectively catalyze the cleavage of the O–C(allyl) bond to afford the corresponding alcohol or phenol derivatives in good yields. The related *ortho*-halogenated allyl ether substrates, in the presence of Ni(II) catalysts with cyclam-type macrocyclic ligands undergo intramolecular cyclizations. The nature of the ligand on nickel strongly influences the reactivity and the chemoselectivity of these processes. A review with 62 references.
Key words: Electrochemical reductions; Nickel; Allyl ethers; Cleavage; Cyclization; Protecting groups; Bipyridine ligands.

1. INTRODUCTION

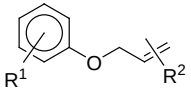
In the field of electrosynthesis associated with organometallic chemistry[1], there has been some interest in the synthesis of organic compounds involving C–C bond formation catalyzed by nickel complexes. Electrogenerated $L_nNi(0)$ or $L_nNi(I)$ complexes (L = ligand, n = 1–4) can be obtained from electrochemical reduction of stable Ni(II) derivatives depending on the nature of the ligand associated to the metal complex. Thus, $L_nNi(0)$ complexes with L = phosphine[2,3], diphosphine[4] or 2,2′-bipyridine[5,6] have been electrochemically prepared and used in several coupling reactions. In contrast, with tetraazamacrocycle ligands, Ni(I) species are known to be generated upon electrochemical reduction of the corresponding Ni(II) complexes[7,8].

This review summarizes studies on the chemoselectivity observed in the electrochemical reduction of functionalized and non-functionalized allyl aryl ethers in the presence of several metal complex catalysts, particularly of Ni(II) catalyst precursors, as well as studies on organically mediated or non-catalyzed electrochemical reactions. The reports in the literature indicate that the reactivity of allyl ether substrates is very dependent on the nature of the organometallic catalytic species involved in the processes. Tandem reactions in the presence of carbon dioxide have also been reported.

2. ELECTROREDUCTION OF ALLYL ETHERS IN THE ABSENCE OF CATALYST

Electrochemical reactivity of allyl ether substrates of type **1** has been studied in the presence of several organometallic complexes as well as in the absence of catalyst. The allyl ether substrates are generally prepared in almost

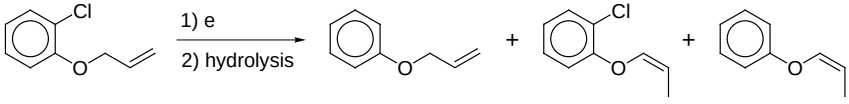
quantitative yields by treatment of the corresponding phenol derivatives with the desired allyl chloride or bromide, in basic medium.



1

1	R^1	R^2
a	H	H
b	2-Cl	H
c	2-Br	H
d	2-I	H
e	2-Cl	(*E*)-3-Ph
f	2-Cl	2'-Me
g	4-Cl	H
h	2-Br	2-Me
i	2-COOMe	H
j	2-CN	H
k	4-CN	H

A direct, non-catalyzed electroreduction of 1-allyloxy-2-chlorobenzene, **1b**, in a two-compartment cell has been reported[9]. The reaction led mainly to dehalogenation with formation of allyl phenyl ether, together with double bond isomerization to (prop-1-en-1-yloxy)benzene (Scheme 1).



SCHEME 1

The product ratio and selectivities were very dependent on the nature of the cathode material. However, no intramolecular cyclization occurred.

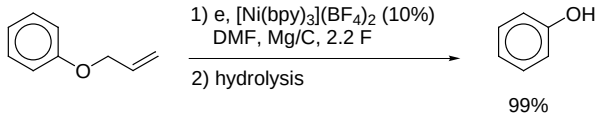
3. ELECTROCHEMICAL REDUCTION OF ALLYL ETHERS IN THE PRESENCE OF NICKEL-BIPYRIDINE COMPLEXES

Nickel(II) complexes with 2,2′-bipyridine ligands are stable and can be easily prepared in absolute ethanol from the corresponding hydrated Ni(II) salts in the presence of the ligand. The cationic pink complex $[Ni(bpy)_3](BF_4)_2$ (ref.[10]) has been used as catalyst precursor in several electro-chemical coupling reactions[11,12].

3.1. Reactivity of Allyl Haloaryl Ethers

The $[Ni(bpy)_3](BF_4)_2$ complex has been reported to catalyze the electroreduction of **1a** to phenol in 99% yield after consumption of 2.2 F (ref.[13]).

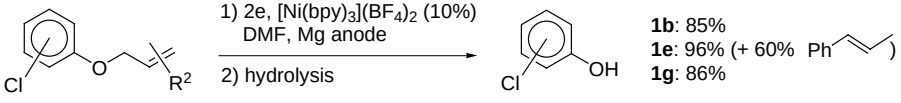
The reaction was carried out in a one-compartment cell fitted with a consumable magnesium anode[14,15] in DMF at room temperature, under constant current conditions (Scheme 2).



SCHEME 2

The chloro derivative **1b**, electrolyzed in the presence of $[Ni(bpy)_3](BF_4)_2$, led to 2-chlorophenol in 85% yield after consumption of 2 F (Scheme 3).

Under the same conditions, the reaction in the absence of the nickel complex was reported to afford a non-selective mixture of phenol, 2-chlorophenol, (prop-1-en-1-yloxy)benzene, formed by isomerization of the side-chain double bond, in agreement with the direct electroreduction of **1b** in a two-compartment cell[9]. The Ni–bpy system plays an important role in controlling both the chemical and current yields and in selectivity of the process. The behaviour of other halogenated allyl aryl ethers has been reported[13]. 2-Chloro derivative **1e**, as well as 4-chloro **1g** gave the corresponding chlorophenols in excellent yields (Scheme 3). The results indicate that the C–O bond of the allyl ether was cleaved preferentially to the aromatic C–Cl bond when the nickel–bipyridine complex was present as a catalyst.



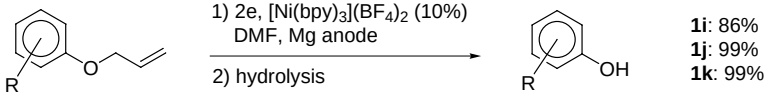
SCHEME 3

The electrolysis of substrate **1e** gave, besides 2-chlorophenol, 60% of (*E*)-(prop-1-en-1-yl)benzene indicating that the allyl moiety was protonated by the reaction medium and did not dimerized. The remaining allyl moiety was polymerized. The electrolysis of the allyl bromoaryl derivative **1c** led quantitatively to phenol after consuming 4.5 F, in one-compartment cells with magnesium anodes and under constant current conditions. Only a very low concentration of 2-bromophenol or allyl phenyl ether could be detected during the reaction, indicating that both the cleavage of the aryl–Br bond and of the O–C(allyl) bond occurred simultaneously. The same reaction carried out at a controlled potential (*e.g.* at –1.2 V *vs* SCE, the potential of the Ni(II)/Ni(0) reduction) in a two-compartment cell afforded 2-bromophenol in a quantitative yield. The reaction was more selective un-

der controlled potential. In this case, only the allyl moiety was cleaved[16]. However, catalytic reactions worked more efficiently when run in one-compartment cells with consumable anodes.

3.2. Electroreduction of Other Functionalized Allyl Aryl Ethers

Functionalized allyl aryl ethers with ester or cyano groups (**1i**–**1k**) were reduced under one-compartment cell conditions in the presence of $[Ni(bpy)_3](BF_4)_2$ using a magnesium anode to give the corresponding phenols in excellent yields (Scheme 4), without reduction of the ester or of the cyano functions[13].

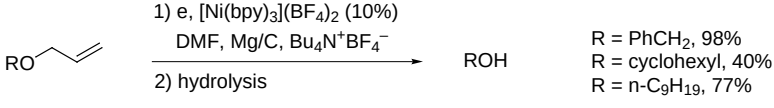


SCHEME 4

The $[Ni(bpy)_3](BF_4)_2$-catalyzed electrolysis of substrates **1** is thus a general and efficient method for allyl aryl ether deprotection yielding the parent phenols under mild conditions.

3.3. Electroreduction of Aliphatic Allyl Ethers

The above method was also applied to aliphatic and benzylic allyl ethers, constituting an interesting alternative to chemical procedures of allyl deprotection. These generally involve a strong base such as *t*-BuOK (ref.[17]) or the Rh(I)-catalyzed[18] double bond isomerization followed by strong acid hydrolysis. The combination of sodium borohydride with Pd(0) has also been described[19]. Aliphatic and benzylic allyl ethers were deprotected giving parent alcohols in good yields under mild conditions, as shown in Scheme 5.

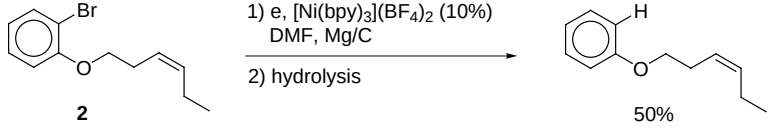


SCHEME 5

Electrochemistry offers an interesting approach for the mild functional group deprotection[20,21], particularly, Sm(III) catalysts have been reported for the electrochemical allyl aryl ether deprotection[22].

3.4. Electroreduction of Homoallyl Ethers and Enol Ethers

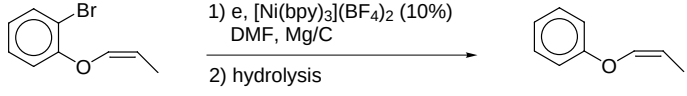
The Ni–bipy catalytic system has also been tested for the C–O cleavage reaction of homoallylic ethers such as compound **2**. However, in this case, **2** underwent debromination without cleavage of the C–O bond[13] (Scheme 6).



2 50%

SCHEME 6

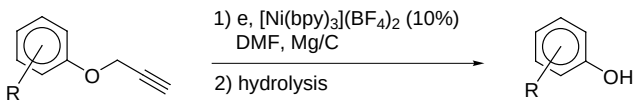
The question whether enol ethers could be reaction intermediates in the electrochemical deallylation reaction, like in the chemical methods involving double bond isomerization was adressed. Electrolysis of enol ether **3** (*Z*/*E* 9 : 1)[17], followed by neutral hydrolysis did only affect the C–Br bond reduction, but did not modify the enol ether functionality[16] (Scheme 7).



3, (*Z*/*E* 9 : 1) 75%

SCHEME 7

This result is taken to indicate that the electrochemical allyl ether cleavage does not proceed through double bond isomerization. Propargylic aryl ethers and esters have also been reported to be cleaved by the $[Ni(bpy)_3](BF_4)_2$-catalyzed electrochemical reduction[23] (Scheme 8).

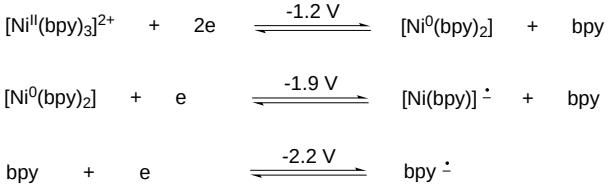


SCHEME 8

3.5. Mechanistic Considerations

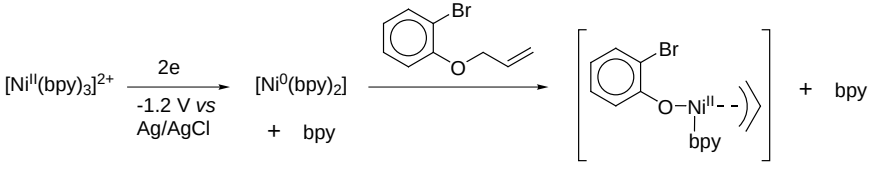
Mechanistic studies on the allyl cleavage by electrogenerated Ni–bipyridine complexes have not yet been reported. However, the mechanism of electrochemical ether cleavage involving the formation of (π^3-allyl)nickel intermediates has been proposed[16]. (π^3-Allyl)nickel complexes have been reported to form from reaction of Ni(0) with allyl halides or acetates[24–26]. In electrochemical reactions, the $[Ni^0(bpy)_2]$ species are known to be formed in re-

duction of Ni(II) complexes, as follows from cyclic voltammetry studies[27,28] (Scheme 9).



SCHEME 9

These electrogenerated $[Ni^0(bpy)_2]$ species have been proposed to react with allyl ether derivatives by Ni(0) insertion into the O–C(allyl) bond, to form a (π^3-allyl)nickel intermediate (Scheme 10).



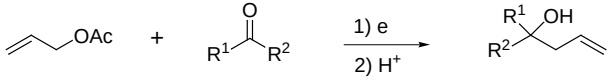
SCHEME 10

Further hydrolysis should allow isolation of the corresponding phenol derivatives.

Controlled-potential electrolyses carried out at the Ni(II)/Ni(0) reduction potential indicated that Ni(0) was the active catalytic species responsible for the O–allyl cleavage in this system[16]. As compared to chemical reactions involving Ni^0 complexes and allyl ethers, the stoichiometric reaction with allyl phenyl ether has been reported to afford a (π^3-allyl)nickel complex[25]. (π^3-Allyl)nickel complexes have been reported to undergo dimerization and to present a low nucleophilic character, as shown be their slow reactivity towards carbonyl compounds[24].

3.6. Electrochemical Allylation of Carbonyl Compounds

Several electrochemical reactions involving the reduction of allyl halides or acetates in the presence of carbonyl compounds for the synthesis of homoallyl alcohols have been described (Scheme 11).

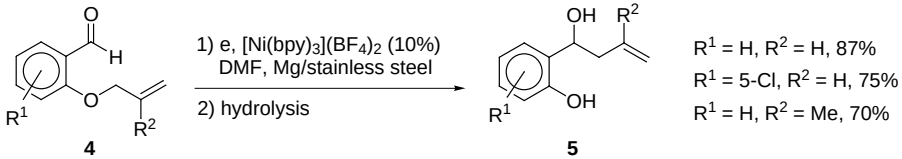


SCHEME 11

In the absence of catalysts, the reaction has been described to afford mixtures of homoallylic alcohols together with pinacol and aldol-type adducts and alcohols of reduction[29]. Allylation in the presence of tin catalysts[30], Sm(III) species[31] or in the presence of [Ni(bpy)]Br_2 and using a zinc anode[6a,32] have also been reported to afford the corresponding homoallylic alcohols in good yields. (π^3-Allyl)nickel species have been suggested as intermediates in the latter case. Stoichiometric allylations of carbonyl compounds with (π^3-allyl)nickel complexes were slow reactions, the complexes having the tendency to dimerize[24,25]. Electrochemical allylation of carbonyl compounds with allyl aryl ethers as the source of allyl group have also been examined in the presence of Ni–bpy catalytic systems, but low yields of homoallyl alcohols have been reported[16].

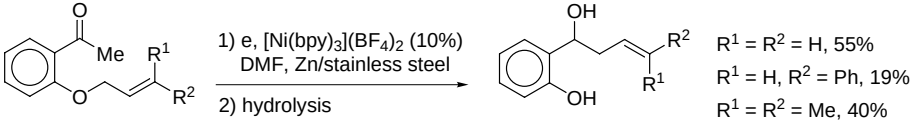
3.7. Intramolecular Allylation of Carbonyl Compounds from Allyl Aryl Ethers

The allyl ether cleavage and further intramolecular allyl transfer reaction have been examined with aromatic substrates such as **4** (Scheme 12)[33].



SCHEME 12

Aldehydes were efficiently converted into the corresponding alcohol-phenol derivatives **5** in a [Ni(bpy)$_3$](BF$_4$)$_2$-catalyzed reaction in a one-compartment cell with a magnesium anode, as shown in Scheme 12. The intramolecular allyl transfer to ketones was not efficient using a Mg anode; the reaction of **6** afforded the deallylated phenol, formed from the allyl ether cleavage without allyl transfer. However, with a zinc anode, the intramolecular allylation of ketones to **7** could be effected in moderate yields, as shown by the examples in Scheme 13 (ref.[33]).



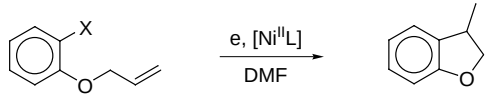
SCHEME 13

The analogous propargyl transfer reaction to carbonyl groups in propargyl ethers analogous to **4** has also been reported to afford homopropargyl alcohols in good yields[34].

4. REACTION OF ALLYL ETHERS IN THE PRESENCE OF NICKEL-TETRAAZA MACROCYCLE COMPLEXES

4.1. Intramolecular Cyclization Reactions

Intramolecular cyclizations of halogenated derivatives **1** have been reported with several Ni(II) complexes associated to nitrogen-containing macrocyclic ligands. Thus, the electrolysis of iodo allyl ether **1d** in the presence of $[Ni(teta)](ClO_4)_2$ as the catalyst (teta = Me_6cyclam = 5,7,7,12,14,14-hexamethyl-1,4,8,11-tetraazacyclotetradecane) allowed the preparation of 3-methyl-2,3-dihydro-1-benzofuran **8b** in 75% yield[35] (Scheme 14). The cyclization was carried out at controlled potential in two-compartment cells.

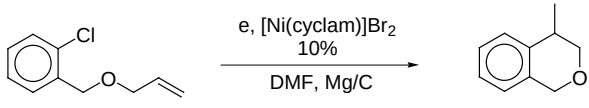


8b

1d, 2 compartments, [Ni(Me6cyclam)] $(ClO_4)_2$, 75%
1d, 1 compartment, $[Ni(cyclam)]Br_2$, 90%
1c, 1 compartment, $[Ni(cyclam)]Br_2$, 86%
1b, 1 compartment, $[Ni(cyclam)]Br_2$, 60%

SCHEME 14

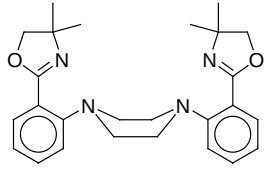
Cyclization of **1d**, as well as that of **1b** and **1c** have also been described under constant current conditions, in DMF, in one-compartment cells and using a magnesium anode[36] (Scheme 15). The process was catalyzed by $[Ni(cyclam)]Br_2$ (cyclam = 1,4,8,11-tetraazacyclotetradecane) and afforded **5b** in 60–90% yields, depending on the nature of the halogen group. Substituted allyl groups allowed the preparation of substituted 2,2-dihydrofuran analogs[36]. The preparation of dihydro-1- or -2-benzopyrans using the same procedure has been reported, by cyclization of homoallyl ethers or of allyl benzyl ethers, respectively (Scheme 15).



56%

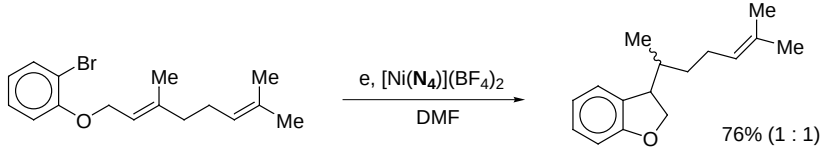
SCHEME 15

Intramolecular cyclizations have also been reported using analogous cyclam ligands such as Me_4cyclam (1,4,8,11-tetramethyl-1,4,8,11-tetraazacyclotetradecane). Salen-type ligands (H_2salen = *N*,*N*′-bis(salicylidene)-ethylenediamine) have also been reported in connexion with intramolecular cyclization[37]. Ni(II) complexes with tetraazamacrocycle ligands have also been used for related electrochemical intramolecular cyclizations involving triple bonds[36], vinyl bromides[38] and unsaturated bromoacetals[39,40]. The use of open tetraaza-type ligands (**N_4**) based on bis-(pyridine-oxazoline) structures have also been reported for the above



N_4

cyclizations, and good yields of 2,3-dihydrofuran or 2,3-dihydropyran derivatives have been obtained[41,42]. In the case of allyl ether with an additional double bond, a single cyclization occurred (Scheme 16).



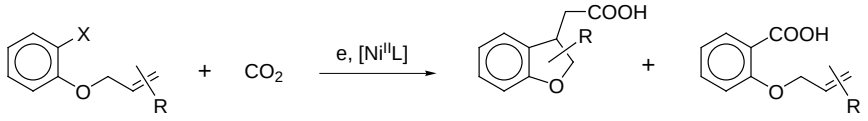
SCHEME 16

*4.2. Cyclization-Carboxylation Reactions of Compounds **1***

The electrolysis of several halogenated compounds **1** in the presence of carbon dioxide has been reported to lead to a tandem cyclization-carboxylation reaction in the presence of [Ni(cyclam)]Br_2 or [Ni(bpy)$_3$]$(BF_4)_2$ leading to the synthesis of 2,3-dihydro-1-benzofuran-3-acetic acid derivatives[43] (Scheme 17).

The Ni–cyclam system is known to efficiently catalyze the electrochemical reduction of CO_2 to CO in water-containing media[44,45]. However, in anhydrous DMF and in the presence of *ortho*-halogenated allyl ethers of type **1**, a cyclization with further CO_2 uptake has been recently reported. The direct carboxylation of the aryl–halogen bond leads to benzoic acid derivatives[2b,4a,14,15,46], by-products of this reaction (Scheme 17). The propargyl an-

alog of **1c** and **1d** has also been described to undergo a reductive cyclization with the carbon dioxide uptake in the presence of $[Ni(cyclam)]Br_2$ (ref.[43]). A mixture of mono- and dicarboxylated compounds was obtained.

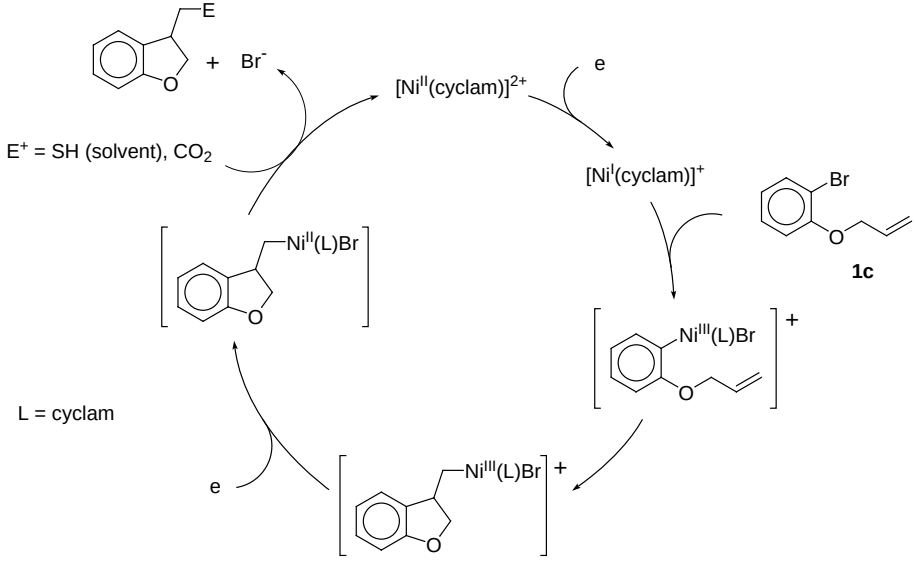


1c:	50%	36%
1d:	41%	13%
1f:	70%	15%
1h:	40%	–

SCHEME 17

4.3. Mechanistic Studies of the Electrochemical Intramolecular Cyclizations

Some mechanistic aspects of the cyclization of **1c** with $[Ni(cyclam)]Br_2$ have been studied by cyclic voltammetry and preparative controlled-potential electrolyses[47]. Cyclic voltammetry of $[Ni(cyclam)]^{2+}$ systems have shown the Ni(II)-to-Ni(I) reversible reduction at –1.45 V *vs* Ag|AgCl (refs[7,8]). This peak doubled its intensity and became irreversible on addition of one or more equivalents of **1c** (ref.[47]). A catalytic cycle for the cyclization of **1c** has been proposed (Scheme 18). The reaction involved electrochemical generation of Ni(I) complexes, which can insert replacing the aryl–halogen bond



SCHEME 18

of **1c** undergoing further side-chain cyclization on the double bond. The oxidative addition of electrogenerated $[Ni^{I}(cyclam)]^{+}$ complexes to alkyl bromides have been suggested to form alkyl Ni(III) intermediates[48]. The formal Ni(III) species were reduced to Ni(II) and then protonated by the electrolytic medium (solvent, supporting electrolyte), or in the presence of an electrophile, such as carbon dioxide[43]. It was shown that the Ni(II) species were more efficiently recycled in the presence of Mg^{2+} ions. The overall catalytic reaction consumed 2 F of **1c** and could be carried out at the Ni(II)/Ni(I) reduction potential.

Mechanistic aspects of the electrochemical cyclization of **1c** with Ni(II) with open bis(pyridine-oxazoline) ligands such as $\mathbf{N_4}$ have been reported[42]. In this case, a two-electron reduction of the Ni(II) complex was needed for the oxidative addition of **1c** onto the C–Br bond and its further cyclization in a Heck-type process[49]. Electrochemical and mechanistic studies on the cyclization-carboxylation process of **1c** with $[Ni(cyclam)]Br_2$ have also been described[43].

5. REACTIONS OF ALLYL ETHERS IN THE PRESENCE OF NICKEL PHOSPHINE COMPLEXES

Intramolecular cyclization of **1c** with electrogenerated Ni complexes have also been effected in the presence of phosphine ligands such as PPh_3 or dppe, 1,2-bis(diphenylphosphino)ethane to give **8b** in 35 or 48% yield, respectively[16]. Some cleavage of the O–C(allyl) group occurred, as well as some dehalogenation. The homoallyl ether **2** (see Scheme 6) afforded the cyclized 4-propyl-2,3-dihydro-1-benzopyran in 57% yield. No homocoupling to Ar–Ar was observed with these substrates. However, bromobenzene is known to undergo the coupling to biphenyl in the presence of electrogenerated Ni–PPh_3 complexes[2,3]. The cyclization-carboxylation of **1c** has also been described in the presence of Ni–PPh_3 complexes, to afford the corresponding cyclized-carboxylated adduct in 45% yield[43] (Scheme 17). The same Ni–PPh_3 system has been reported to catalyze the cyclization-carboxylation of *N*-allyl carbamates derived from bromoaniline to the carboxylated 2,3-dihydroindole compounds[50].

6. ELECTROCHEMICAL REDUCTIONS OF ALLYL ETHERS WITH OTHER METAL COMPLEXES AND ORGANIC MEDIATORS

6.1. Electroreduction of Allyl Ethers in the Presence of Palladium Catalysts

2,2′-Bipyridine[51] or bis(pyridine-oxazoline) $\mathbf{N_4}$ dichloropalladium complexes[41] have been reported as catalysts for electrochemical cleavage the allyl–O bond of allyl ethers (Schemes 2 and 3). Excellent yields of phenol derivatives were obtained with substrates such as **1a**, **1b** or **1c**.

The electrochemical allyl cleavage followed by allyl transfer reaction with allyl ether substrates such as **4** (Scheme 13) has also been reported in the presence of Pd(II)–2,2′-bipyridine and bis(pyridine-oxazoline)$\mathbf{N_4}$ complexes[52]. The use of Pd(II) complexes constitutes a good alternative to Ni(II) complexes for allyl ether cleavage reactions. Cyclizations of *N*-allylbromoanilines with Pd–PPh_3 systems have also been reported to give the corresponding 2,3-dihydroindole products[52].

6.2. Electrochemical Reactions of Allyl Ethers with Cobalt Catalysts

Co(II) complexes with oxime ligands have been reported to react with propargylic bromoacetaldehyde diethyl acetate derivatives to afford cyclization products in good yields[53]. [Co(cyclam)]Cl_2 was able to catalyze the electrochemical reductive cyclization of **1c** to **8b** (Scheme 14) in 60% yield[16]. Electrogenerated cobalt complexes involving vitamin B_{12} have also been reported to catalyze related cyclization reactions[54].

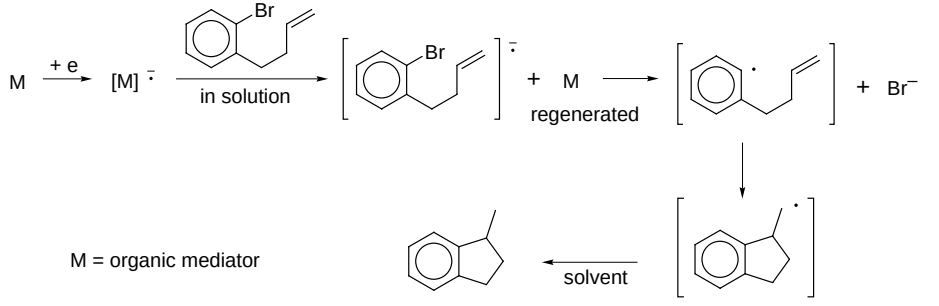
6.3. Electrochemical Reactions of Allyl Ethers with Samarium Catalysts

Compounds **1b** and **1c** have been reported to undergo an intramolecular cyclization in electrochemical reactions catalyzed by $SmCl_3$, affording **5b** in 75 and 70% yields, respectively[22] (Scheme 14). In contrast, with the same catalytic system, other aryl allyl ethers such as **1a** or **1i** selectively underwent cleavage of the O–C(allyl) bond to afford the corresponding phenol derivatives in quantitative yields[22].

6.4. Cyclizations in the Presence of an Organic Mediator as the Catalyst

The use of organic mediators in cyclization of **1c** or analogous compounds, to obtain an aryl radical intermediate, is also an interesting alternative to electrochemical intramolecular cyclizations[55]. The intramolecular cycli-

zation of 1-allyloxy-2-halobenzenes in the presence of an organic mediator has, to our knowledge, not been described. However, related cyclizations with 1-bromo-2-(but-3-en-1-yl)benzene in the presence of 3-methylbenzonitrile have been reported[55] (Scheme 19).



SCHEME 19

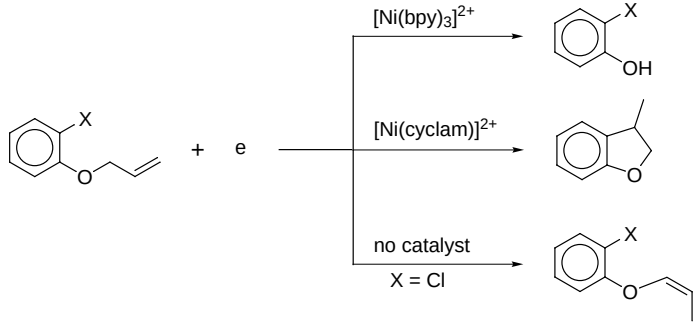
The cyclization of 1-allyl 2-bromoaniline derivatives to the corresponding 2,3-dihydroindole derivatives in the presence of (*E*)-stilbene as a mediator has also been studied[56].

7. CONCLUSIONS AND FUTURE PERSPECTIVES

The electrochemical reactivity of allyl ethers is an interesting example of the possibility of controlling chemoselectivity of electroreduction of an organic substrate by the choice of the catalytic system. Different reaction patterns can be considered according to the various experimental data. Thus, model substrates such as **1b** or **1c** can undergo protodehalogenation and isomerization of the double bond in uncatalyzed reactions[9]. In the presence of $[Ni(bpy)_3](BF_4)_2$ as a catalyst, cleavage of the C(allyl)–O bond of the side-chain occurs selectively, and 2-chlorophenol can be obtained in high yield[13]. The same substrate, in a $[Ni(cyclam)]Br_2$-catalyzed electroreduction undergoes an intramolecular cyclization to afford 3-methyl-2,3-dihydro-1-benzofuran with high chemoselectivity[36] (Scheme 20).

This strong influence of the catalytic system on the reactivity of **1b** or **1c** and analogous substrates is due to the effect of the ligand of the nickel complex, which can direct the reduction of Ni(II) either to Ni(0) or to Ni(I) species, respectively, with bipyridine-type or cyclam-type ligands. Ni(0) species selectively react with the allyl group of the allyl ether to form *p*-allyl-nickel species in a process involving the C–O bond cleavage. In contrast, Ni(I) intermediates undergo selective insertion replacing the aryl–

halogen bond, even in the case of chloro derivatives, with further radical-type reactions involving cyclization on the side-chain double bond.



SCHEME 20

In terms of synthetic applicability, the electrochemical reactions of reductive allyl cleavage constitute a new and interesting method of allyl ether deprotection. The alternative non-electrochemical approaches for such allyl ether deprotection mainly involve the double bond isomerization using Rh(I) complexes[18] or potassium *tert*-butylate[17]. Both methods need a two-step procedure with a second step involving treatment under strong acidic conditions, thus with low compatibility with acid-sensible functionality. The use of K^+*t*-BuO^-, a strong base, makes the chemical process non-compatible with several base-sensible functional groups. The use of Rh(I) requires controlled inert atmosphere and is an expensive method. A Pd(0)-catalyzed deprotection method has also been reported, and requires the combination with a stoichiometric amount of sodium borohydride as the reductant[19]. In comparison, the Ni(II)-catalyzed electrochemical procedure is carried out under neutral and mild conditions, at room temperature. The method avoids the use of strong acid or basic conditions and therefore widdens the compatibility with numerous (but non easily reductible) functional groups.

As an additional advantage, the electrochemical method uses stable and easily available Ni(II) compounds as the catalysts. Moreover, the electrochemical set-up of the reactions is very simple; it just needs a constant current supply and the procedure can be easily adapted by organic chemists. Thus, the electrochemical methodology can be advantageously used for the allyl aryl ether deprotection and particularly for functionalized derivatives.

Potential synthetic applications of the electrochemical methodology involving allyl ethers lie in the use of the selective cleavage reaction for fur-

ther synthetic reactivity of the allyl unit. In this perspective, the intramolecular allylation of carbonyl compounds has been reported[33] (see Schemes 12 and 13), and the highly functionalized phenol alcohols obtained should allow the synthesis of bicyclic compounds by further intramolecular cyclizations. Thus, the acid-catalyzed or the oxidative cyclizations of the phenol group on side-chain double bond should allow the synthesis of differently functionalized benzopyran or benzofuran structures in the family of chromanes, chromenes, flavones and other products of interest in the fields of pharmacology and flavor chemistry. The trapping of the allyl units by a variety of electrophilic centers such as carbonyl compounds, imines, esters, nitriles, ... (see Scheme 12) constitutes a complementary and intersting approach for the synthesis of allylic derivatives by intramolecular reactions. Such nucleophilic-type Ni-catalyzed allylations constitute an "umpolung" alternative to the Pd-catalyzed allylic alkylations, in which the allyl-Pd species are known to react with nucleophilic reagents[57,58].

In a different synthetic perspective, conveniently functionalized allyl ethers can undergo intramolecular reductive cyclizations to specific five- or six-membered ring ethers, such as dihydrobenzofuran or benzopyran systems (see Schemes 14–16), of potential interest in pharmacology and in agricultural chemistry. Here again, the electrochemical reductive cyclizations are to be advantageously compared to the chemical procedures. The chemical methods of reductive cyclization generally use tin hydrides in stoichiometric amounts and require the more activated iodo, or sometimes bromo derivatives[59,60]. The stoichiometric use of SmI_2 has also been reported for similar reductive cyclizations[61,62]. The interest of the electrochemical procedure lies in the possibility of using chloro or bromo allyl derivatives, more easily available and less expensive than the corresponding iodo compounds. The method is catalytic in nickel (II) and allows several functionalities. Cyclizations take place under very mild conditions (room temperature, neutral medium) using a simple electrochemical set-up. As future synthetic perspective, the electrochemical methodology of intramolecular cyclization can be applied to specific substrates, as well as to propargyl analogs, for the preparation of target molecules of particular interest.

To summarize, the electrochemical procedure involving allyl ethers constitutes a useful alternative as a synthetic method, for the mild and catalytic conditions and for the ease of set-up, as well as for the high selectivity found in the several described reactions.

REFERENCES

1. Nédélec J. Y., Périchon J., Troupel M. in: *Organic Electroreductive Coupling Reactions Using Transition Metal Complexes as Catalyst,* Topics in Current Chemistry (E. Steckhan, Ed.), p. 141. Springer, Berlin 1997.
2. a) Troupel M., Rollin Y., Sibille S., Fauvarque J. F., Périchon J.: *J. Organomet. Chem.* **1980**, *202*, 435; b) Troupel M., Rollin Y., Périchon J., Fauvarque J. F.: *New J. Chem.* **1981**, *5*, 62.
3. a) Amatore C., Jutand A.: *Organometallics* **1988**, *7*, 203; b) Amatore C., Jutand A.: *J. Electroanal. Chem.* **1991**, *306*, 125.
4. a) Fauvarque J. F., Chevrot C., Jutand A., François M., Périchon J.: *J. Organomet. Chem.* **1984**, *264*, 273; b) Fauvarque J. F., Jutand A., François M.: *New J. Chem.* **1986**, *10*, 119; c) Fauvarque J. F., Jutand A., François M.: *J. Appl. Electrochem.* **1988**, *18*, 109; d) Fauvarque J. F., Jutand A., François M.: *J. Appl. Electrochem.* **1988**, *18*, 116.
5. a) Meyer G., Rollin Y., Périchon J.: *J. Organomet. Chem.* **1991**, *56*, 2018; b) Derien S., Clinet J. C., Duñach E., Périchon J.: *J. Org. Chem.* **1993**, *58*, 2578.
6. a) Durandetti S., Sibille S., Périchon J.: *J. Org. Chem.* **1989**, *54*, 2198; b) Conan A., Sibille S., Périchon J.: *J. Org. Chem.* **1990**, *56*, 2018.
7. Gosden C., Healy K. P., Pletcher D.: *J. Chem. Soc., Dalton Trans.* **1978**, 972.
8. Healy K. P., Pletcher D.: *J. Organomet. Chem.* **1978**, *161*, 109.
9. Kimura M., Miyahara H., Moritani N., Sawaki Y.: *J. Org. Chem.* **1990**, *55*, 3897.
10. Duñach E., Périchon J.: *J. Organomet. Chem.* **1988**, *352*, 239.
11. Garnier L., Rollin Y., Périchon J.: *New J. Chem.* **1989**, *13*, 53.
12. Gosmini C., Lasry S., Nédélec J. Y., Périchon J.: *Tetrahedron* **1998**, *54*, 1289.
13. Olivero S., Duñach E.: *J. Chem. Soc., Chem. Commun.* **1995**, 2497.
14. a) Sock O., Troupel M., Périchon J.: *Tetrahedron Lett.* **1985**, *26*, 1509; b) Chaussard J., Folest J. C., Nédelec J. Y., Périchon J., Sibille S., Troupel M.: *Synthesis* **1990**, 369.
15. Silvestri G., Gambino S., Filardo S., Gullota G.: *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 979.
16. Olivero S.: *Ph.D. Thesis*. University of Nice, Nice 1998.
17. Gigg J., Gigg R.: *J. Chem. Soc. C* **1966**, 82.
18. Corey E. J., Suggs J. W.: *J. Org. Chem.* **1973**, *38*, 3224.
19. a) Beugelmans R., Bourdet S., Bigot A., Zhu J.: *Tetrahedron Lett.* **1994**, *35*, 4349; b) Zhang H. X., Guibé F., Balavoine G.: *Tetrahedron Lett.* **1988**, *29*, 619.
20. a) Mairanovsky V. G.: *Angew. Chem., Int. Ed. Engl.* **1976**, *15*, 281; b) Montenegro M. I.: *Electrochim. Acta* **1986**, *31*, 607.
21. Steckhan E.: *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 683.
22. Espanet B., Duñach E., Périchon J.: *Tetrahedron Lett.* **1992**, *33*, 2485.
23. Olivero S., Duñach E.: *Tetrahedron Lett.* **1997**, *38*, 6193.
24. a) Hegedus L. S., Wagner S. D., Waterman E. L., Siirala-Hansen K.: *J. Org. Chem.* **1975**, *40*, 593; b) Hegedus L. S., Thompson D. H. P.: *J. Am. Chem. Soc.* **1985**, *107*, 5663.
25. a) Ishizu J., Yamamoto T., Yamamoto A.: *Chem. Lett.* **1976**, 1091; b) Yamamoto T., Ishizu J., Yamamoto A.: *J. Am. Chem. Soc.* **1981**, *103*, 6863.
26. a) Semmelhack M. F.: *Org. React.* **1972**, 19, 115; b) Eisch J. J., Im K. R.: *J. Organomet. Chem.* **1977**, *139*, C45.
27. a) Derien S., Duñach E., Périchon J.: *J. Am. Chem. Soc.* **1991**, *133*, 22; b) Derien S., Duñach E., Périchon J.: *J. Am. Chem. Soc.* **1991**, *133*, 8447; c) Garnier L., Rollin Y., Périchon J.: *New J. Chem.* **1989**, *13*, 53.

28. Daniele S., Ugo P., Bontempelli G., Fiorani M.: *J. Electroanal. Chem. Interfacial Electrochem.* **1987**, *219*, 259.
29. Tokuda M., Satoh S., Suginome H.: *J. Org. Chem.* **1989**, *54*, 2198.
30. Torii S., Uneyama K., Matsuda H.: *Tetrahedron Lett.* **1984**, *25*, 6017.
31. Hebri H., Duñach E., Périchon J.: *Tetrahedron Lett.* **1993**, *34*, 1475.
32. Sibille S., d'Incan E., Leport L., Massebiau M., Périchon J.: *Tetrahedron Lett.* **1987**, *28*, 55.
33. Franco D., Olivero S., Duñach E.: *Electrochim. Acta* **1997**, *42*, 2159.
34. Franco D., Duñach E.: *Tetrahedron Lett.* **1999**, *40*, 2951.
35. Ozaki S., Matsushita H., Ohmori H.: *J. Chem. Soc., Chem. Commun.* **1992**, 1120.
36. Olivero S., Duñach E.: *Tetrahedron Lett.* **1995**, *36*, 4425.
37. Mubarak M. S., Peters D. G.: *J. Electroanal. Chem.* **1992**, *332*, 127.
38. Ozaki S., Matsushita H., Ohmori H.: *J. Chem. Soc., Perkins Trans. 1* **1993**, 649.
39. Irhara M., Katsumata A., Setsu F., Tokunaga Y., Fukumoto K.: *J. Org. Chem.* **1996**, *61*, 677.
40. a) Ozaki S., Horiguchi H., Matsushita H., Ohmori H.: *Tetrahedron Lett.* **1994**, *35*, 5; b) Ozaki S., Horiguchi H., Matsushita H., Ohmori H.: *Tetrahedron Lett.* **1994**, *35*, 725.
41. Clinet J. C., Duñach E.: *J. Organomet. Chem.* **1995**, *C48*, 503.
42. Gomez M., Muller G., Paneyella D., Rocamora M., Duñach E., Clinet J. C.: *Organometallics* **1997**, *16*, 5900.
43. Olivero S., Duñach E.: *Eur. J. Org. Chem.* **1999**, 1885.
44. Fischer B. J., Eisenberg R.: *J. Am. Chem. Soc.* **1980**, *102*, 7361.
45. a) Beley M., Rollin J. P., Ruppert R., Sauvage J. P.: *J. Chem. Soc., Chem. Commun.* **1984**, 1315; b) Beley M., Rollin J. P., Ruppert R., Sauvage J. P.: *J. Am. Chem. Soc.* **1986**, *108*, 7461.
46. a) Troupel M., Rollin Y., Périchon J., Fauverque J. F.: *New J. Chem.* **1991**, *5*, 62; b) Fauvarque J. F., Chevrot C., Jutand A., François M., Périchon J.: *J. Organomet. Chem.* **1984**, *264*, 273; c) Amatore C., Jutand A.: *J. Am. Chem. Soc.* **1991**, *113*, 2819; d) Amatore C., Jutand A.: *J. Electroanal. Chem.* **1991**, *306*, 141.
47. Olivero S., Rolland J. P., Duñach E.: *Organometallics* **1998**, *17*, 3747.
48. Gosden C., Pletcher D.: *J. Organomet. Chem.* **1980**, *186*, 401.
49. Heck R. F.: *Acc. Chem. Res.* **1979**, *12*, 146.
50. Tanaka H., Ren Q., Torii S. in: *Novel Trends in Electroorganic Synthesis* (S. Torii, Ed.), p. 195. Kodanska, Tokyo 1995.
51. Franco D., Panyella D., Rocamora M., Gomez M., Clinet J. C., Muller G., Duñach E.: *Tetrahedron Lett.* **1999**, *40*, 5685.
52. Torii S., Tanaka H., Morisaki K.: *Tetrahedron Lett.* **1995**, *26*, 1655.
53. Inokuchi T., Kawafuchi H., Aoki K., Yoshida A., Torii S.: *Bull. Chem. Soc. Jpn.* **1994**, *67*, 595.
54. Gao J., Rusling J. F.: *J. Org. Chem.* **1998**, *63*, 218.
55. Koppang M. D., Ross G. A., Woolsey N. F., Bartak E.: *J. Am. Chem. Soc.* **1986**, *108*, 1441.
56. Grimshaw J. in: *Novel Trends in Electroorganic Synthesis* (S. Torii, Ed.), p. 268. Kodanska, Tokyo 1998.
57. Pregosin P. S., Salzmann R.: *Coord. Chem. Rev.* **1996**, *155*, 35.
58. Trost B. M., Van Vranken D. L.: *Chem. Rev.* **1996**, *96*, 395.
59. Beckwith A. J. L., Meijs G. F.: *J. Chem. Soc., Chem. Commun.* **1981**, 136.
60. Giese B.: *Radicals in Organic Synthesis: Formation of Carbon–Carbon Bonds*. Pregamon Press, London 1986.
61. Molander G. A., Harring L.: *J. Org. Chem.* **1990**, *55*, 6171.
62. Curran D. P., Totleben M. J.: *J. Am. Chem. Soc.* **1992**, *114*, 6050.