Electrosynthesis of Unsymmetrical Polyaryls by a $S_{RN}1$-Type Reaction

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Unsymmetrical polyaryls are electrosynthesized in liquid ammonia by a single-step $S_{RN}1$ reaction in the presence of a redox mediator starting from aromatic halides and 2,6-di-*tert*-butyl phenoxide. With monoaryl halides activated by electron-withdrawing substituents (N of pyridyl or quinolyl, trifluoromethyl, cyano, sulfone, ester, ketone, alkyl sulfide, N^+ of anilinium), biaryls are obtained in good yields (between 50 and 95%). The yields of ter- and quateraryls are lower (40% maximum). The reaction is extended to other *ortho*-disubstituted phenols. Elimination reactions of the *tert*-butyl groups from the products are achieved by a Friedel–Crafts reaction using either trifluoromethanesulfonic acid or aluminum trichloride as catalysts.

Introduction

The synthesis of unsymmetrical biphenyls by chemical methods is a well-documented subject. There are mainly two methods: the chemical functionalization of a biphenyl[1] and the coupling of two phenyl entities.[2] Most of these reactions are nonspecific and consequently the yields of coupling products are low. Among the coupling reactions, SNAr and organometallic-catalyzed reactions can be mentioned. SNAr reactions[3] are specific and offer good yields, but one of the aryl entities has to be activated by a strong electron-withdrawing group such as NO_2. The reactions using organometallic catalysts[4] offer two main advantages: (i) a large range of examples and (ii) good yields. Coupling reactions with phenols have nevertheless not been described yet by these methods.

$S_{RN}1$ reactions are another type of coupling reaction. These reactions have been extensively studied using nucleophiles derived from many elements (C, Si, N, P, S, ...)[5a] under either chemical,[5b] photochemical,[5c] or electrochemical inducement.[5d] The synthesis of (aryl/phenol) or (aryl/naphthol) compounds has been carried out using phenoxides or naphthoxides as nucleophiles, and aromatic halides as substrates.[6,7]

Here we describe the synthesis of (aryl/phenol) coupling products by an electrochemically induced $S_{RN}1$ reaction in liquid ammonia starting from an aromatic halide and a phenol. This reaction has first been described with phenoxide itself and 4-bromobenzophenone or 4-chlorobenzonitrile as aromatic halides.[6a,b] It led to a mixture of two isomers corresponding to the coupling in the *ortho* and *para* positions of the hydroxyl group of phenol. With 2,6-di-*tert*-butyl phenoxide and chlorobenzonitriles or chloropyridines as starting aromatic halides, the reaction was shown to be specific;[6c,d] on a preparative scale, the advantages of redox catalysis inducement over direct cathodic inducement were clearly demonstrated; an equation of the yield of coupling product as a function of the different experimental parameters was proposed. For applications of these molecules in materials, elimination of the *tert*-butyl groups from some coupling products was achieved on treatment with aluminum trichloride in toluene.[8]

We have extended the scope of the reaction to a large variety of aromatic halides bearing CF_3, SO_2, CO_2, and CO groups and to other *ortho*-disubstituted phenoxides. We have shown that it was possible to eliminate the *tert*-butyl groups in all cases using either trifluoromethanesulfonic acid or aluminum trichloride as catalysts.

Results and Discussion

1. $S_{RN}1$ Reactions with *Ortho*-Disubstituted Phenols. Principle of the Reaction. The molecules were synthesized via a previously described electrochemical method.[6d] It consisted of a single-step reaction starting from an aromatic halide and an *ortho*-disubstituted phenol such as 2,6-di-*tert*-butylphenol under $S_{RN}1$ conditions (cf. Figure 1).

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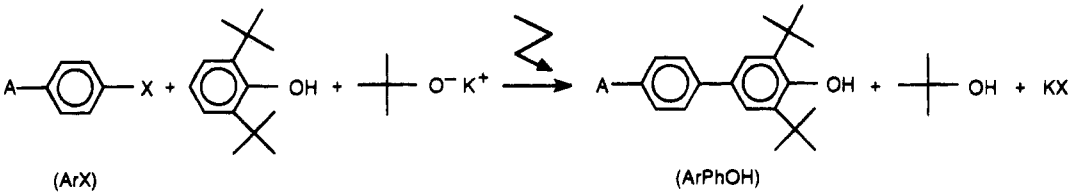

Figure 1. Reaction of a monoaryl halide and 2,6-di-*tert*-butylphenol under $S_{RN}1$ conditions. X^-: halide; A: electron-withdrawing group (trifluoromethyl, cyano, sulfone, ester, ketone, alkyl sulfide); A–Ph can be a pyridyl, a quinolyl or an anilinium ring. Di- and teraryl halides can be used instead of monoaryl halides.

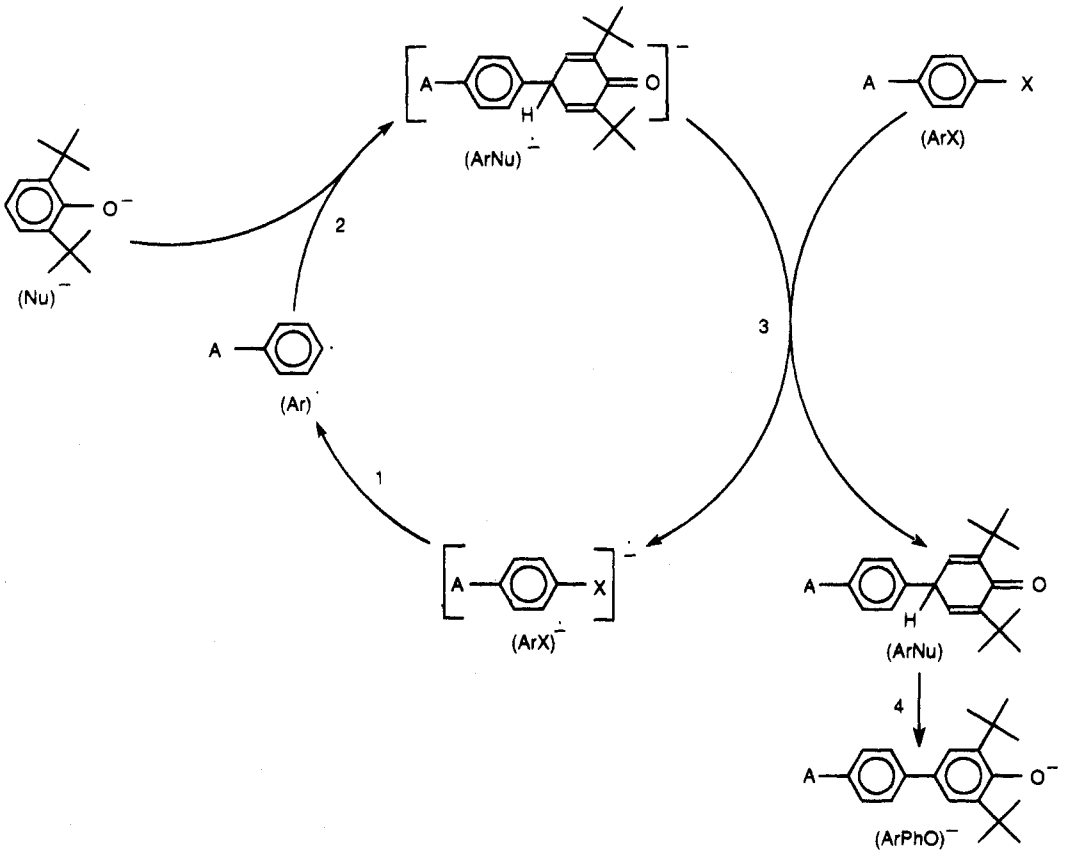

Figure 2. Sequence of reactions involved to synthesize unsymmetrical polyaryls under $S_{RN}1$ conditions. Starting aromatic halide ArX = *p*-A-ArX. Nucleophile Nu^- = 2,6-di-*tert*-butyl phenoxide.

The reaction was carried out in liquid ammonia which is a better solvent to perform $S_{RN}1$ reactions[9] than organic solvents, in which hydrogen atom abstraction from the solvent would have competed with the coupling reaction.[10] The mechanism of the reaction[6b] is summarized in Figure 2. It combines a classical $S_{RN}1$ loop (reactions 1, 2, 3) and a deprotonation reaction (4). The key species of the process, Ar•, obtained by the reductive cleavage of $ArX^{\bullet -}$ (reaction 1), combines with the phenoxide to give $ArNu^{\bullet -}$ (reaction 2) which in turn reduces the starting aromatic halide (reaction 3). The obtained product (ArNu) is deprotonated by a base present in the medium (the starting phenoxide for example) to give the *para*-substituted phenoxide ($ArPhO^-$) (reaction 4) which can be protonated by a strong acid (NH_4Br). The anion-radical $ArX^{\bullet -}$ is regenerated by reaction 3. The loop is induced by the reduction of the starting aromatic halide ArX by the reduced form of a redox mediator. The use of redox mediators under $S_{RN}1$ conditions has been extensively studied both from the kinetic[9b,11] and synthetic points of view.[6c,d,12] The role of a redox mediator is to minimize the main secondary reaction which is the two-electron reduction of the aromatic halide. The advantages of an indirect inducement of the process by a redox mediator compared to a direct inducement at the reduction potential of the aromatic halide have already been demonstrated and the strategy used to select an adequate mediator has been described.[6d]

Redox Mediators. A large variety of redox mediators can be used in liquid ammonia. The most commonly used and their standard potentials in liquid ammonia at −40 °C *versus* Ag/Ag^+ are gathered in Table 1.

On a preparative scale, most of these mediators are not stable whatever the pH. Two groups of mediators

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Table 1. Standard Potentials of Some Mediators in Liquid Ammonia at −38 °C[a]

mediator	$E°$ (V), vs Ag/Ag^+ [a]	group[b]
terephthalonitrile	−1.04	C
quinoxaline	−1.085	B
phthalonitrile	−1.13	A
4-cyanopyridine	−1.25	A
2,3-dimethylquinoxaline	−1.25	B
4,4′-dipyridyl	−1.33	B
2-cyanopyridine	−1.43	A
2,4′-dipyridyl	−1.475	B
1,10-phenanthroline	−1.50	B
pyridazine	−1.565	B
2,2′-dipyridyl	−1.625	B
quinoline	−1.625	B
4-phenylpyridine	−1.675	B
2,3′-dipyridyl	−1.685	B
3,3′-dipyridyl	−1.755	B
benzonitrile	−1.785	B
2-phenylpyridine	−1.85	B
4-toluonitrile	−1.87	C
3-phenylpyridine	−1.905	B
naphthalene	−2.025	C
2-methoxynaphthalene	−2.07	C
1-methoxynaphthalene	−2.105	C

[a] Potentials were measured with Ag/Ag^+ (10^{-1} M) as a reference system.[13] [b] pH group of the mediator; group A: the mediator requires the presence of an excess of 2,6-di-*tert*-butylphenol; group B: the mediator requires the presence of an additional base (see the Experimental Section for concentrations); group C: mediator not studied on a preparative scale.

can be defined according to the behavior of M and $M^{\bullet-}$ when the pH is varied.[6d]

The first group of mediators (group A) consists of those which bear electron-withdrawing groups (phthalonitriles, cyanopyridines). These compounds react with basic species and cannot therefore be used when the pH is too high (ammonolysis of the CN group). Since in the case of the electrosynthesis of unsymmetrical polyaryls, electrogenerated bases appear during the competitive reduction of the starting aromatic halide ArX to ArH:

$$ArX + 2e + HA \rightarrow X^- + A^- + ArH$$

HA: acidic impurity of the solvent (H_2O) or the solvent itself; $A^- = NH_2^-$ or HO^-. The reaction was performed in the presence of an excess of phenol. The destruction of mediators from the first group by base A^- was then avoided.

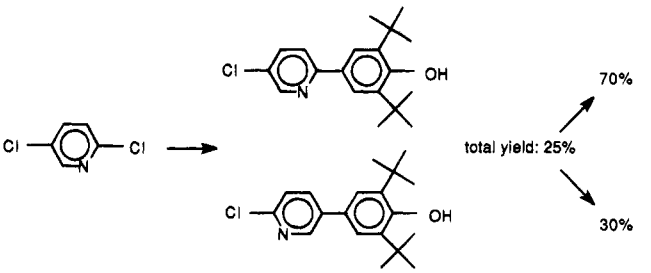
The second group of mediators corresponds to those for which anion-radicals $M^{\bullet-}$ are protonated by acidic species (which is the case for heteroaromatic rings such as quinoxalines, bipyridyls and quinoline). The reduction of M, which then becomes irreversible involves 2 electrons per mole of M and the anion-radical $M^{\bullet-}$ can no longer play its role as mediator. Such mediators cannot therefore be used when the pH is too acidic. Since 2,6-di-*tert*-butylphenol, which is an acid in liquid ammonia, is generated by the deprotonation reaction following the $S_{RN}1$ loop, a stronger base than 2,6-di-*tert*-butyl phenoxide (generally potassium or sodium hydroxide) has to be present in the system when using mediators from the second group. The groups corresponding to the different mediators are given in Table 1.

Results with 2,6-Di-*tert*-butyl Phenoxide as the Nucleophile. The electrolyses were performed under intensiostatic conditions using a stainless steel or a platinum grid as the anode and a magnesium rod as the cathode. The current density was set between 0.3 and 0.6 A dm^{-2} except when solubility problems occurred.

Most of the products were synthesized using a general experimental procedure.[6c,d] The natures of the halides and mediators are gathered in Table 2 with the yields of isolated products and the references where products (**1**, **2**, **4**−**7**, **9**−**14**) are described. New products (**3**, **8**, **15**−**17**, and **21**) are described in the Experimental Section.

The yields of biaryls (**1**, **2**, **4**−**16**, **21**) were 50% or higher. They could be increased by decreasing the electrolysis current density.[6d]

3 could not be synthesized directly from 2-chloropyridine because of the poor reactivity of the 2-pyridyl radical.[9b] It was synthesized in two steps starting from 2,5-dichloropyridine:[15] (i) the substitution by 2,6-di-*tert*-butyl phenoxide which yields mainly two monosubstituted isomers;



(ii) the quantitative reduction of the first isomer.

In the case of **9**, the starting aromatic halide could either be 4-chlorobenzonitrile or 4-(trifluoromethoxy)-benzonitrile.[16]

In the case of **14**, the starting compound was bis(4-chlorophenyl) sulfone; the reaction gave no disubstituted products.[17]

The yield of (**17**) was only 40%, which could be due to the electron-donating character of sulfur which decreased the electrophilicity of the transient aryl radical.

The yields of ter- and quateraryls (**18**−**20**) were the lowest.[14c] The first problem encountered in these electrosyntheses was the insolubilities of the starting aromatic halides. The reactivities of the involved bi- or teraryl radicals could also be lower than that of the corresponding monoaryls. In order to increase the yields and to determine these reactivities, we are at present trying to find new leaving groups to substitute at the starting aromatic moieties.

21 was synthesized starting from 4-chloro-*N*,*N*,*N*-trimethylanilinium iodide, which was obtained by methylation of 4-chloroaniline.

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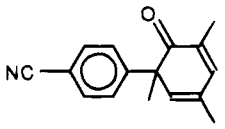
(16) We have shown recently that the reduction of 4-(trifluoromethoxy)benzonitrile could be mediated by 2,4′-dipyridyl and gave benzonitrile. OCF_3 behaves therefore as a leaving group in this case, such as halides or thiophenoxide. Consequently, 4-cyanophenyl radical generated by reductive cleavage of 4-(trifluoromethoxy)benzonitrile reacts under $S_{RN}1$ conditions with nucleophiles to give coupling products. Thermodynamic constants of 4-(trifluoromethoxy)benzonitrile (ArX) in liquid ammonia at −38 °C: Standard potential $E°$ ($ArX/ArX^{\bullet-}$) = −1.64 V vs Ag/Ag^+; cleavage rate constant of $ArX^{\bullet-}$, $k_1 = 4000\ s^{-1}$.

(17) Chahma, M.; Combellas, C.; Marzouk, H.; Thiébault, A. *Tetrahedron Lett.* **1991**, *32*, 6121.

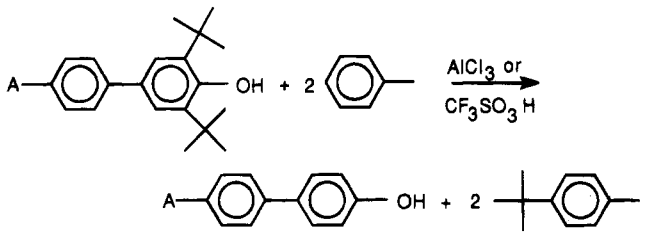
Extension to Other Phenoxides. The reaction was extended to other *ortho*-substituted phenoxides, mainly 2,6-dimethyl phenoxide, 2,6-diisopropyl phenoxide, and 2,6-dipentyl phenoxide.[18] The yields were lower than with 2,6-di-*tert*-butyl phenoxide. For example, with (4-chlorophenyl)methyl sulfone, in the same experimental conditions as those described in the above paragraph, the yield of isolated product was equal to 30 instead of 90%.

Such behavior could be explained when using 2,4,6-trimethyl phenoxide as a nucleophile. Under the same experimental conditions as for 2,6-di-*tert*-butyl phenoxide, when taking 4-chlorobenzonitrile as the starting aromatic halide, many reaction products were formed. Among them, the following *ortho*-substitution product could be identified by mass and ^{13}C and ^{1}H NMR spectroscopies:



Other isomers of this product and of their reduced forms could also be detected by mass spectroscopy. *Ortho* and *para* couplings are therefore possible with phenols *ortho* and *para* substituted by methyl groups. *Para* coupling has already been mentioned with a *para*-substituted naphthoxide.[7a] It is reasonable to assume that such couplings also occur with phenols substituted by longer chains (isopropyl, pentyl, ...) than a methyl group. Such a coupling is not possible with *tert*-butyl groups present, as experimenting with 2,4,6-tri-*tert*-butyl phenoxide showed.

2. De-*tert*-butylation Reactions. De-*tert*-butylation of many aromatic rings can be achieved by a trans-alkylation reaction[19] using either aluminum trichloride[8] or trifluoromethanesulfonic acid[14a] as catalyst:



In most cases, the reaction could be performed with both de-*tert*-butylation agents. Trifluoromethanesulfonic acid could not be used for cyano compound **9** because when using this acid, the cyano group was hydrolyzed into an amide. Aluminum trichloride could be used in all cases, but in many cases (pyridyl or quinolyl compounds, sulfones, and ketones), the kinetics were slower and the reaction was not specific (elimination of only one *tert*-butyl group was also observed) nor complete.

The results are gathered in Table 3. The yields of de-*tert*-butylation products are always higher than 60% for both trifluoromethanesulfonic acid and aluminum trichloride-catalyzed processes.

Conclusion

The synthesis of unsymmetrical polyaryls substituted by a hydroxyl group and different electron-withdrawing groups was achieved by an electrochemically induced $S_{RN}1$ reaction in liquid ammonia, starting from aromatic halides and 2,6-di-*tert*-butyl phenoxide. The reaction was carried out indirectly at the reduction potential of a redox mediator. Biaryls were obtained in good yields (>50%). Ter- and quateraryls were obtained in lower yields because of the poor solubilities of the starting aromatic halides. Electrochemical inducement proved to be well adapted to this synthesis, but similar results should be expected for photochemical inducement. Pyridine/phenol compounds are especially interesting because they can be easily transformed into zwitterions,[20] which are highly efficient for nonlinear optics applications.[21]

The reaction could also be performed with phenoxides *ortho*-disubstituted by less hindered groups. The yields were lower because of *ortho*-coupling.

The *tert*-butyl groups could be eliminated from the products using either trifluoromethanesulfonic acid or aluminum trichloride, depending on the nature of the electron-withdrawing group. The products obtained are interesting for liquid crystal applications.[22]

Experimental Section

All the reagents were purchased from Aldrich and used without further purification. The electrochemical cell used with liquid ammonia is described in ref 23. Melting points were measured with a hot stage microscope. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker spectrometer operating at 300 and 75.5 MHz, respectively. Some mass spectra were recorded on a Nermag R-10−10B instrument with electronic impact at 70 eV. The others were recorded on a Hewlett-Packard 5971 gas chromatograph equipped with a mass-selective detector. Combustion analyses were performed by the "Service de microanalyse de l'Université Pierre et Marie Curie", Paris.

Synthesis of 4-Chloro-*N,N,N*-trimethylanilinium Iodide. Na_2CO_3 (123 mmol, 13 g) and 4-chloroaniline (39.2 mmol, 5 g) were dissolved in DMF (100 mL). To the solution, the temperature of which was maintained below 10 °C, was slowly added methyl iodide. The temperature of the mixture was gently left to increase until room temperature and the solution was left stirring for 15 h. The product was then precipitated by adding diethyl ether (200 mL), filtered, and washed successively in diethyl ether and in water. It was recrystallyzed first in water and then in ethanol. The yield of isolated product was 71%.

4-Chloro-*N,N,N*-trimethylanilinium iodide: mp 204 °C dec. Anal. Calcd for $C_9H_{13}ClIN$: C, 36.33; H, 4.40; N, 4.71. Found: C, 36.80; H, 4.39; N, 4.69.

Electrosynthesis of Unsymmetrical Polyaryls with 2,6-Di-*tert*-butyl Phenoxide. The same procedure was used to obtain **1**, **2**, **4**−**17**, and **21**).

The mediator (2 mmol), the aromatic halide (5 mmol), 2,6-di-*tert*-butylphenol (20 mmol, 4.12 g), and potassium *tert*-butoxide (20 mmol, 2.24 g) were successively introduced into an electrochemical cell containing 100 mL of liquid ammonia and potassium bromide (40 mmol, 4.8 g) as supporting electrolyte. Temperature was maintained at −40 °C with a

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(23) Combellas, C.; Lu, Y.; Thiébault, A. *J. Appl. Electrochem.* **1993**, *23*, 841.
(24) When ArX is reduced according to a DISP process, the reduction of Ar• occurs in the solution instead of at the electrode in an ECE mechanism. Since a mediator is used to avoid the reduction of Ar• at the electrode, it is therefore not needed in a DISP process.

Table 2. Polyaryl Synthesis by an Electrochemically Induced $S_{RN}1$ Reaction of Aromatic Halides and 2,6-di-*tert*-Butyl Phenoxide in Liquid Ammonia at −38 °C[a]

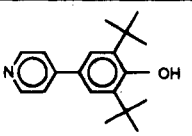
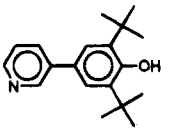
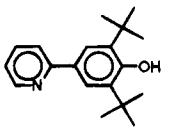
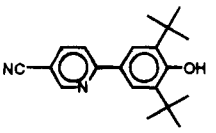
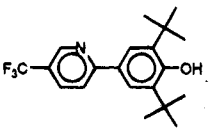
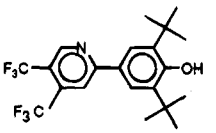
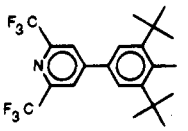
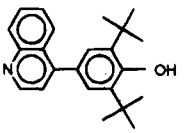
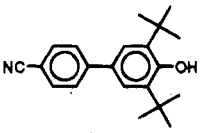
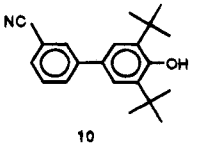
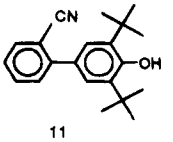
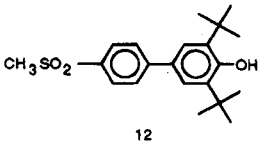
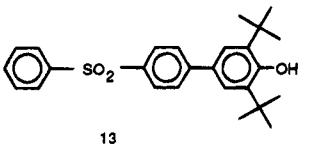
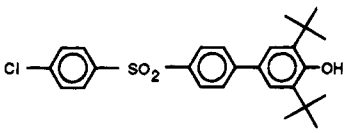
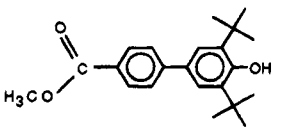
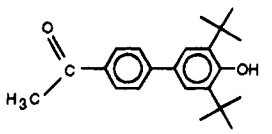
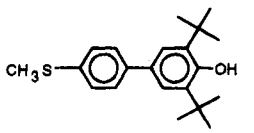
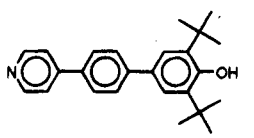
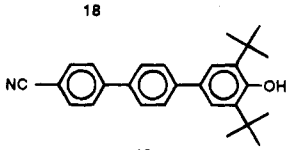
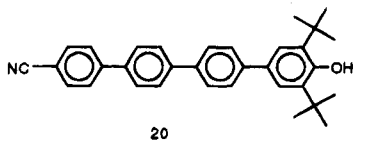
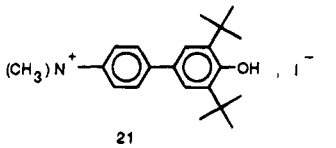
leaving group	mediator	product	ref	% yield[b]
Cl	2,4′-dipyridyl	 1	6d	56
Cl	2,2′-dipyridyl	 2	6d	84
Cl, Cl[c]	4,4′-dipyridyl	 3		16
Cl[d]	phthalonitrile	 4	6d	77
Cl	phthalonitrile	 5	14a	50
Cl	*e*	 6	14a	50
Cl	terephthalonitrile	 7	14a	50
Cl	quinoxaline	 8		76
Cl[f]	4,4′-dipyridyl		6d	83
OCF_3	2,4′-dipyridyl	 9		70
Cl	2-cyanopyridine	 10	6d	80
Cl	4-cyanopyridine	 11	6d	95
Cl	4,4′-dipyridyl	 12	14b	90

Table 2. (Continued)

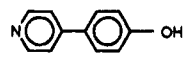
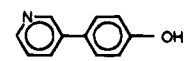
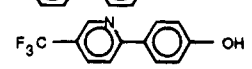
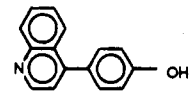
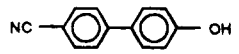
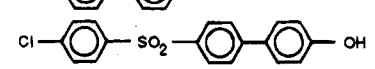
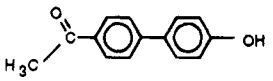
leaving group	mediator	product	ref	% yield[b]
Cl	4,4′-dipyridyl	 13	14b	90
Cl	quinoxaline	 14	14b	90
Cl	phthalonitrile	 15		50
Cl	phthalonitrile	 16		50
Br	2,2′-dipyridyl	 17		40
Br[g]	phthalonitrile	 18	14c	40[h]
Br[i]	4,4′-dipyridyl	 19	14c	25[h]
Br[j]	4,4′-dipyridyl	 20	14c	<10[h]
Cl[k]	2,2′-dipyridyl	 21		85

[a] Electrolysis performed at −38 °C in 80 mL of liquid ammonia, 5 mmol of ArX, 20 mmol of 2,6-di-*tert*-butylphenoxide and 2 mmol of mediator. Cathode: Platinum; stainless steel also used for **1**, **8**, **9**, **21**; same yields as with platinum. For other cathode materials, see ref 23. [b] Yield of isolated biphenyl obtained under galvanostatic conditions, with respect to the consumed aromatic halide (conversion about 90%). See the Experimental Section. [c] Starting aromatic halide: 2,5-dichloropyridine. [d] Starting aromatic halide obtained by dehydration of 6-chloronicotinamide.[14d] [e] Electrosynthesis without any mediator, because the reduction of the corresponding aromatic halide involves a DISP process.[24] [f] The starting aromatic halide could either be 4-chlorobenzonitrile or 4-(trifluoromethoxy)benzene. [g] The starting aromatic bromide was synthesized by a palladium-catalyzed reaction of 1,4-dibromobenzene and 4-bromopyridine hydrochloride. [h] Electrolysis performed in the presence of 20 mL of THF under a 15 mA current intensity. [i] Same as for *g* with 1,4-dibromobenzene and 4-bromobenzonitrile. [j] Same as for *g* with 4,4′-dibromobiphenyl and 4-bromobenzonitrile. [k] Starting aromatic chloride: 4-chloro-*N*,*N*,*N*-trimethylanilinium iodide obtained by methylation of 4-chloroaniline. See the Experimental Section.

cryocooler (Bioblock Scientific). Depending on the nature of the mediator (cf. Table 1), the reaction was carried out in the presence of either an additional base: potassium hydroxide (5 mmol) prepared in situ by deprotonation of water by potassium *tert*-butoxide or an excess of 2,6-di-*tert*-butylphenol (5 mmol, 1.03 g). The electrodes: cathode is a stainless steel or platinum grid (cf. Table 2), 10 cm^2, 1024 mesh per cm^2; anode is a magnesium rod, h = 8 cm, Φ = 1 cm. They were then introduced into the reactor and the electrolysis was performed under controlled current (i = 0.5 A dm^{-2}). It was stopped when there was no more aromatic halide in the solution (checked by HPLC). After ammonia evaporation, the products were extracted by dichloromethane. The biaryl was precipitated by adding *n*-pentane and recrystallized from *n*-heptane.

The experimental conditions for the synthesis of **3** are the following: (i) the substitution of 2,5-dichloropyridine by 2,6-di-*tert*-butyl phenoxide via the general procedure described

Table 3. Elimination of the *tert*-Butyl Groups by a *Trans*-Alkylation Reaction[a]

starting product		product	ref	% yield[b]
1	**22**			90[c,d]
2	**23**			90[c,d]
5	**24**		14a	80[c,d]
8	**25**			87[c,d]
9	**26**			90[e]
14	**27**			80[c,d]
16	**28**			65[c,f]

[a] Reaction performed in toluene in the presence of a catalyst (trifluoromethanesulfonic acid or aluminum trichloride). [b] Yield in isolated de-*tert*-butylated biaryl with respect to the starting coupling product. [c] Catalyst: trifluoromethanesulfonic acid (3 equiv/mol of starting substrate). [d] Reaction temperature: 100 °C; reaction time: 3 h. [e] Catalyst: aluminum trichloride (7 equiv/mol of starting substrate); reaction temperature: 100 °C; reaction time: 15 h. [f] Reaction temperature: 50 °C; reaction time: 2 h.

above; (ii) the separation of the two obtained isomers by flash chromatography over silica (eluent: dichloromethane/pentane (70/30, v/v)); (iii) the reduction of the first eluted isomer in liquid ammonia (80 mL) containing potassium bromide (40 mmol, 4.8 g) and potassium *tert*-butoxide (1.4 mmol, 0.16 g) under a 0.15 A dm^{-2} current density. After separation by flash chromatography over silica (eluent: dichloromethane), product **3** was recrystallized from pentane/dichloromethane (90/10, v/v).

The syntheses of the starting aromatic halides used to obtain products **18**–**20** are described in refs 4d and 14c. **18**–**20** were obtained according to the general procedure except that (i) THF (20 mL) was added to liquid ammonia (80 mL) and (ii) the electrolyses were performed under a 0.15 A dm^{-2} current density.[14c]

Most of the products are described in the refs indicated in Table 2. Description of the new ones is given below.

2-(3,5-Di-*tert*-butyl-4-hydroxyphenyl)pyridine (3): mp 170 °C; MS (CPV/MS) *m/z* 283 (M), 268. Anal. Calcd for $C_{19}H_{25}NO$: C, 80.5; H, 8.89; N, 4.94. Found: C, 80.5; H, 8.48; N, 4.93.

4-(3,5-Di-*tert*-butyl-4-hydroxyphenyl)quinoline (8): mp 170 °C. Anal. Calcd for $C_{23}H_{27}NO$: C, 82.84; H, 8.16; N, 4.20. Found: C, 82.73; H, 8.18; N, 4.20.

Methyl 3′,5′-di-*tert*-butyl-4′-hydroxybiphenyl-4-carboxylate (15): mp 177 °C. Anal. Calcd for $C_{22}H_{28}O_3$: C, 77.6; H, 8.3. Found: C, 77.6; H, 8.32.

1-(3′,5′-Di-*tert*-butyl-4′-hydroxybiphenyl-4-yl)ethanone (16): mp 147 °C. Anal. Calcd for $C_{22}H_{28}O_2$: C, 81.5; H, 8.64. Found: C, 81.6; H, 8.86.

3′,5′-Di-*tert*-butyl-4′-(methylthio)biphenyl-4-ol (17): mp 132 °C. Anal. Calcd for $C_{21}H_{28}OS$: C, 76.78; H, 8.59. Found: C, 76.73; H, 8.51.

4-(3,5-Di-*tert*-butyl-4-hydroxyphenyl)-*N,N,N*-trimethylanilinium iodide (21): mp 171 °C. Anal. Calcd for $C_{23}H_{34}INO$: C, 58.72; H, 7.28; N, 2.98. Found: C, 58.99; H, 7.51; N, 2.85.

De-*tert*-butylation Reactions with Trifluoromethanesulfonic Acid. The *tert*-butylated product (1 mmol) was introduced into toluene (15 mL) and then trifluoromethanesulfonic acid (3 equiv) was added. The mixture was left for 3 h at 100 °C (**22**–**25**, **27**); in the case of **28**, it was left 2 h at 50 °C. Toluene was then distilled.

With the products containing a pyridyl ring (**22**–**25**), in order to get the trifluoromethanesulfonic salt, the mixture was poured into water and the products were extracted by cyclohexane. After decantation and neutalization by NaOH until a neutral pH, the neutral molecule was precipitated. It was then filtered, washed in water, and recrystallized from ethanol.

With the products which do not contain any pyridine ring (**27**, **28**), $NaHCO_3$ was added to the mixture until no more CO_2 evolved. The product was then precipitated in pentane, filtered, and washed in pentane and then in water. It was recrystallized from ethanol/*n*-heptane (95/5, v/v).

4-(4-Hydroxyphenyl)pyridine (22): mp 252 °C. Anal. Calcd for $C_{11}H_9NO$: C, 77.17; H, 5.03; N, 8.18. Found: C, 76.66; H, 5.23; N, 7.93.

3-(4-Hydroxyphenyl)pyridine (23): mp 199 °C; MS (EI) *m/z* 171 (M), 117, 115, 89. Anal. Calcd for $C_{11}H_9NO$: C, 77.17; H, 5.23; N, 8.18. Found: C, 76.60; H, 5.18; N, 8.05.

4-(4-Hydroxyphenyl)quinoline (25): mp 251 °C; MS (EI) *m/z* 221 (M). Anal. Calcd for $C_{15}H_{11}NO$: C, 81.43; H, 5.01; N, 6.33. Found: C, 80.87; H, 4.95; N, 6.25.

4′-[(4-Chlorophenyl)sulfonyl]biphenyl-4-ol (27): mp 274 °C; MS (EI) *m/z* 346 (M ^{37}Cl), 344 (M ^{35}Cl), 185, 115, 111, 86, 84, 75. Anal. Calcd for $C_{18}H_{13}ClO_3S$: C, 62.70; H, 3.80. Found: C, 62.40; H, 3.70.

1-(4′-Hydroxybiphenyl-4-yl)ethanone (28): mp 211 °C; MS (CPV/MS coupling) *m/z* 212 (M), 197. Anal. Calcd for $C_{14}H_{12}O_2$: C, 79.23; H, 5.70. Found: C, 78.90; H, 5.68.

De-*tert*-butylation Reactions with Aluminum Trichloride. The experimental procedure was similar to that described with trifluoromethanesulfonic acid for compounds which do not contain any heteroatom. Aluminum trichloride was used instead of trifluoromethanesulfonic acid (7 equiv/mol of starting product). The mixture was left at 100 °C for 15 h.

4′-Hydroxybiphenyl-4-carbonitrile (26): mp 198 °C. Anal. Calcd for $C_{13}H_9NO$: C, 79.98; H, 4.65. Found: C, 79.39; H, 4.52; N, 7.05.

Acknowledgment. This work was partially supported by CNRS (UA 429) and by DRET (contrat No. 93-1087) which are acknowledged. F. Tournilhac is gratefully acknowledged for the synthesis of 2-chloro-5-cyanopyridine (starting aromatic halide for the electrosynthesis of **4**).

Registry nos. supplied by author: terephthalonitrile, 623-26-7; quinoxaline, 91-19-0; phthalonitrile, 91-15-6; benzophenone, 119-61-9; 4-cyanopyridine, 100-48-1; 2,3-dimethylquinoxaline, 2379-55-7; 4,4′-dipyridyl, 553-26-4; 2-cyanopyridine, 100-70-9; 2,4′-dipyridyl, 581-47-5; 1,10-phenanthroline, 66-71-7; pyridazine, 289-80-5; 2,2′-dipyridyl, 366-18-7; quinoline, 91-22-5; 4-phenylpyridine, 939-23-1; 2,3′-dipyridyl, 581-50-0; 3,3′-dipyridyl, 581-46-4; benzonitrile, 100-47-0; 2-phenylpyridine, 1008-89-5; 4-toluonitrile, 104-85-8; 3-phenyl-

pyridine, 1008-88-4; naphthalene, 91-20-3; 2-methoxynaphthalene, 93-04-9; 1-methoxynaphthalene, 2216-69-5; 2,6-di-*tert*-butylphenol, 128-39-2; 4-chloropyridine hydrochloride, 7379-35-3; 3-chloropyridine, 626-60-8; 2,5-dichloropyridine, 16110-09-1; 2-chloro-5-cyanopyridine, 33252-28-7; 2-chloro-5-(trifluoromethyl)pyridine, 55334-81-3; 2-chloro-4,5-bis(trifluoromethyl)pyridine, 109919-25-7; 4-chloro-2,6-bis(trifluoromethyl)pyridine, 81269-96-7; 4-chloroquinoline, 611-35-8; 4-chlorobenzonitrile, 623-03-0; 4-trifluoromethoxybenzonitrile, 332-25-2; 3-chlorobenzonitrile, 766-84-7; 2-chlorobenzonitrile, 873-32-5; 4-chlorophenyl methyl sulfone, 98-57-7; 4-chlorophenyl phenyl sulfone, 80-00-2; bis(4-chlorophenyl) sulfone, 80-07-9; 4-chlorobenzoic acid methyl ester, 1126-46-1; 4′-chloroacetophenone, 99-91-2; 4-bromophenyl methyl sulfide, 104-95-0; 4-bromopyridine hydrochloride, 19524-06-2; 1,4-dibromobenzene, 106-37-6; 4-bromobenzonitrile, 623-00-7; 4-chloroaniline, 106-47-8; aluminum trichloride, 7446-70-0; trifluoromethanesulfonic acid, 1493-13-6; 4-(3′,5′-di-*tert*-butyl-4′-hydroxyphenyl)pyridine, 129708-81-2; 3-(3′,5′-di-*tert*-butyl-4′-hydroxyphenyl)pyridine, 129708-80-1; 5-cyano-2-(3′,5′-di-*tert*-butyl-4′-hydroxyphenyl)pyridine, 114460-18-3; 5-(trifluoromethyl)-2-(3′,5′-di-*tert*-butyl-4′-hydroxyphenyl)pyridine, 139218-72-7; 2,6-bis(trifluoromethyl)-4-(3′,5′-di-*tert*-butyl-4′-hydroxyphenyl)pyridine, 139218-73-8; 4,5-bis(trifluoromethyl)-2-(3′,5′-di-*tert*-butyl-4′-hydroxyphenyl)pyridine, 139218-74-9; 4-cyano-3′,5′-di-*tert*-butyl-4′-hydroxy-1,1′-biphenyl, 114460-19-4; 3-cyano-3′,5′-di-*tert*-butyl-4′-hydroxy-1,1′-biphenyl, 129708-82-3; 2-cyano-3′,5′-di-*tert*-butyl-4′-hydroxy-[1,1′-biphenyl], 118720-23-3; 4-(methylsulfonyl)-3′,5′-di-*tert*-butyl-4′-hydroxy-[1,1′-biphenyl], 139225-64-2; 4′-(phenylsulfonyl)-3,5-di-*tert*-butyl-[1,1′-biphenyl]-4-ol, 139225-65-3; 4′-[(4-chlorophenyl)sulfonyl]-3,5-di-*tert*-butyl-[1,1′-biphenyl]-4-ol, 139225-66-4; 3,5-di-*tert*-butyl-4′-(4-pyridinyl)-[1,1′-biphenyl]-4-ol, 139780-25-9; 3″,5″-di-*tert*-butyl-4″-hydroxy-[1,1′:4′,1″-terphenyl]-4-carbonitrile, 139780-23-7; 3‴,5‴-di-*tert*-butyl-4‴-hydroxy-[1,1′:4′,1″:4″,1‴-quaterphenyl]-4-carbonitrile, 139780-24-8; 4-(4-hydroxyphenyl)pyridine, 77409-99-5; 3-(4-hydroxyphenyl)pyridine, 68223-13-2; 5-(trifluoromethyl)-2-(4-hydroxyphenyl)pyridine, 139218-75-0; 4′-hydroxybiphenyl-4-carbonitrile, 19812-93-2; 1-(4-hydroxybiphenyl-4-yl)ethanone, 13021-17-5.