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METAL-ASSISTED REACTIONS—13[1]

RAPID, SELECTIVE REDUCTIVE CLEAVAGE OF PHENOLIC HYDROXYL GROUPS BY CATALYTIC TRANSFER METHODS

BRENDAN J. HUSSEY and ROBERT A. W. JOHNSTONE*
The Robert Robinson Laboratories, University of Liverpool, Liverpool L69 3BX, England

and

IAN D. ENTWISTLE
Shell Research Limited, Sittingbourne, Kent ME9 8AG, England

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Abstract—Previous work has shown that, after converting phenols into suitable phenolic ethers, the aromatic C–O bond of the original phenol can be reductively cleaved heterogeneously to give a C–H bond through the use of molecular hydrogen or hydrogen donors together with a transition metal catalyst. The present work provides a method for selectively replacing a phenolic OH group by H in just a few minutes, compared with the 2 to 4 hr required previously using a hydrogen donor and the several hours under pressure required for molecular hydrogen. Various kinds of groups are suitable for preparing the required phenolic ethers from phenols, but the best ones are strongly electron-withdrawing heteroaromatic entities. Solvent appears to play an important role in this heterogeneous reaction, the mechanism of which is discussed.

In an earlier paper,[2] we described briefly the use of catalytic transfer hydrogenation to effect replacement of a phenolic OH group by H through the intermediacy of a phenolic ether (Scheme 1). The group R in Scheme 1 needs to be strongly electron-withdrawing and, in early experiments, was generally 5-phenyltetrazolyl (I). We now report other groups, R, which are as effective as the tetrazolyl (I) and that, by proper choice of solvent and hydrogen donor, the catalytic transfer reductive cleavage of phenolic C–O bonds can be effected rapidly, in high yield, under mild conditions.

$$\mathrm{ArOH} \xrightarrow[-[\mathrm{HCl}]]{\mathrm{RCl}} \mathrm{ArOR} \xrightarrow[\text{catalyst}]{\text{H-donor}} \mathrm{ArH} + \mathrm{HOR} \qquad (1)$$

There have been many attempts[3–6] to find a general, mild method for the reductive cleavage of phenolic OH groups to give the corresponding aromatic hydrocarbon. The majority of these methods involves conversion of the phenol into a phenolic ether or ester before cleavage is attempted and few of the methods attempt to reduce the phenol directly. The phenolic ethers or esters are invariably prepared from electron-withdrawing substituents coupled to the phenol and cleavage is effected either by addition of electrons followed by protons (dissolving metal or electrolytic type) or by hydrogenation using molecular hydrogen and a catalyst. The most widely-used of these methods to date have been probably those based[5] on the work of Musliner and Gates,[4] in which the strongly electron-withdrawing 5-phenyltetrazolyl ethers of phenols are cleaved with molecular hydrogen under pressure. These methods work reasonably well for many phenols, but tend to be rather slow, and with the extended times (and sometimes relatively high temperatures and pressure) needed for reduction, other reducible functional groups that may be present in the molecule can be hydrogenated also. Another approach has been the rearrangement of phenolic thio-derivatives into thiophenolic derivatives followed by reductive cleavage of the resulting C–S bond with Raney-Ni (Scheme 2). Al-

$$\mathrm{ArOH} \longrightarrow \mathrm{ArOCNR_2} \;(\mathrm{S}) \xrightarrow{\Delta} \mathrm{ArSCNR_2} \;(\mathrm{O}) \longrightarrow \mathrm{ArSH} + \mathrm{R_2NH} + \mathrm{CO_2} \xrightarrow{\mathrm{Ni/H_2}} \mathrm{ArSH} \qquad (2)$$

though this method uses a cheap catalyst, it requires a high temperature (170–335°) to effect the rearrangement of the initially produced O-aryldialkylthiocarbamates into S-aryldialkylcarbamates. Some of the thiocarbamates cannot be rearranged because of decomposition on heating and the long reaction times (typically 8–16 hr) militate against the use of this method for any, but very stable molecules. In our earlier adaptation[2] of Musliner and Gates' method, through use of catalytic transfer hydrogenation with a Pd–C catalyst and sodium phosphinate as the H-donor, we were able to reductively remove phenolic OH groups in 2–4 hr at 60–70°. The new method described here can effect conversion of the phenol into a suitable ether in about 20–30 min, and then the reductive cleavage of the ether in 10–15 min at 60–70°. During the progress of this research, an isolated report appeared on the use of catalytic transfer reduction of the 5-phenyltetrazolyl ether of L-tryosine into L-phenylalanine in 69% yield, using cyclohexene as H-donor;[7] this last publication prompted the preliminary report of our own investigations.[2]

In the following sections, the variables of Scheme (1)

are discussed, *viz* types of group (R), catalysts, H-donors and solvents.

Types of group (R; Scheme 1) used to prepare phenolic ethers. In our initial experiments, we hypothesized that strongly electronegative groups (R) could be efficient for the reductive cleavage by reducing the donation of the lone-pair electrons on the oxygen of the phenol group into the aromatic ring, i.e. the groups (R) would delocalize the oxygen lone-pair electrons into the strongly electron-withdrawing heteroaromatic system (R) and away from the phenolic aromatic system. This electronic effect would make the C–O bond of the phenol more like the single bond of an aliphatic ether and more susceptible to cleavage. Accordingly, a variety of electronegative groups (R) was examined, all of them being heteroaromatic. An added advantage of these systems lies in the stability of the group (R), in the availability of compounds, RCl, and in the ease with which this chloride group can be substituted by the phenolate anion. Of all the groups examined (I–X), those with the triazole (III), tetrazole (I, II) and triazine (X) ring systems gave very similar rates of reductive cleavage under similar reaction conditions. Of the remaining groups (R), only 6-cyanopyridazyl (V) showed some evidence for reductive cleavage, even under forcing conditions. With 3-(6-cyano)pyridazyl ethers of phenols, a promising initial rapid reductive cleavage of the phenolic C–O bond had to compete with rapid reduction of the cyano group itself to $-CH_2NH_2$. The formation of this aminomethylene substituent on the pyridazyl nucleus stopped further reductive cleavage of the phenolic ether linkage. For example, with the 3-(6-cyano)pyridazyl ether of 2-naphthol, reductive cleavage stopped when 32% of naphthalene had been formed; the remainder of the reaction product was the unreactive 3-(6-aminomethylene)pyridazyl ether of 2-naphthol. Thus, although most of the groups (R) are strongly electronegative (as demonstrated by the ease of nucleophilic displacement of Cl^- in compounds, RCl), only certain of them were effective in the reduction (1), the remainder being inactive. This finding tends to negate the hypothesis that the groups (R) act by simply weakening the phenolic C–O bond. Further evidence against this hypothesis came with the observation that alkyl ethers of 5-phenyltetrazole were completely inert towards reductive C–O bond-cleavage and gave, after prolonged reaction, only products of hydrolysis of the ether linkage, namely, the starting alcohol and 5-phenyltetrazolone. Further discussion of the mechanism appears below.

Hydrogen donors, catalysts and solvents effective for reductive cleavage of phenolic ethers, ArOR. Of the four metals, Pd, Pt, Ru and Rh (all as 5 or 10% by weight of metal precipitated on C), only Pd was active in this heterogeneous transfer reduction. Accordingly, all experiments described here were carried out with Pd catalysts and work with the other metals is not described.

A variety of H-donors was examined. Because most of the donors are water-soluble and relatively insoluble in organic solvents, catalytic transfer reductions were carried out either with a single-phase system of water-miscible solvents, or, better, with vigorously stirred two-phase systems consisting of a lower aqueous phase and an upper phase of an organic solvent such as benzene, benzene/ethanol or benzene/tetrahydrofuran. Sometimes a phase-transfer catalyst (e.g. benzyltriethylammonium chloride) was added to the two-phase systems to improve transfer of the H-donor from the aqueous layer to the catalyst and substrate in the organic solvent layer. The following selection of solvent systems illustrates typical results of a series of experiments on the reductive cleavage of the 5-phenyltetrazolyl ether of 2-naphthol to naphthalene. The other product of this reduction, 5-phenyltetrazolone, is soluble in weakly basic aqueous solution and can be removed readily from reaction mixtures by simple extraction. The table illustrates the range of phenolic ethers which were reduced by one or other of the following procedures (10% Pd/C catalyst):

(a) *Methanol/cyclohexene.* Under reflux (*ca* 65°), reduction with cyclohexene as H-donor was slow, requiring about 3 hr although naphthalene was obtained in 70% yield; most of the remaining reaction product was 2-naphthol.

(b) *Formic acid* (100%) *or formic acid/methanol.* With neat refluxing formic acid (*ca* 100°) as both H-donor and solvent, reduction to naphthalene was reasonably fast (75 min) and no 2-naphthol was formed. At the lower temperature (65°) of the refluxing methanol/formic acid system, reduction to naphthalene was slower, requiring about 4 hr.

(c) *Aqueous phosphinates/ethanol/benzene.* With phosphinic acid as H-donor in aqueous ethanol, no reductive cleavage of the 5-phenyltetrazolyl ether to naphthalene was observed after 4 hr at 78°. However, sodium phosphinate, which has a greater redox potential than phosphinic acid, in aqueous ethanol reduced the ether to naphthalene in 2.25 hr at 78°; no formation of 2-naphthol was observed. To improve the solubility of the substrate, a two-phase solvent system of benzene/ethanol/water was found to be advantageous. Using only benzene and water and no ethanol, reductive cleavage was very slow. In this benzene/ethanol/water system, with sodium phosphinate, reduction of the 5-phenyltetrazolyl ether of 4-hydroxyacetophenone gave a 74% yield of acetophenone in 55 min, but further reaction, to improve the yield resulted in a decrease in the amount of acetophenone because of its reduction to 1-phenylethanol.

(d) *Hydrazine hydrate/ethanol/benzene (or tetrahydrofuran).* At 78°, the H-donor, hydrazine, effected complete reduction of the 5-phenyltetrazolyl ether of 2-naphthol to naphthalene in 85% yield in only 50 min and, at room temperature, in 1.5 hr. About 8% of 2-naphthol was formed. As in (c) above, the rate of reduction was increased through increasing the solubility of substrate by using a two-phase system on benzene/ethanol/water. Thus, at room temperature with this two-phase system, total reductive cleavage to naphthalene required about 75 min.

Hydrazine has some disadvantages as a H-donor because of its reactivity towards some functional groups. For example, with the 5-phenyltetrazolyl ether of 4-hydroxyacetophenone, although reductive cleavage to give a 54% yield of acetophenone was rapid (15 min), it was observed that the yield of acetophenone then steadily declined so that, after 180 min, very little remained. On work-up of the reaction mixture, the azine of acetophenone was isolated in high yield. However, in the presence of KOH, which was used to reduce the hydrogen ion concentration, and therefore the reactivity of hydrazine towards the carbonyl group, formation of the azine was suppressed and, after 45 min, an 84% yield of acetophenone was obtained. With hydrazine (or formic acid or sodium phosphinate) as hydrogen-donor, the 5-

Table 1. Catalytic transfer reduction of phenolic ethers, ArOR[a]

Aromatic Group, Ar	Product, ArH[b]	Hydrogen donor[c]	Reaction Time (min)	% Yield[d] of ArH
1-Naphthyl	Naphthalene	P	45	70
		N	75	83
2-Naphthyl	Naphthalene	P	45	80
		N	75	85
		F	10	85
Phenyl	Benzene	P	50	86
		F	10	83
4-Methylphenyl	Toluene	N	210	100
4-Aminophenyl	Aniline	N	50	83
4-Cyanophenyl	Cyanobenzene	N	275	84
		P	70	95
2-Methoxyphenyl	Anisole	N	110	100
		P	95	94
4-Acetylphenyl	Acetophenone (Acetophenone azine*)	N	15	54
	Acetophenone	N+KOH	45	84
	Acetophenone	P	55	74
	Acetophenone (1-phenylethanol*)	F	5	53[e]
4-Formylphenyl	Benzaldehyde	P	150	<10
4-2-(1,3-dioxalinyl)-phenyl	2-phenyl-1,3-dixolan	N	395	52
		P	200	61
4-Phenoxycarbonylphenyl	Phenylbenzoate	P	70	95
		F	10	100
2-chlorophenyl	chlorobenzene (benzene*)	P	250	5-10[f]
		C	250	0[g]
3-Methyl-4-nitrophenyl	2-methylaniline	P	90	81
4-Carboxyphenyl	benzoic acid	P	50	80
7-(1-methanesulphonyl) naphthyl	1-methanesulphonyl-naphthalene	N	90	75
7-Coumarinoxyl	Coumarin (3,4-dihydrocoumarin*)	P	55	91[h]

a. For this comparative Table, all groups, R, are 5-phenyltetrazolyl, the catalyst is 10% Pd/C and two-phase (benzene/ethanol/water) systems are used. Typical experimental details appear in the experimental section.

b. Products other than those arising from simple reductive cleavage are marked by an asterisk.

c. Type of hydrogen donor: N = $NH_2NH_2.H_2O$; P = NaH_2PO_2; F = HCO_2H; C = cyclohexene.

d. The yield refers to isolated yield or, for mixtures, the yield estimated from gc or ^1H - n.m.r. spectroscopy after inclusion of a standard substance in known amount.

e. In addition, a 25% yield of 1-phenylethanol was obtained.

f. The yield of benzene, according to gc results, was about 90%.

g. Only benzene (100%) was isolated.

h. Some of the product of over-reduction, 3,4-dihydrocoumarin, was isolated.

phenyltetrazolyl ether of 4-hydroxybenzaldehyde was reduced quickly until about a 5–10% yield of benzaldehyde had been obtained after which reductive cleavage stopped. As benzaldehyde has been found earlier[7] to be an effective poison for the Pd–C and cyclohexene system, the cessation of reductive cleavage of the 5-phenyltetrazolyl ether of 4-hydroxybenzaldehyde can be ascribed to poisoning of the catalyst by the initially formed benzaldehyde. Successful transfer reduction of aromatic ketones and aldehydes has been achieved through the use of small amounts of Lewis acids to co-ordinate with the carbonyl compounds.[8] This poisoning of the catalyst by the benzaldehyde was circumvented by converting the aldehydic group of the 5-phenyltetrazolyl ether of 4-hydroxybenzaldehyde into its 1,3-dioxolan derivative with 1,2-dihydroxyethane. Reductive cleavage to the 1,3-dioxolan of benzaldehyde proceeded smoothly in high yield.

Partial catalyst poisoning was noted also with the 5-phenyltetrazolyl ether of 4-cyanophenol. Using hydrazine as H-donor, a 61% yield of cyanobenzene could be obtained in 75 min, but beyond this point the yield increased only slowly to 84% after a further 200 min, indicating that the cyanobenzene, as it was formed, was competing for catalyst sites and partially poisoning the catalyst. On the other hand, by using sodium phosphinate as H-donor, a 95% yield of cyanobenzene was obtained in 70 min with no evidence for catalyst poisoning. The propensity for a cyano group to bind to the catalyst surface was exemplified in the 6-cyanopyridazyl (V) ether of 2-naphthol. This gave naphthalene in a 32% yield but competitive reduction of the cyano group to aminomethylene stopped further reduction and the 6-aminomethylenepyridazyl ether of 2-naphthol was the only other product isolated.

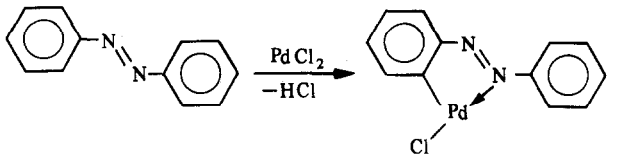
Reductive cleavage of the C–O bond of phenolic ethers containing an aromatic nitro group was slower than reduction on the nitro group itself to amine. Thus, reductive cleavage of nitrophenols is not selective, because the nitro group is reduced to amino before cleavage of the C–O bond of the phenolic ether.

From the above, it can be seen that aldehyde groups appear to poison the Pd catalyst and must be converted to a suitable derivative, cyano groups may reduce the rate of reduction with some H-donors (although this does not prevent high yields being obtained) and nitro groups are reduced preferentially to amino. Finally, one other functional group that needs special mention is chloride. 5-Phenyltetrazolyl ethers of chlorophenols exhibit unusually reactive dechlorination. Whereas, the hydrogen-donor formic acid, will slowly reduce halo, nitrobenzenes to aminobenzenes with loss of halogen,[9] sodium phosphinate or phosphinic acid do not cause dehalogenation even with reactive halogens.[9] For example, 2,5-dinitrochlorobenzene can be reduced to 2,5-diaminochlorobenzene. However, reductive cleavage of the 5-phenyltetrazolyl ether of 2-chlorophenol using sodium phosphinate gave benzene as the major product, together with some 5–10% of expected chlorobenzene. Independent experiments showed that chlorobenzene was reduced to benzene only very slowly under the same conditions, and that the 5-phenyltetrazolyl ether of 2-chlorophenol was dehalogenated rapidly to the corresponding ether of phenol. Therefore, the difficulty with the chlorophenol lies in an enhanced rate of dechlorination observed for the ether rather than in dechlorination of the expected reaction product, chlorobenzene.

Occasionally, tetrahydrofuran/water was used as the solvent system with hydrazine as H-donor, but variability of reaction times and yields made this a solvent system to be avoided. For example, in tetrahydrofuran/water, reductive cleavage of some 5-phenyltetrazolyl ethers (as with 7-hydroxycoumarin and 4-hydroxybenzoic acid) was rapid, but with other 5-phenyltetrazolyl ethers, such as that of 2-naphthol, cleavage was very slow, taking as much as 18 hr for completion.

(e) *Formic acid/benzene/water.* Although in (b) above, formic acid is described as both H-donor and solvent, reductive cleavage of phenolic ethers was not as fast nor as complete as with hydrazine or sodium phosphinate. Remarkably, a two-phase system of formic acid/benzene/water afforded a reducing medium in which reductive cleavage of phenolic ethers was very much faster than the systems (a)–(d). This H-donor and solvent system became the one of choice. For example, the 5-phenyltetrazolyl ether of 2-naphthol afforded an 85% yield of naphthalene in only 10 min. Other examples of the use of this system are shown in the table.

Mechanism of reductive cleavage. A simple view of the mechanism would be one in which phenolic ethers are adsorbed onto the surface of the catalyst which is saturated with hydrogen from the hydrogen-donor. If the phenolic ether lies flat along the surface, i.e. with the aromatic rings parallel to the surface, approach of the ether to the surface could be sufficiently close atomically that hydrogen atoms could be transferred, thereby reductively cleaving the C–O bond of the phenolic ether. The effectiveness of the tetrazoles and triazoles could be described as arising from the effect of their electronegativity in weakening the original phenolic C–O bond. Several experimental observations suggest this view is too simple. For example, H-donors which obviously generate hydrogen during attempted catalytic transfer reduction (as shown by copious evolution of hydrogen gas) usually afford a weakly effective or even ineffective reducing system. Contrariwise, most of the highly active reducing systems show little or no hydrogen evolution. Thus, simply providing hydrogen gas is not a criterion for a catalyst/H-donor system to be effective in transfer reduction. Although aliphatic alcohol C–O bond strengths are less than those of aromatic phenol C–O bonds, 5-phenyltetrazolyl ethers of alcohols are not reductively cleaved under the conditions that serve to cleave the corresponding phenolic ethers. Therefore, simply reducing the C–O bond strength of a phenol by suitable ether formation does not in itself appear to be sufficient to allow reduction to proceed. The idea that the whole system needs to lie close to the catalyst surface can be rebutted from the observation that phenolic ethers prepared with the 5,6-diphenyl-1,2,4-triazinyl group (Scheme 1, R=X) undergo rapid reductive cleavage; the planes of the phenyl substituents in the 5,6-positions must be almost perpendicular to the plane of the 1,2,4-triazine system because of severe steric constraints so that this part of the ether system cannot get closer than about 3.5 Å to the catalyst surface (half the width of the phenyl ring, plus a C–H bond length plus an H/catalyst surface non-bonded interaction). Therefore, it seems that the group R in the phenolic ethers (Scheme 1) does not need to lie close to the catalyst surface. Lastly, with



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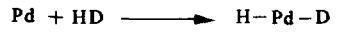

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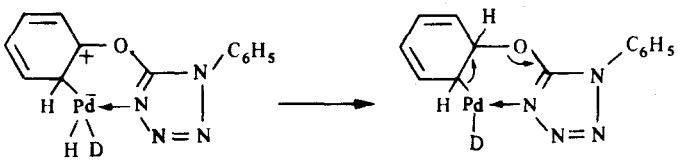
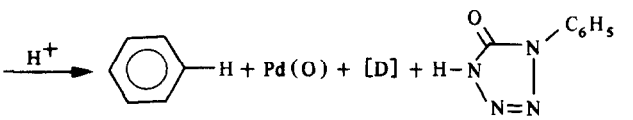
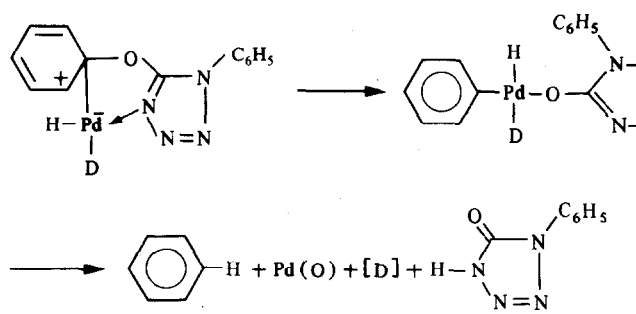




(5)

tetrazolyl ethers of phenols, a 5-phenyl substituent in R (Scheme 1) can be substituted by a 5-Me group without significant change in the rate of reductive cleavage. This again indicates that close proximity of the ether group, R, to the catalyst surface is not vital for rapid reduction.

An alternative view of this heterogeneous reaction can be achieved by a consideration of homogeneous reactions of organo-Pd compounds. Addition of Pd(II) to aromatic systems is well-known,[10] particularly where there is a suitable co-ordinating ligand to stabilize an intermediate or transition state. For example, $PdCl_2$ adds to azobenzene to give the complex shown in reaction (3) by insertion into the ortho position of the aromatic ring.[11] If, in the heterogeneous reductive cleavage described here, the Pd(O) state of the metal on the charcoal surface is changed to the +2 state by oxidative addition of hydrogen-donor (H–D in reaction 4), then a similar insertion of Pd into the *ortho*-position of a phenolic ether could be envisaged (reaction 5). Rapid transfer of hydrogen from the Pd to the C of the phenolic C–O bond followed by elimination of 5-phenyltetrazole, a good leaving group, would yield the aromatic hydrocarbon and return the Pd to its zerovalent state, ready for a new reaction cycle. However, the known reactions[10] of the type shown in reaction (3) almost invariably involve the Pd in a 5-membered ring intermediate or transition state species and not the 6-membered ring shown in reaction (5)[12,13] and this fact may invalidate the sort of mechanism envisaged in reaction (5). On the other hand, stabilization of a Pd species through a 5-membered ring could be envisaged if the Pd attacked the C of the phenolic C–O bond directly, leading to oxidative addition of the ether to the Pd (reaction 6); simple elimination from this product of oxidative addition gives the aromatic hydrocarbon and returns Pd to its zerovalent state (the entity D in reactions 5,6 could be any one or more of a number of species including hydrogen, depending on the nature of the H-donor used in the reaction). Oxidative addition of aryl cyanides, in which the cyano group is electron-withdrawing, and also a good leaving group, as with the ether groups R in the experiments described here, to Pt(O) is well documented[14] as is the addition of aryl halides to Pd(O) compounds.[15] The oxidative addition of aryl, alkenyl (vinyl) and allyl halides to Pd(II) or Pt(II) compounds appears to proceed *via* initial formation of a π-complex[16] followed by a $\pi \rightarrow \sigma$ rearrangement with insertion of the metal into the aromatic ring. Such a process with the phenolic ethers would require the aromatic (phenolic) ring of the phenolic ethers of these experiments to lie close to the catalytic metal surface, but would not require the ether group, R (Scheme 1) to do so, as is implicit in the experimental observations discussed above. For alkyl halides, this $\pi \rightarrow \sigma$ mechanism cannot operate and oxidative additions with these aliphatic compounds seem to proceed through radical or S_N2 mechanisms. If initial π-complex formation between the phenolic ethers



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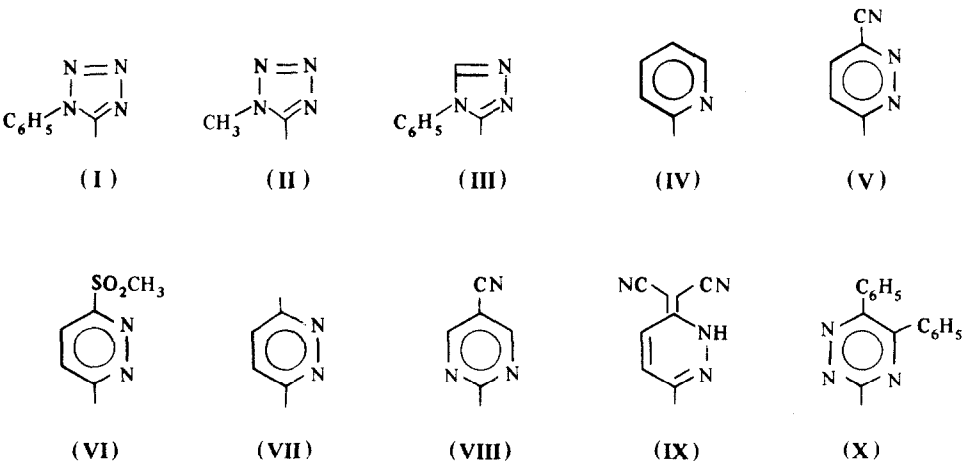

(I) (II) (III) (IV) (V)

(VI) (VII) (VIII) (IX) (X)

and the catalytic metal is essential for oxidative addition to occur, the lack of reactivity of the corresponding aliphatic ethers, for which such complexes are not possible, is readily explained and is in keeping with either of the mechanisms shown in reactions (5, 6).

CONCLUSION

The replacement of phenolic OH groups by H *via* formation of a suitable phenolic ether is a fast, specific reaction under the catalytic transfer conditions described here. Suitable phenolic ethers can be made rapidly, under mild conditions, by reaction of the phenolate anion with a chloro-substituted, electron-withdrawing group such as 5-methyltetrazolyl, 5-phenyltetrazolyl, 4-phenyl-1,2,4-triazolyl and 5,6-diphenyl-1,2,4-triazinyl. Pd–C was found to be an excellent, recoverable and re-usable heterogeneous catalyst and formic acid (formates), phosphinates (hypophosphites) and hydrazine hydrate in suitable solvent systems were found to be the best H-donors. Reductive cleavage of these phenolic ethers could be achieved in 10–15 min at 60–70°. Aromatic nitro groups and, in some cases, aromatic halides were found to be reduced faster than reductive cleavage of the phenolic ethers could occur.

EXPERIMENTAL

All new compounds were checked for structure and purity by elemental analysis, ^{1}H NMR, mass spectrometry and TLC.

Typical preparation of an aryl ether (ArOR)

To a soln of *p*-cresol (0.86 g; 7.96 mmole) in dry DMF (20 ml) under argon was added t-BuOK (1.0 g; 8.93 mmole) with stirring. When all the base had dissolved (approx 5–10 min), 1-chloro-5-phenyltetrazole (1.43 g; 7.9 mmole) in dry DMF (5 ml) was added. The mixture was stirred at room temp for a further 10 min and then poured into a large excess of ice-water. The resulting solid was filtered off, air-dried and recrystallized from aqueous EtOH to give the 5-phenyltetrazolyl ether of *p*-cresol, m.p. 91–92°. Ethers containing other groups (R=II–X) were prepared similarly.

This method of preparing aryl ethers was found to be much faster and higher yielding than the method using K_2CO_3 as a base and acetone as solvent.[4]

Typical reductive cleavages of aryl ethers (ArOR) *to give arenes* (ArH).

(a) *Using aqeuous formic acid.* Distilled water (2 ml), abs EtOH (3 ml) and Pd/C catalyst (10%; 99 mg) were added to a vigorously stirred soln of 1-(2-naphthoxy)-5-phenyltetrazole in benzene (7 ml). Formic acid (98% 0.5 ml) was added and the mixture was heated to gentle reflux (*ca* 80°). After 10 min, TLC showed that no starting material remained. After filtration from catalyst, the benzene layer was extracted with NaOHaq and then dried to give, on work-up, naphthalene (37.7 mg; 85% yield), m.p. 79–80°.

(b) *Using sodium phosphinate.* A soln of sodium phosphinate (99.1 mg; 1.13 mmole) in water (2.5 ml) was added to 1-(4-phenoxycarbonyl - 1 - phenoxy) - 5 - phenyltetrazole (122 mg; 0.34 mmole) in benzene (7 ml). EtOH (3 ml) and Pd/C catalyst (10%; 102 mg) were added and the mixture was heated under reflux (*ca* 70°) with vigorous stirring. After 45 min, TLC showed that no starting material remained. The mixture was filtered from catalyst, poured into NaOHaq (0.5 M; 15 ml) and extracted with diethyl ether (3 × 15 ml) to yield phenyl benzoate (100%).

(c) *Using hydrazine hydrate.* To a soln of 1-(4-amino-1-phenoxy)-5-5-phenyltetrazole (98.3 mg; 0.39 mmole) in benzene (7 ml) was added EtOH (3 ml), water (2 ml) and Pd/C catalyst (10%; 97 mg). Hydrazine hydrate (0.3 ml) was added dropwise to the vigorously stirred mixture over a period of 5 min at room temp. After 50 min, GLC showed that aniline had been formed in 83% yield (an internal standard of pentamethylbenzene was used to calibrate the GLC instrument and to estimate the yield of aniline).

Heteroaromatic chloro (or bromo) compounds (RCl or RBr)

The chloro compounds required for preparation of aryl ethers (ArOR) by the methods described above were synthesized following literature methods as follows: 1-chloro-5-phenyltetrazole (R=I),[17] 1-bromo-5-methyltetrazole (R=II),[18] 3-chloro-4-phenyl-1,2,4-triazole (R=III),[19] 3-chloro-6-cyanopyridazine (R=V),[20] 3-chloro-6-methylsulphonylpyridazine (R=VI),[21] 3,6-dichloropyridazine (R=VII; *bis*-substituted ethers),[22] 2-chloro-5-cyanopyrimidine (R=VIII).[23] 3-Chloro-5,6-diphenyl-1,2,4-triazole (R=X) was prepared by a literature method[24] but attempted crystallization from MeOH as recommended[24] gave only 3-methoxy-5,6-diphenyl-1,2,4-triazole; the 3-chloro compound was successfully crystallized from benzene/petroleum ether (b.p. 60–80°), m.p. 155–156°. 3-Chloro-6(H)-dicyanomethylenepyridazine (R=IX) was prepared by a modified literature method[25]: Under anhydrous conditions, 3,6-dichloropyridazine (3 g; 20.1 mmole)[22] in THF (50 ml) was heated under reflux with the K-salt of malononitrile (2.1 g; 20.2 mmole; prepared from t-BuOK and malononitrile in EtOH and precipitated by pouring the product into excess of diethyl ether) in the presence of 18-crown-6-ether (2 g; 7.6 mmole) for 16 hr. The solvent was evaporated in vacuo and the residue was dissolved in water (40 ml); this aqueous soln was acidified by addition of dil HCl and the precipitated yellow solid was recrystallized from EtOH (yellow prisms, 2.4 g, m.p. 268–270°; lit.[25] 258° (Found: C, 47.1; H, 1.9; N, 31.3; $C_7H_3ClN_4$ requires: C, 47.1; H, 1.7; N, 31.4%).

Analytical details for the 5-phenyltetrazolyl ethers shown in the Table

The ethers were prepared from 1-chloro-5-phenyltetrazole and the required phenol by the methods given above. In the following list, the details are presented as: phenol, m.p. of tetrazolyl ether, solvent for crystallization, elemental analysis (with the required percentage values given in parentheses) or literature ref. 2-Naphthol, 135–136°, EtOAc, lit. ref. 4; 1-naphthol, 107–108°, EtOAc, lit. ref. 4; 2-chlorophenol, 78–79°, aq. EtOH, C, 57.5 (57.3); H, 3.4 (3.3); N, 20.7 (20.5); 4-methylphenol, 91–92°, aq. EtOH, C, 66.6 (66.7); H, 4.8 (4.8); N, 22.2 (22.2); 4-aminophenol, 175–176°, EtOAc/petroleum ether (b.p. 60–80°), lit. ref. 4; 4-cyanophenol, 123–124°, EtOAc/petroleum ether (b.p. 60–80°), C, 63.8 (63.9); H, 3.6 (3.5); N, 26.9 (26.6); phenol, 132–133°, aq. EtOH, C, 65.4 (65.5); H, 4.4 (4.2); N, 23.6 (23.5); 2-methoxyphenol, 115–116°, EtOAc/petroleum ether (b.p. 60–80°), lit. ref. 4; 4 - formylphenol (4-hydroxybenzaldehyde), 117–118°, EtOAc/petroleum ether (b.p. 60–80°), C, 62.9 (63.2); H, 3.9 (3.8); N, 21.3 (21.0); 2-(4-hydroxyphenyl)-1,3-dioxolan, 103–104°, EtOAc/petroleum ether (b.p. 60–80°), C, 61.8 (61.9); H, 4.4 (4.6); N, 18.3 (18.1); 4-phenoxycarbonylphenol, 163–165°, EtOAc, C, 67.1 (67.0); H, 3.9 (3.9); N, 15.4 (15.6); 3-methyl-4-nitrophenol, 84.5–85.5°, EtOAc/petroleum ether (b.p. 40–60°), C, 56.3 (56.6); H, 3.5 (3.7); N, 23.1 (23.6); 4-carboxylphenol (4-hydroxybenzoic acid), 215–216°, EtOAc/petroleum ether (b.p. 60–80°), C, 59.3 (59.6); H, 3.5 (3.6); N, 19.8 (19.9); 7-methanesulphonyl-1-naphthol, 195–196°, EtOAc/petroleum ether (b.p. 60–80°), C, 59.0 (59.0); H, 3.9 (3.8); N, 15.3 (15.3); 7-hydroxycoumarin, 215–216°, EtOH.

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