Hydrodehalogenation of Halogenated Aryl Ketones under Multiphase Conditions. 5. Chemoselectivity toward Aryl Alcohols over a Pt/C Catalyst

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Halogenated aryl ketones (XC₆H₄COR: X = Cl, F; R = Me, Et, Ph) and benzyl alcohols (XC₆H₄-CH(OH)R: X = Cl; R = Me, Et) have been reduced catalytically over Pt/C at 50 °C, by bubbling H₂ at atmospheric pressure into a multiphase system consisting of a hydrocarbon solvent (isooctane) and an alkaline aqueous phase (KOH 50%) in the presence of a phase-transfer (PT) agent (onium salts or polyoxyethylene monoalkyl ethers). The chemoselectivity of the reaction is sharply modified by the PT-agent: in its absence, a wide range of products is observed, including those deriving from the complete reduction of both the aromatic ring and carbonyl functions. Instead, the presence of the PT-agent allows several different halo ketones to be transformed into their corresponding benzylic alcohols: that is, the hydrodechlorination occurs only with the partial hydrogenation of the CO group to the CH(OH) one, while further reductions are totally prevented. Under such conditions, both ionic (onium salts) and nonionic (polyoxyethylene monoalkyl ethers: Brij 35, 52, 56, and 58) compounds have been tested, and results seem to suggest that the higher their hydrophilicity is, the better the chemoselectivity toward the formation of dehalogenated alcohols is as well. Moreover, under multiphase conditions, also halo aryl alcohols lead to the corresponding dechlorinated alcohols in quantitative yields although a slower reaction is observed with respect to ketones.

Introduction

The environmental and health impact of halogenated aromatics poses a serious concern which has stimulated the development of a great variety of chemical methodologies for the degradation of these compounds.[1−8] Among the reported procedures (including photodegradations, oxidations, catalytic reductions, and nucleophilic substitutions), hydrodehalogenation reactions are becoming very attractive since they allow polyhalogenated aromatics to be reduced to the parent hydrocarbons without the production of wastes. Hydrodehalogenation reactions are usually carried out in polar solvents (such as MeOH, EtOH) in order to obtain a high solubilization of the molecolar hydrogen supplied.[9,10] Even so, severe conditions are often required: high H₂ pressures and/or elevated temperatures are necessary,[11,12] and also the presence of active catalysts such as Pd and Raney-Ni.

As previously reported by us,[13−15] by operating in a multiphase system composed by an aqueous phase (KOH 50%) and a hydrocarbon solvent (isooctane), aromatic halides undergo a facile hydrodehalogenation at low temperatures (50 °C), using H₂ at atmospheric pressure, Pd/C or Raney-Ni as catalysts, and the presence of a quaternary onium salt (Aliquat 336 − tricaprylylmethylammonium chloride). Under such conditions, the onium salt coats the metal catalyst, thus modifying the environment where the reaction takes place. This may result in a 2-fold effect: (i) an eased adsorption of the reactants over the catalytic surface, and (ii) in the case of polyfunctionalized substrates (i.e. halogenated aryl ketones), in a high chemoselective process toward the halogen removal. As a consequence, under multiphase conditions, even sterically hindered aryl halides can be rapidly reduced to the corresponding aromatic hydrocarbons,[14] and halogenated aryl ketones may yield selectively the corresponding ketones without any concomitant ring reduction and/or hydrogenation of the carbonyl group.[16] For instance, the reaction of *p*-chloropropiophenone carried out over Pd/C in the absence of Aliquat 336 gives propylbenzene as the sole product, while only propiophenone is observed in the presence of the onium salt.

Also, when Raney-Ni is used as a catalyst, the multiphase hydrodehalogenation expressly needs Aliquat 336 to occur, while no reaction is observed at all in its absence.[15]

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The remarkable chemoselectivity observed under multiphase conditions can be exploited for synthetic purposes by using halogen atoms as protecting and orientating groups which can be selectively removed via a hydrodehalogenation reaction. Accordingly, by coupling the Friedel−Crafts acylations of chloro (and fluoro) alkylbenzenes with the multiphase hydrodehalogenation procedure, we reported a high-yield synthesis of ortho- and meta-substituted aryl ketones otherwise not directly obtainable through a direct electrophilic aromatic substitution.[17]

We herein report further studies on the peculiar aspect dealing with the chemoselectivity in hydrodehalogenation reactions: in particular, the multiphase Pt-catalyzed hydrodehalogenations of chlorinated aryl ketones have been investigated.

Results and Discussion

All reactions were carried out in a 25-mL three-necked flask equipped with a condenser and a system for the bubbling of hydrogen. If not otherwise indicated, they were carried out on 7.0 mL of an isooctane solution of the substrate (0.49 mmol) to be reduced, 4.0 mL of 50% KOH aqueous solution, 0.0586 g of 5% Pt/C (0.015 mmol of Pt), and 0.0725 g of Aliquat 336 (0.20 mmol). Hydrogen was bubbled at atmospheric pressure through the organic phase at a rate of about 1 mL/min. The reaction flask was thermostated at 50 ± 0.1 °C (if not otherwise indicated), and the mixture was magnetically stirred at 1000 rpm with a bar 2.5 cm in length and 0.6 cm in diameter. The reaction course was followed by gas chromatography. Conversions are referred to the internal standard (*n*-decane).

At first, we investigated how the reaction conditions could induce chemoselectivity and, in this case, modify reactivity. *p*-Chloropropiophenone (*p*-ClC$_6$H$_4$COEt, **1**) was chosen as a model substrate as it bears three different reduction sites: the chlorine atom, the carbonyl group, and the aromatic ring. Consequently, depending on reaction conditions, many different products can be observed. For instance, when **1** was reacted under "classical" conditions,[18] in the presence of Pt/C and ethanol as the solvent, a mixture of seven products (whose structures were assigned by GC/MS analyses) was obtained including propiophenone (PhCOEt, **2**), 1-(*p*-chlorophenyl)propan-1-ol [*p*-ClPhCH(OH)Et, **3**], 1-phenylpropan-1-ol [PhCH(OH)Et, **4**]; cyclohexylethyl ketone (C$_6$H$_{11}$COEt, **5**); 1-cyclohexylpropan-1-ol [C$_6$H$_{11}$CH(OH)-Et, **6**], propylbenzene (PhPr, **7**), and propylcyclohexane (C$_6$H$_{11}$Pr, **8**). The use of the above-mentioned multiphase system resulted in a completely different reaction outcome. As can be seen in Table 1, the simultaneous presence of KOH$_{aq}$ and Aliquat 336 brings a sharp decrease in the number of reduction products (entry 5); actually, only the hydrogenation of the carbonyl group to the alcoholic one occurs along with the chlorine removal, while neither the further reduction of the alcohol to alkane nor the ring reduction are observed (entry 5). After 6 h, compounds **4** and **3** were 88 and 12%, respectively, at a complete substrate conversion. For a comparison, Figures 1a,b show the course of the

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Table 1. Reactions of 4-Chloropropiophenone in Multiphase Conditions[a]

entry	KOH	Aliquat 336	time (h)	convn (%)	products (%)[b]						
					2	3	4	5	6	7	8
1	yes	no	0.5	89	—	35	11	—	10	27	6
			4.5	100	—	—	9	—	20	46	25
2	no	yes	0.5	78	36	—	28	7	—	7	—
			6	100	—	—	10	17	44	18	11
3	no	no	0.5	84	—	20	6	—	4	44	10
			1.75	100	—	—	—	—	8	—	92
4	no	yes	0.5	61	13	—	27	6	4	11	—
			6	100	—	—	—	15	39	27	19
5	yes	yes	0.5	100	26	20	54	—	—	—	—
			6	100	—	12	88	—	—	—	—

[a] All reactions were carried out using 5% Pt/C (0.0586 g; 0.015 mmol Pt), an isooctane solution of the substrate (7 mL, 0.07 M), and Aliquat 336 (0.0725 g, 0.18 mmol; entries 2, 4, and 5). Entries 1 and 5: 4.0 mL of KOH acqueous solution (50%). Entries 2 and 3: 4.0 mL of H$_2$O. Entry 4: starting from an acidic aqueous solution (pH $\cong$ 3 per concd HCl). [b] Yields were determined by gc. Further details are in the Experimental Section.
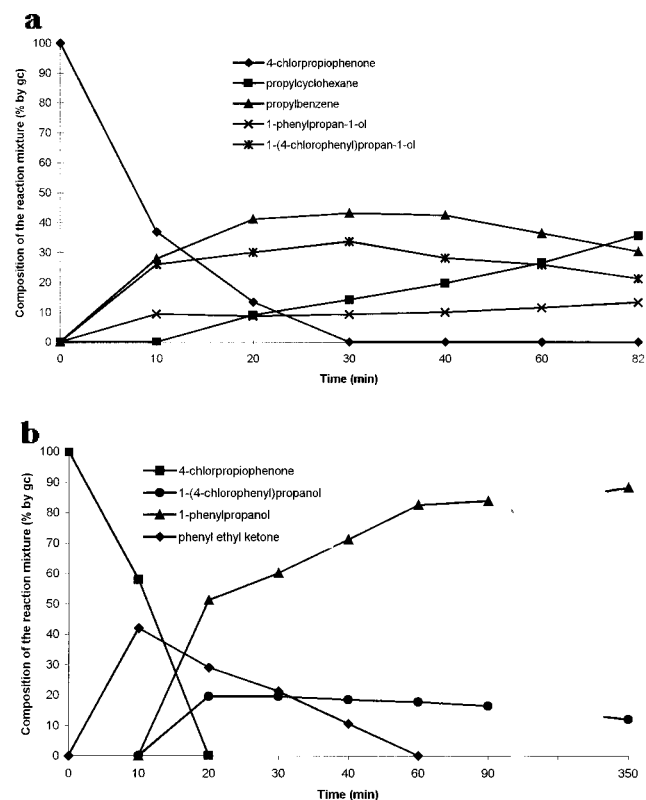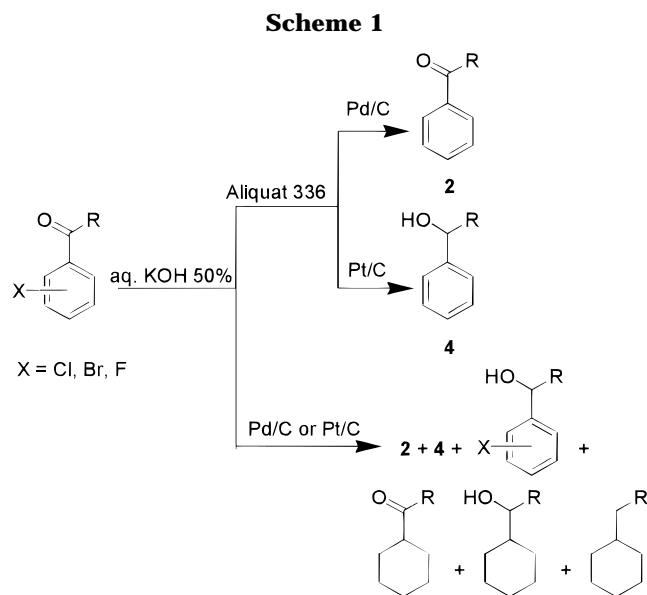

Figure 1. (a) Hydrodechlorination of 4-chloropropiophenone carried out using Pt/C in ethanol as solvent. (b) Hydrodechlorination of 4-chloropropiophenone carried out using Pt/C under multiphase conditions (entry 5, Table 1).

hydrodehalogenation of **1** under classical (ethanol as solvent; Figure 1a) and multiphase conditions (Figure 1b).

Under the multiphase conditions, a different situation arises when the alkaline solution is replaced by an equal volume (4 mL) of water and Aliquat 336 is absent. In this case, the full reduction of the substrate is obtained with no particular chemoselectivity toward partially reduced derivatives: propylcyclohexane becomes the major product (92%, by GC after 105 min of reaction: entry 3, Table 1). Likewise, a nonselective reaction is observed if an acidic aqueous solution (4 mL; initial pH $\cong$ 3 per concd HCl) and Aliquat 336 are used (entry 4).

Scheme 1

The scenario is slightly modified even when the KOH acqueous phase is used in the absence of Aliquat 336 (entry 1), or, alternatively, the onium salt is employed without any basic solution (entry 2). In both cases, although propylcyclohexane is no longer the main product, still a range of products coming from the reduction of the carbonyl group and/or the aromatic ring is obtained. However, in the case of entry 2, two peculiar products **5** and **6** form in a relatively high amount (20 and 44%, respectively): the chlorine removal takes place along with the ring reduction to the ketone **5** and the hydrogenation to the alcohol **6**. Once formed, **5** and **6** do not undergo any further reduction as confirmed by using acetylcyclohexane ($C_6H_{11}COCH_3$) as the substrate; in fact, under the conditions of entry 2, this compound gave no reaction at all.

This chemoselectivity is interesting from a synthetic point of view: actually, under phase-transfer catalysis conditions, the catalytic reduction of aromatic ketones to yield alicyclic ketones and alcohols has been successfully claimed in the presence of chloro(1,5-hexadiene)−rhodium dimer [1,5-HDRhCl]$_2$ as a homogeneous catalyst and an aqueous buffered solution.[19] Under the conditions reported here, this aspect is now the matter of further investigation.

Hence, as for the Pd/C catalyst,[16] also the Pt/C may allow a neat chemoselective multiphasic hydrodehalogenation of a chlorinated aromatic ketone, though a difference arises: while the former (Pd/C) permits a selective chlorine removal to yield a nonhalogenated ketone (compound **2**), the latter (Pt/C) catalyzes the hydrodechlorination and the hydrogenation of the carbonyl to the corresponding hydroxyl group (compound **4**) with comparable reaction rates (Scheme 1).

To investigate the reasons of such a peculiar chemoselectivity, the effect caused by different amounts of Aliquat 336 on the hydrodehalogenation of *p*-chloropropiophenone **1** was studied under the conditions of Table 1 (entry 1). Table 2 reports the results.

For comparison, the composition of the reaction mixture is shown after 1 h reaction in all cases. Data clearly

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Table 2. Influence of Different Amounts of Aliquat 336 on the Hydrodehalogenation of 4-Chloropropiophenone Carried out under Multiphase Conditions[a]

entry	Aliquat 336 (mg)	Pt/Aliquat 336 (molar ratio)	products (%)			byproducts[b] (%)	
			2	**3**	**4**	**5**	**7**
1	72	0.084	−	18	82	−	−
2	53	0.114	−	6	94	−	−
3	36	0.168	8	−	86	4	2
4	22	0.275	54	−	38	5	3

[a] All reactions were carried out using 5% Pt/C (0.0586 g, 0.015 mmol of Pt), an isooctane solution of the substrate (7 mL; 0.07 M), and a aqueous KOH solution (4 mL; 50%). In all cases, the composition of the mixture (%, by gc) is shown after 1 h of reaction. [b] Propylbenzene (**7**) and cyclohexyl ethyl ketone (**5**).
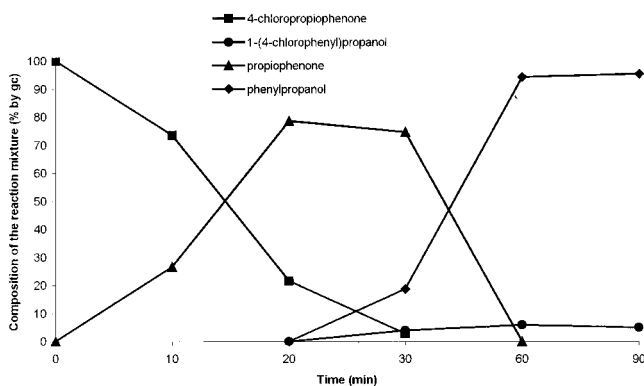

Figure 2. Hydrodeclorination of 4-chloropropiophenone under multiphase conditions using Pt/C (5%, 0.015 mmol) and Aliquat 336 (53 mg, Pt/A336 = 0.114).

suggest that an optimal Pt to Aliquat 336 (Pt/A336) molar ratio can be found in order to have the maximum chemoselectivity toward the formation of 1-phenylpropan-1-ol **4**: in fact, compound **4** is obtained in a 94% yield at complete conversion, when the Pt/A336 ratio is 0.114 (entry 2).

While the chance to get side reactions, such as the ring reduction or the hydrogenation of the carbonyl group, is enhanced by decreasing the quantity of Aliquat 336, when the amount of salt is nearly halved (Pt/A336 ranged from 0.114 to 0.275), both propylbenzene **7** and cyclohexyl ketone **5** are observed (6 and 8%, in total; see entries 3 and 4). Instead, the increase of the amount of Aliquat 336 over a defined value disfavors the C−Cl bond cleavage: when the Pt/A336 ratio is decreased to 0.084, a higher formation of the halogenated alcohol **3** results, and as a consequence, a much longer reaction time is required for the complete hydrodechlorination to **4** (entries 1, 2). In fact, a major determinant for complete halogen removal is the formation of the alcohol **3** which is particularly recalcitrant to dehalogenation. The situation is clear from the comparison of Figures 1b and 2 which detail the course of the multiphasic hydrodechlorination of *p*-chloro propiophenone **1** carried out using a Pt/A336 ratio of 0.084 (Figure 1b) and 0.114 (Figure 2), respectively. As the quantity of the added onium salt is increased, the formation of the alcohol **3** is favored as well: after 30 min, **3** rises to a maximum of 18% when the Pt/A336 ratio is 0.084 (Figure 1b), while it reaches only 6% if Pt/A336 is 0.114 (Figure 2). Subsequently dehalogenation of **3** is extremely slow and the halo alcohol **3** amount drops only 6% (from 18 to 12%) in the next 5 h of reaction.

Table 3. Hydrodehalogenation of 4-Chloropropiophenone Carried out in the Presence of Different Phase Transfer Catalysts[a]

| entry	PTC	amount (mg)	Pt/PTC molar ratio	time (h)	products[b]						
					2	**3**	**4**	**5**	**6**	**7**	**8**
1	TEBA	18	0.196	12	–	5	95	–	–	–	–
2	TBBA	80	0.042	4	–	–	77	9	14	–	–
3	Brij 35 $CH_3(CH_2)_{11}(OCH_2CH_3)_{23}OH$	100	0.180	7	3	–	97	–	–	–	–
4	Brij 52 $CH_3(CH_2)_{15}(OCH_2CH_2)_2OH$	118	0.042	2	2	3	77	5	5	7	1
5	Brij 56 $CH_3(CH_2)_{15}(OCH_2CH_2)_{10}OH$	154	0.066	6	–	71	29	–	–	–	–
6	Brij 58 $CH_3(CH_2)_{15}(OCH_2CH_2)_{20}OH$	201	0.084	3.5	–	13	82	–	3	2	–

[a] All reactions were carried out using 5% Pt/C (0.0586 g, 0.015 mmol of Pt), an isooctane solution of the substrate (7 mL; 0.07 M), an aqueous KOH solution (50%), and the phase-transfer catalyst (PTC) in the reported molar ratio. [b] Yields were determined by gc.

Table 4. Hydrodehalogenation Reactions Carried out under Multiphase Conditions on Different Halogenated Aryl Ketones[a]

entry	substrate	Aliquat 336 (mg)	time (h)	product (%)	yield[b] (%)
1	*p*-chloropropiophenone	21	2	1-phenylpropan-1-ol	95
2	*p*-chloroacetophenone	72	0.25	acetophenone	100
			2	1-phenylethan-1-ol	100
3	*p*-chlorobenzophenone	21	3	diphenylcarbinole	95
4	4,4′-dichlorobenzophenone	42	2.5	diphenylcarbinol	86
5	2-chloro-4-fluoro-5-methylacetophenone	21	6	1-(4-fluoro-3-methylphenyl)ethan-1-ol	77

[a] All reactions were carried out using 5% Pt/C (0.0586 g; 0.015 mmol of Pt), an isooctane solution of the substrate (entries 1–3 and 5: 7 mL, 0.07 M; entry 4: 7 mL, 0.035 M), and Aliquat 336 in the reported amount. [b] Yields were determined by gc.

The results presented in Figures 1b an 2 can be explained in terms of the following scheme:

Scheme 2
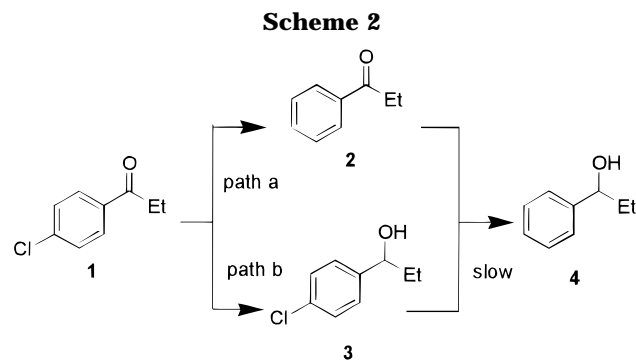
As **3** is undesired and quite unreactive, the strategy is to enhance the selectivity for **1 → 2** vs **1 → 3** since the **2:4** ratio is simply controlled by the reaction time (see Figure 2, and Table 4, entry 2). To achieve this, the key is to delay the onset of carbonyl hydrogenation of both the halogenated and nonhalogenated ketones until the maximum conversion of **1** to **2** is reached. The introduction of the PTC seems to be the proper mean to favor the affinity of the catalyst for **1** instead of **2**, and the observed chemoselectivity likely reflects the PTC action as an inhibition of the carbonyl functions interactions with the catalyst which disfavors the adsorption of **1** decreasing its conversion to **3**. However, these results indicate that the compromise between the selectivity and the reaction time also requires an accurate control of the amount of onium salt: an increase of the Pt/A336 ratio produces sizable quantities of byproducts, while an excessive lowering of that ratio favors the formation of the halo alcohol **3** (path "b" in Scheme 2) which hardly dehalogenates.

The lipophilicity features of the salt may have a decisive influence on the reaction outcome under such multiphase conditions.[13–16] Indeed, is the observed pat-

tern of chemoselectivity correlated to the chemical structure and properties of the added onium salt? And how do other onium salts or compounds with similar behaviors act?

To this end, an investigation was carried out by performing Pt-catalyzed multiphase hydrodechlorinations of **1** in the presence of both different onium salts and poly(ethylene glycol) mono-alkyl ethers. In particular, (triethylbenzyl)- and (tributylbenzyl)ammonium chlorides (TEBA and TBBA) along with Brij 35, 52, 56, and 58 [$HO(CH_2CH_2O)_nOR$: $n = 23, 2, 10$, and 20; $R = C_{12}H_{25}$, and $C_{16}H_{33}$, respectively] were used, these latter compounds being known phase-transfer catalysts (PTC) like onium salts.[20]

A number of reactions were accomplished by adding each of the chosen compounds (PTCs) in different amounts. The chemoselectivity trend (toward the alcohol **4**) behaved analogously to the case of Aliquat 336: the increasing of the PTC amount could enhance selectivity but decrease the halogen removal rate as well. Thus, case by case, the proper Pt/PTC ratio that could fit the highest selectivity with the shortest reaction time had to be determined. Accordingly, Table 3 reports the best results obtained for each of the tested PTCs.

In the case of onium salts, TEBA clearly allows a much more selective reaction than TBBA. After 12 h, 95% of the alcohol **4** is observed in the presence of TEBA (entry 1); while, if TBBA is used, **4** reaches a maximum of only 77%, the remainder (23%) being products coming from ring reduction (compounds **5** and **6**) (entry 2). In this latter case, the formation of secondary products **5** and **6** is hardly avoidable even using the onium salt in an amount higher than that reported in Table 3. In fact, a further decreasing of the Pt/TBBA ratio (below 0.042, entry 2) produces a huge embodiment of the metal catalyst by the salt. As a consequence, a progressive

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(20) Dehmlov, E. V.; Dehmlov, S. S. In *Phase Transfer Catalysis*, 2nd ed.; Verlag Chemie: Weinheim, 1983.
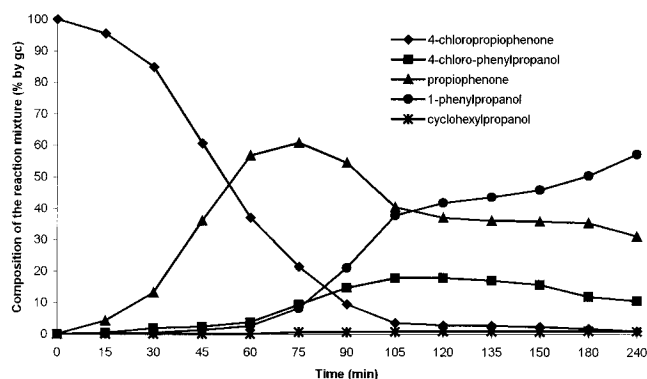
Figure 3. Hydrodechlorination of 4-chloropropiophenone with Pt/C under multiphase conditions in the presence of Brij 35 as PT agent.

agglomeration of Pt/C occurs with its subsequent deactivation due to the loss of the active surface.

As for the use of Brijs as PT agents, they are well-known surfactants whose different amphipathic structures determine HLB (hydrophile−lipophile balance[21a]) numbers of 17, 5, 13, and 15, for Brij 35, 52, 56, and 58, respectively. Accordingly, they are placed in detergent-solubilizer (35, 56, and 58) and water-in-oil emulsifier (52) classes.[21b]

In the case of multiphase hydrodehalogenation of **1**, Brij 35 is the most effective in promoting chemoselectivity toward the alcohol **4** which is obtained in a 97% amount, after 7 h of reaction (entry 3); whereas, Brij 52 is the least efficacious since sizable quantities (23%) of ring reduction byproducts (compounds **5** and **6**) are observed (entry 4). An intermediate behavior is exhibited by Brij 56 and 58: the former prevents the formation of secondary products but the complete chlorine removal is rather slow due to the accumulation of the halogenated alcohol **3** (71%, after 6 h; entry 5). The latter allows a fairly good selectivity toward **4** (82%, after 3.5 h; entry 6), though the formation of **3** is still not negligible (13%).

The reaction run in the presence of Brij 35 exemplifies how the PT agent can affect the reaction rate, and it may provide further insight into the mechanism of the PTC action. Figure 3 shows the outcome of the hydrodechlorination reaction of 4-chloropropiophenone in the presence of Brij 35: after the substrate **1** is totally consumed, the disappearance rate of **2** exhibits a sharp flex point, as does also the related rate of formation of **4**. This may indicate that the halo ketone **1** has a higher affinity for the Brij 35-modified catalyst surface than the dehalogenated ketone **2**; therefore, as long as **1** is present, the reaction proceeds rapidly, allowing a sufficiently high accumulation of **2** on the catalyst surface (path "a" of Scheme 2). However, when **1** is totally consumed, **2** is chemisorbed much less efficiently, and both its reaction rate and the formation of **4** are concurrently slowed. From that point on, the formation of **4** is controlled by the disappearance of **2** and **3** which proceeds with comparable rate constants (see also path "b" in Scheme 2): i.e., the Brij-modified catalyst shows similar affinity for **2** and **3**.

In the case of Aliquat 336, this trend is much less evident, if at all present (Figure 1b), indicating that the

(21) (a) In the case of simple ethoxylated alcohols such as Brijs, HLB is defined as *E*/5 where *E* is the weight % of the ethylene oxide in the molecule. (b) *Kirk-Othmer, Encyclopedia of Chemical Technology*, 3rd ed.; J. Wiley & Sons: 1983; Vol. 22, pp 360−365.

chemisorption processes of the substrate and of the intermediates can be significantly altered by the nature of the PTC. Different PTCs presumably alter the metal catalyst by causing distinct and selective interactions in the binding of reactant functionalities over the active surface sites.

At present, a relationship between the structure and the effect for PTCs is hardly inferable; however, our preliminary results seem to support the fact that for nonionic surfactants, the higher the HBL number is, the better the selectivity toward alcohol **4** is as well. That is, the examined chemoselectivity seems to be improved by increasing the hydrophilicity of the added Brij. On this point, back-tracking to the case of onium salts, it happens that also the water-soluble TEBA is more effective than TBBA in promoting the formation of **4**. On the whole, the situation suggests that PTC-induced partitioning phenomena between the aqueous and organic phases may promote chemoselectivity by mass-transfer processes where the basic aqueous phase may be involved.

As aforementioned, hydrodehalogenation of chlorinated aromatic ketones may have a high synthetic potential if aromatic or aliphatic ketones and alcohols can be afforded selectively, these products being often encountered in the preparation of fine chemicals and speciality intermediates.[17,19] Therefore, the applicability of the multiphase conditions with Pt/C as the catalyst has been tested over different chlorinated ketones. This was also in order to comprehend (i) the effects (if any) induced by the presence of either a bulky aromatic ring or an alkyl substituent on the reacting molecule, and (ii) the behavior of polychloro- or polyhalo-substrates toward multiphase dehalogenation. Results are reported in Table 4.

p-Chloroacetophenone shows a slightly different behavior than *p*-chloropropiophenone (**1**). In the case of **1**, the hydrogenation of the carbonyl group is never totally prevented before the dechlorination is complete; and the hydrogenation also takes place on the dechlorinated ketone **2** which forms from the direct dechlorination of the substrate. As a consequence, a mixture of compounds **2**−**4** is observed during the reaction (Table 2); in the long run, only the alcohol **4** can be obtained with up to 95% selectivity (entry 1, Table 4). Instead, the C−Cl bond cleavage can occur selectively on *p*-chloroacetophenone yielding the corresponding dehalogenated ketone (C_6H_5-$COCH_3$) in a quantitative yield (100% after 0.25 h of reaction, entry 2); then, in a second step, the hydrogenation takes place giving the dechlorinated alcohol (C_6H_5-$CH(OH)CH_3$: 100% after 2 h of reaction, entry 2).

Sterically hindered molecules are also effectively dehalogenated to the corresponding alcohols. For instance *p*-chlorobenzophenone affords diphenylcarbinol in a 95% yield after 3 h reaction (entry 3), being cyclohexylphenyl ketone (5%) the sole byproduct. In the case of polychlorinated substrates, a lower selectivity is observed: for instance, 4,4′-dichlorobenzophenone gives the corresponding dechlorinated alcohol (diphenylcarbinol) in a 86% yield (after 2.5 h reaction, entry 4) along with different byproducts such as dicyclohexyl ketone, cyclohexylphenyl ketone, 1-cyclohexyl-1-phenylmethanol (1%, 1%, and 6%, respectively) and phenyl(*p*-methoxyphenyl)methane (6%, structure assigned through GC/MS analysis). In this case, the reaction was carried out by halving the concentration of the organic solution (from 0.07 to 0.035 M)

because of the low solubility of the substrate (4,4′-dichlorobenzophenone) in isooctane.

In the case of polyhalogenated ketones, the ease of the halogen removal depends on the relative strength of the carbon to halogen bonds. Thus, the cleavage of the weaker C−Cl bond occurs preferentially though the concurrent defluorination cannot be completely avoided: as an example, the hydrodehalogenation of 2-chloro-4-fluoro-5-methylacetophenone yields the corresponding dechlorinated alcohol 1-(4-fluoro-3-methylphenyl)ethan-1-ol (77%, after 6 h reaction) along with the fully dehalogenated alcohol (3-methylphenyl)ethan-1-ol (15%) (entry 5).

Under the conditions of Table 1 (entry 5), multiphase hydrodehalogenations have been carried out by also reacting chlorinated benzyl alcohols as substrates: for instance, 1-(4-chlorophenyl)propan-1-ol [p-ClC$_6$H$_4$CH-(OH)Et, (**3**)] and 1-(4-chlorophenyl)ethan-1-ol [p-ClC$_6$H$_4$-CH(OH)Me, (**9**)]. Both compounds undergo extremely selective dechlorinations yielding the corresponding alcohols [PhCH(OH)R; R = Et, **4**; R = Me, **10**] although reaction times are longer than those of ketones. After 7 h reaction, a yield of 96 and 59% is observed for **4** and **10**, respectively.

As mentioned before, halogenated alcohols coming from multiphase hydrodechlorination of ketones appear recalcitrant to dehalogenation (see entries 1 and 2, Table 2). However, if the alcohol is used straight as the substrate, its dechlorination takes place much more easily: for instance, we observe a 50% conversion of p-ClC$_6$H$_4$CH-(OH)Et into PhCH(OH)Et after 20 min of reaction; whereas, the dechlorination of p-ClC$_6$H$_4$CH(OH)Et which forms during the reaction of the ketone **1** proceeds very slowly yielding PhCH(OH)Et in only a 6% amount after 5 h (Figure 1b).

These results suggest that the metal catalyst may suffer from deactivating effects due to both physical and chemical causes. In fact, the initial dechlorinating rate is very high for both ketones and alcohols, but, as the reaction proceeds, the added PTC adsorbs on the catalyst and visibly tends to embody it, thus likely leading to a loss of the active surface. Moreover, the HCl which is released by the reaction may lead to several problems. It is well-known that HCl is responsible for leaching processes,[22] inhibition of the activation of molecular hydrogen over catalytic surfaces,[23] and promotion of hydrogenolysis rather than hydrogenation reactions of the carbonyl functionalities.[24]

However, under multiphase conditions, the presence of a strong base likely minimizes the HCl effects. Also, a relationship between the observed chemoselectivity and

the "clustering" effect of the metal catalyst induced by the PTC adsorption cannot be excluded.

Conclusions

Under the multiphase conditions reported here, the Pt-catalyzed hydrodehalogenation of chlorinated aromatic ketones may proceed toward the formation of the corresponding benzylic alcohols with a selectivity up to 100%, providing that a suitable onium salt or a polyglycol be present. However, reaction conditions need to be properly tuned-up for such a high chemoselectivity to be reached; in particular, a major effect is played by the Pt to onium salt molar ratio which requires a case-by-case optimization.

From a synthetic point of view, the multiphase procedure also offers a promising starting point for the selective obtainment of alicyclic ketones and alcohols; experiments are in progress on this subject.

Experimental Section

All reagents and solvents were ACS grade and were used without further purification. The 5% Pt/C was from Fluka, Art. No. 80982; its surface area was 700−800 m^2/g. GC analyses were performed on a Varian GC 3400 using a fused silica capillary column (30 m × 0.25 mm) with SPB-5 as the liquid phase (film thickness 0.25 mm). GC/MS analyses were performed on a HP 5971 mass detector coupled to a HP 5890 gas chromatograph fitted with a 30 m × 0.25 DB5 capillary column.

1-(4-Chlorophenyl)propan-1-ol (**3**) and 1-(4-chlorophenyl)-ethan-1-ol (**9**) were prepared by reduction of the corresponding ketones, according to established procedures.[16,25]

General Procedure for the Hydrodehalogenation of Aromatic Ketones (Tables 1−4) and of Benzylic Alcohols. A 25-mL three-necked round-bottomed flask thermostated at the reaction temperature (50 ± 0.1 °C) and connected with a system for the addition of hydrogen was loaded with a mixture of an aqueous KOH solution (4.0 mL; 50%), 5% Pt/C (0.0586 g; 0.015 mmol of Pt), and a phase-transfer catalyst [PTC: both onium salts and poly(ethylene glycol) mono-alkyl ethers (Brij) were used. Pt/PTC molar ratio: for details see Tables 1−4] was magnetically stirred at 1000 rpm. A volume of 7.0 mL of the specific organic solution (0.07 M of the halogenated ketone in the corresponding solvent), containing n-decane as the internal standard, was added. Hydrogen was bubbled at atmospheric pressure into the organic phase at about 1 mL/min.

In the case of both 4,4′-dichlorobenzophenone, the reagent amount was halved and dissolved by ultrasounds in isooctane solvent (0.035 molar concentration: entry 4, Table 4).

The hydrodechlorination of benzylic alcohols (compounds **3** and **9**) was carried out as for ketones; only Aliquat 336 was used (0.0725 g, 0.18 mmol; Pt/A336 molar ratio: 0.084).

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