

Solvent and Temperature Effects in the Free Radical Aerobic Oxidation of Alkyl and Acyl Aromatics Catalysed by Transition Metal Salts and *N*-Hydroxyphthalimide: New Processes for the Synthesis of *p*-Hydroxybenzoic Acid, Diphenols, and Dienes for Liquid Crystals and Cross-Linked Polymers

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Abstract:

The aerobic oxidation of 4,4'-diisopropyldiphenyl and 2,6-diisopropynaphthalene, catalysed by *N*-hydroxyphthalimide and Co(II) salts, leads to the corresponding tertiary benzyl alcohols with high conversion and selectivity under mild conditions (temperature 30–60 °C and atmospheric pressure). Solvent and temperature effects, as resulting from the pioneering work of C. Walling, and more recently from the conclusive resolution of K. U. Ingold and co-workers on a quantitative kinetic basis, strongly affect the selectivity of the aerobic oxidation. This is related to the ratio between the rate of β -scission of the alkoxyl radical, which leads to acetophenone derivatives, and the rate of hydrogen atom abstraction, leading to tertiary benzyl alcohols. These latter are efficiently converted either to diphenols for the production of liquid crystals, by reaction with H₂O₂, or to dienes, useful as cross-linking agents, by dehydration. The aerobic oxidation of *p*-hydroxyacetophenone catalysed by Mn(NO₃)₂ and Co(NO₃)₂ leads with high selectivity to *p*-hydroxybenzoic acid, a useful monomer for liquid crystals.

The production of phenol and acetone from cumene through the hydroperoxide is one of the main industrial chemical processes, which has replaced traditional processes, such as the alkaline fusion of benzenesulfonic acid.

Analogous processes have been developed for the production of diphenols, such as resorcinol from *m*-diisopropylbenzene. However, compared to the phenol process, additional complexities are encountered in the making of resorcinol. In the peroxidation of cumene a higher selectivity is achieved by keeping conversion low, since the separation of cumyl hydroperoxide from cumene is a relatively simple process. On the other hand, a partial conversion of *m*-diisopropylbenzene yields a mixture of mono- and dihydro-

peroxides, whose separation is more difficult. Thus, the benzene sulfonation process is still competitive with the peroxidation process, and the world's major producers of resorcinol utilise both the alkaline fusion of *m*-benzenedisulfonic acid (INDSPEC Chemical Corp. in the U.S.A.) and the peroxidation of *m*-diisopropylbenzene (Sumitomo Chemical Company and Mitsui Petrochemical Industries in Japan). The benzene sulfonation process forms 2.47 kg of sodium sulfite per kg of resorcinol, whereas the peroxidation process requires 2.08 kg of *m*-diisopropylbenzene per kg of resorcinol. The cost for the disposal of the byproduct sodium sulfite is a major component of the total cost of the sulfonation process, while the price of the *m*-diisopropylbenzene feedstock is a major component of the total cost of the peroxidation process. A change in the price of either material can, therefore, alter the cost ratio of the two processes.¹

Recently,² attempts to improve the industrial peroxidation of *m*-diisopropylbenzene by catalysis of *N*-hydroxyphthalimide (NHPI) under milder conditions did not prove successful; a yield of 36% resorcinol and 17% *m*-isopropylphenol was reported by decomposing the hydroperoxides with H₂SO₄ whereas, with the Lewis acid InCl₃ as catalyst, yields were 56% resorcinol and 16% *m*-isopropylphenol; in any case a mixture of mono- and dihydroperoxides was formed. With more complex diisopropylaromatics, such as diisopropyldiphenyls and diisopropynaphthalenes, these complexities of the peroxidation process further increase.

Recently we³ have determined the absolute rate constants for the hydrogen atom abstraction from benzylic C–H bonds

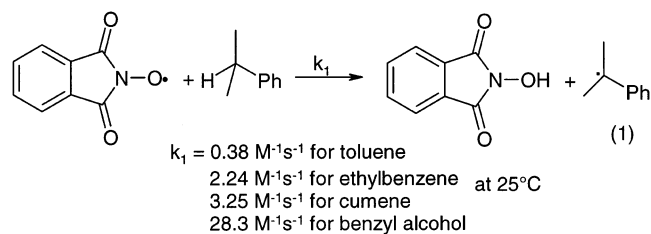
(1) *Chemical Economics Handbook*; SRI International: Menlo Park, CA, (a) June 1997; 691.700A, p 1. (b) May 1999; 580.420C, p 3. (c) February 2001; 695.4021U, p 47.

(2) Fukuda, O.; Sakaguchi, S.; Ishii, Y. *Adv. Synth. Catal.* **2001**, *343*, 809.

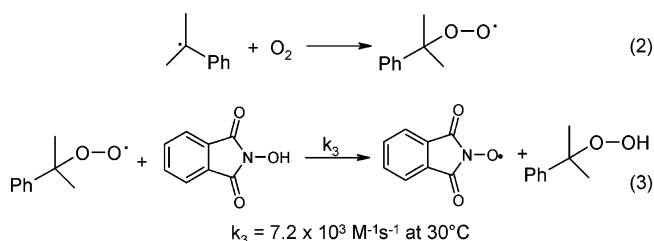
(3) Amorati, R.; Lucarini, M.; Mugnaini, V.; Pedulli, G. F.; Minisci, F.; Recupero, F.; Fontana, F.; Astolfi, P.; Greci, L. *J. Org. Chem.* **2003**, *68*, 1747.

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by phthalimido-*N*-oxyl (PINO) radical (eq 1)

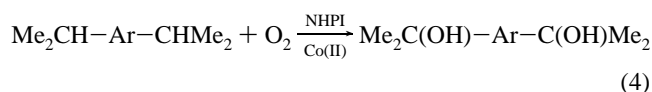


and for the formation of PINO radical by hydrogen atom abstraction from NHPI by peroxy radicals (eqs 2, 3), thus providing a quantitative basis to the study of aerobic oxidation catalysed by NHPI.



These results are also related to the bond dissociation enthalpy (BDE) of the OH bond in NHPI, which we have recently³ determined (88.1 kcal mol⁻¹).

Considering the difficulties for the selective syntheses of hydroperoxides in the biphenyl and naphthalene series from diisopropyl derivatives as well as the industrial interest of the corresponding diphenols, we have developed a different strategy, based on the selective aerobic oxidation of these diisopropyl derivatives to the corresponding tertiary benzyl alcohols through NHPI and Co(II) salts catalysis (eq 4).

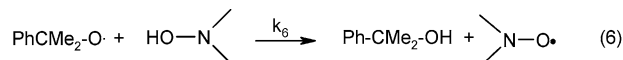


The aerobic oxidation of cumene, catalysed by NHPI, was reported in two further papers by Ishii and co-workers,^{4,5} in addition to the above-mentioned peroxidation,² and in both cases acetophenone was the main reaction product. In acetic acid solution, aerobic oxidation at 100 °C under NHPI and Co(acac)₃ catalysis provided 54% acetophenone, 10% cumyl alcohol, and 17% phenol; however, the conversion was low due to inhibition by the phenol, formed during the reaction by acid-catalyzed decomposition of the hydroperoxide. The oxidation led to 64% acetophenone and 8% cumyl alcohol in PhCN solution, with NHPI catalysis and in the absence of metal salts at 100 °C.

It is well-known that the formation of acetophenone in the oxidation of cumene arises from β -scission of the cumyloxyl radical (eq 5).



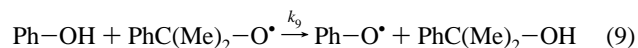
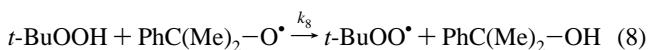
Equation 5 can compete with hydrogen atom abstraction from the O–H bond of NHPI (eq 6) or from C–H bonds (eq 7).



The pioneering results of C. Walling and co-workers^{6,7} have shown that solvents could have a relevant effect on the magnitude of the ratio between β -scission of the alkoxy radical and hydrogen atom abstraction from C–H bonds (k_5/k_7 in the case of cumyloxyl radical). Temperature also influences this ratio since it affects unimolecular (eq 5) more than bimolecular (eq 7) reactions; an increase in temperature therefore favours β -scission, as shown in the Walling report.

Several years later K. U. Ingold and co-workers⁸ provided conclusive resolution of the long-standing problem concerning the solvent effects on the competitive β -scission and hydrogen atom abstraction reactions from C–H bonds of cumyloxyl radical by determining the respective rate constants by laser flash photolysis. The results have clearly demonstrated that hydrogen atom abstraction from C–H bonds (eq 7) is solvent independent (i.e. for R–H = cyclohexane in eq 7 a rate constant of $1.2 \times 10^6 \text{ M}^{-1} \text{ s}^{-1}$ at 30 °C was determined in a variety of solvents of different polarity), whereas the rate of β -scission, k_5 , increases with an increase of solvent “polarity”; this gives a quantitative basis to the Walling suggestion that a decrease of the k_7/k_5 ratio with increasing solvent polarity is due to an increase in k_5 and that any changes in k_7 are of only very minor significance. The values for k_5 at 30 °C were 2.6, 3.7, 5.5, 5.8, 6.3, and $19 \times 10^5 \text{ s}^{-1}$ in CCl₄, C₆H₆, C₆H₅Cl, Me₃C–OH, MeCN, and MeCOOH, respectively. The increase in k_5 with increasing solvent polarity is likely due to increased stabilisation of the transition state for β -scission via increased solvation of the incipient acetophenone product.⁸

A more pronounced solvent effect has been reported more recently^{9,10} for hydrogen atom abstraction by cumyloxyl radical from *tert*-butylhydroperoxide (eq 8) and phenol (eq 9).



Here k_8 spans from $2.5 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$ in CCl₄ to $6.7 \times 10^6 \text{ M}^{-1} \text{ s}^{-1}$ in Me₃C–OH and the range is still larger in the case of k_9 ($8.6 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$ in CCl₄ and $3.6 \times 10^6 \text{ M}^{-1} \text{ s}^{-1}$ in Me₃C–OH). The absence of a solvent effect on hydrogen atom abstraction from C–H bonds by cumyloxyl radical necessarily implies that this dramatic change in

(6) Walling, C.; Padwa, A. *J. Am. Chem. Soc.* **1963**, *85*, 1593.

(7) Walling, C.; Wagner, P. I. *J. Am. Chem. Soc.* **1964**, *86*, 3368.

(8) Avila, D. V.; Brown, C. E.; Ingold, K. U.; Luszytk, J. *J. Am. Chem. Soc.* **1993**, *115*, 466.

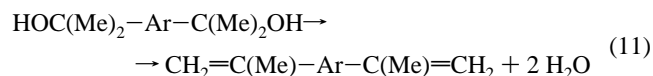
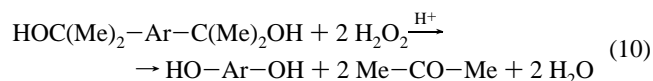
(9) Avila, D. V.; Ingold, K. U.; Luszytk, J. *J. Am. Chem. Soc.* **1995**, *117*, 2929.

(10) Pedrielli, P.; Pedulli, G. F. *Gazz. Chim. Ital.* **1997**, *127*, 509; De Heer, M. I.; Korth, H.-G.; Mulder, P. *J. Org. Chem.* **1999**, *64*, 6969.

behaviour must be due to solvent effect on the substrate, not on the cumyloxy radical. The results suggested that the solvent-induced decrease in k_8 and k_9 is associated with an increase in the strength of complexes formed between the O–H group and *t*-BuOOH or PhOH, the solvent acting as hydrogen bond acceptor. This is also reflected in solvent effect on the BDE values of phenol. The dramatic effect on eqs 8 and 9 indicates, in our opinion, that an analogous solvent effect should be likely involved in eqs 3 and 6; a solvent acting as hydrogen bond acceptor should significantly decrease the rate constants k_3 and k_6 .

This overall kinetic picture suggested that the temperature and the solvent should be the basic factors that can be exploited to achieve maximum selectivity for eq 4, considering that the previous aerobic oxidations catalysed by NHPI reported for cumene mainly led to acetophenone.^{4,5}

The synthetic strategy foresaw then the transformation of diols to diphenols by reactions with H_2O_2 and acid catalysis (eq 10) or to dienes (eq 11), useful industrial products for the synthesis of liquid crystals and cross-linked polymers.



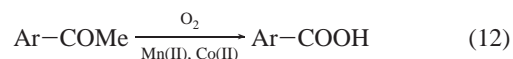
In addition, *p*-hydroxybenzoic acid is another important monomer for liquid crystal polymers. Some of our recent results^{11,12} concerning aerobic oxidation of carbonyl derivatives catalysed by $\text{Mn(NO}_3)_2$ and $\text{Co(NO}_3)_2$ and the mechanism of this catalysis suggested that *p*-hydroxybenzoic acid could be prepared by oxidation of *p*-hydroxyacetophenone with O_2 .

Results and Discussion

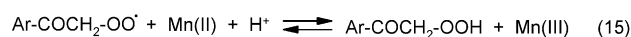
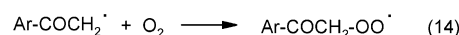
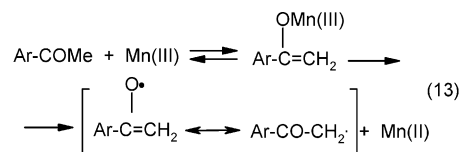
Liquid crystal polymers (LCPs) are a form of aromatic polyester/copolyester resins with excellent flow and mechanical properties. British Petroleum's Xydar LCPs are made from terephthalic acid, *p*-hydroxybenzoic acid, and 4,4'-dihydroxybiphenyl. LCPs were initially used primarily for dual-oven cookware; however, use in cookware declined dramatically in 1989–1990. Electrical/electronic applications, where exacting dimensional stability and surface-mount soldering temperature requirements create the need for a highly specialised material, are now the major market for LCPs; there are also commercial applications for LCPs in the military and in the aerospace, chemical processing, medical, and transportation industries.¹³

Our recent results,^{11,12} concerning the mechanism of aerobic oxidations catalysed by $\text{Mn(NO}_3)_2$ and $\text{Co(NO}_3)_2$ and by NHPI,³ suggested new processes for the production of

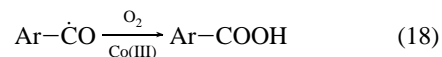
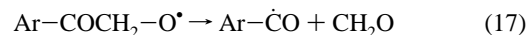
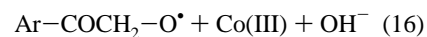
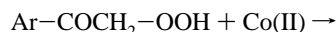
p-hydroxybenzoic acid and 4,4'-dihydroxybiphenyl. Acetyl-aromatics are easily oxidised by O_2 to aromatic carboxylic acids under mild conditions using catalytic amounts of $\text{Mn(NO}_3)_2$ and $\text{Co(NO}_3)_2$ (eq 12).^{11,12}



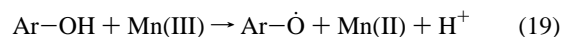
The process is characterised by a free-radical chain initiated by an electron-transfer process involving the enolic form of the ketone and Mn(III) nitrate, which is regenerated in a redox chain (eqs 13–15).^{11,12}



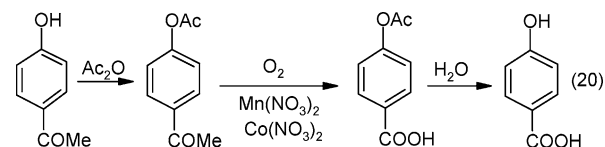
The hydroperoxide is decomposed by Co(II), yielding the aromatic carboxylic acid (eqs 16–18).



This mechanism suggested that the aerobic oxidation is not viable by this catalytic system with *p*-hydroxyacetophenone either because phenols are inhibitors of free-radical chain processes or because metal salts with high oxidation potential, such as Mn(III) and Co(III), rapidly oxidise the phenolic group by an electron-transfer mechanism (eq 19).



Therefore, we considered the possibility of aerobic oxidation of *p*-hydroxyacetophenone in acetic acid solution containing acetic anhydride that, by acetylating the phenolic group, would eliminate the inhibiting effect and the process of eq 19. Actually, in the presence of acetic anhydride the aerobic oxidation of *p*-hydroxyacetophenone leads with high yield to *p*-hydroxybenzoic acid (eq 20) under mild conditions.



On the other hand, *p*-acetoxybenzoic acid was directly reacted with dimethyl terephthalate to yield LCPs.^{1b}

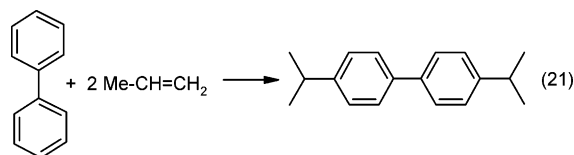
For the synthesis of 4,4'-dihydroxybiphenyl we have taken into consideration the possibility of utilising 4,4'-diisopropylbiphenyl, which is easily obtained from biphenyl and propene (eq 21).

Attempts to obtain dihydroxybiphenyl by the classical autoxidation procedure through dihydroperoxide gave poor results, since mixtures of mono- and dihydroperoxides were

(11) Minisci, F.; Recupero, F.; Fontana, F.; Bjørsvik, H.-R.; Liguori, L. *Synlett* **2002**, 610.

(12) Minisci, F.; Recupero, F.; Pedulli, G. F.; Lucarini, M. *J. Mol. Catal.*, A **2003**, 204–205, 63.

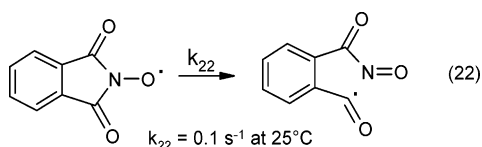
(13) *Chemical Economics Handbook*; SRI International: Menlo Park, CA, February 2001; 695.4021U, p 47.



obtained. Thus, we investigated a different approach, involving aerobic oxidation of diisopropylbiphenyl to the corresponding benzyl alcohol (eq 4), despite the results reported by Ishii and co-workers^{4,5} for the aerobic oxidation of cumene, catalysed by NHPI, mainly leading to acetophenone. We took advantage of the kinetic results of Ingold and co-workers on the temperature and solvent effects on the β -scission (eq 5) and the hydrogen atom abstraction from C–H bonds (eq 7) by cumyloxyl radical.

Acetic acid, used by Ishii as solvent in the aerobic oxidation of cumene, is a particularly unfavourable solvent for our purpose of obtaining benzyl alcohol for three main reasons: (i) it gives the highest rate of β -scission for cumyloxyl radical ($1.9 \times 10^6 \text{ s}^{-1}$ at 30 °C) among the solvents investigated by Ingold, leading to the formation of acetophenone; (ii) it is very likely to decrease the rate of hydrogen atom abstraction from NHPI by cumyloxyl radical, which leads to the benzyl alcohol (eq 6), by acting as a hydrogen bond acceptor solvent,⁹ since we have recently observed³ a similar solvent effect for eq 3; (iii) it catalyses the decomposition of the intermediate cumyl hydroperoxide formed in eq 3, giving the formation of phenol, which inhibits the free-radical chain of the aerobic oxidation.

Temperature is another important factor in the synthesis of benzyl alcohol: a higher temperature favours first-order processes, such as β -scission of cumyloxyl radical (eq 5)^{6–8} and the decomposition of the catalyst through self-decay of PINO radical (eq 22)³ more than second-order hydrogen atom abstractions (eqs 1, 6, 7).



On the basis of the kinetic results^{6–8} and of the Walling–Ingold rationalisation, the best conditions to obtain a high selectivity in benzyl alcohol would be the use of nonpolar solvents and the lowest possible oxidation temperature. Cumene was chosen as a model to investigate the effect of solvent and temperature on the selectivity between cumyl alcohol and acetophenone in the aerobic oxidation catalysed by NHPI. The results, reported in Table 1, essentially support the expectations, considering that the presence of the NHPI catalyst favours the formation of cumyl alcohol according to eq 6, which is faster than eq 7. The mechanism for the formation of cumyl alcohol, in fact, involves the chain process depicted by the equation sequence 1, 2, 3, 23, 6.

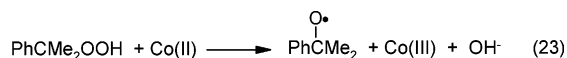
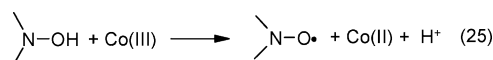


Table 1. Aerobic oxidation of cumene, catalysed by NHPI

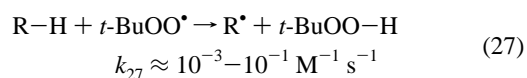
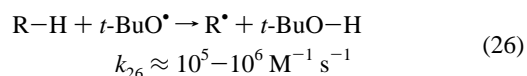
| solvent | <i>T</i> (°C) | time (h) | conversion (%) | cumyl alcohol (%) | acetophenone (%) |
|---|---------------|----------|----------------|-------------------|------------------|
| Ph-CN ^a | 100 | 20 | 76 | 8 | 64 |
| AcOH ^b | 100 | 20 | 40 | 10 | 54 |
| <i>t</i> -BuOH | 50 | 24 | 77 | 62 | 38 |
| MeCOMe ^c | 50 | 5 | 91 | 68 | 20 |
| CCl ₄ | 60 | 24 | 42 | 81 | 19 |
| MeCN | 80 | 8 | 72 | 69 | 31 |
| MeCN | 70 | 24 | 98 | 76 | 23 |
| MeCN | 50 | 24 | 100 | 91 | 9 |
| MeCN ^d | 40 | 9 | 100 | 99 | -- |
| Ph-Cl | 50 | 24 | 40 | 100 | -- |
| 1,2-C ₆ H ₄ Cl ₂ | 50 | 24 | 64 | 100 | -- |
| 1,2-C ₆ H ₄ Cl ₂ | 100 | 2 | 15 | 100 | -- |

^a Reference 5. ^b Reference 4, 17% of phenol is also formed. ^c 2% of Mn(NO₃)₂ was added to the reaction mixture. ^d 20% of NHPI was used.

Co(II) is regenerated either by decomposition of the hydroperoxide (eq 24) or by oxidation of NHPI (eq 25).



We have recently³ evaluated the rate constant for eq 3 ($k_3 = 7.2 \times 10^3 \text{ M}^{-1} \text{ s}^{-1}$ at 30 °C), while we do not know the rate constant for eq 6, for which, however, we expect a much higher rate constant on the basis of the involved enthalpies (the BDE values of the O–H bonds are 104 and 88 kcal mol^{–1}, respectively, for alcohols, RO–H, and hydroperoxides, ROO–H). This is also supported by the great reactivity difference for hydrogen atom abstraction from C–H bonds by *t*-BuO• (eq 26) and *t*-BuOO• (eq 27) radicals.

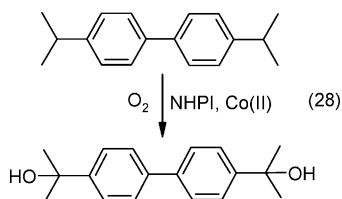


We can expect an analogous difference between eqs 3 and 6.

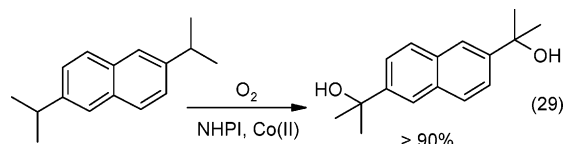
The results of Table 1 suggest that solvents such as chlorobenzenes would be particularly convenient for the synthesis of cumyl alcohol. However, the low solubility of NHPI in these solvents does not allow high conversions; this is a major drawback for the oxidation of diisopropylaromatics, since only a complete oxidation of both isopropyl groups allows industrial application of this process.

A high polarity of the solvent increases the solubility of NHPI, but at the same time it reduces the selectivity in benzyl alcohol. Therefore, a compromise has been achieved with a solvent, acetonitrile, which grants a good solubility for the catalyst NHPI while allowing complete conversion of the diisopropylaromatics at a temperature low enough to favour the selectivity in benzyl alcohol. The low temperature also favours recovery and recycle of the catalyst because it decreases decomposition of the PINO radical (eq 22, $k_{22} = 0.1 \text{ s}^{-1}$ at 25 °C) compared to hydrogen atom abstraction from the isopropyl group (eq 1, $k_1 = 3.25 \text{ M}^{-1} \text{ s}^{-1}$ at 25 °C).

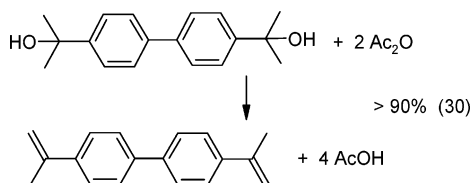
Yields higher than 90% were obtained for the dibenzyl alcohol of eq 28 by working at 40 °C under atmospheric pressure of O₂.



Similar results have been obtained from the catalytic oxidation of 2,6-diisopropynaphthalene (eq 29).



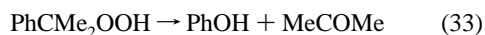
The 4,4'-di(hydroxyisopropyl)biphenyl obtained in eq 28 was previously prepared¹⁴ by a much more expensive procedure involving reaction of 4,4'-diacetylbiphenyl with MeMgI, and it was used for the synthesis of 4,4'-diisopropenylbiphenyl by reaction with acetic anhydride (eq 30).



The diene was used for the synthesis of cross-linked polymers by copolymerisation with styrene.¹⁴

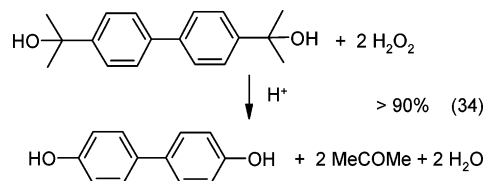
The overall synthetic approach (eqs 28 and 30) reported in this contribution is far more convenient than the previous procedure¹⁴ for the production of 4,4'-diisopropenylbiphenyl.

4,4'-Dihydroxybiphenyl was not previously produced from 4,4'-di(hydroxyisopropyl) biphenyl; however, phenol can be prepared from cumyl alcohol and H₂O₂ by acid catalysis.¹⁵ This latter has a two-fold purpose: it catalyses the formation (eqs 31 and 32) and the decomposition (eq 33) of cumyl hydroperoxide, as in the classical process for the production of phenol from cumene hydroperoxide.

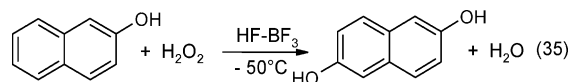


This procedure, applied to 4,4'-di(hydroxyisopropyl) biphenyl in a two-phase system, has given high yields of 4,4'-dihydroxybiphenyl (eq 34).

Thus, the combination of eqs 28 and 34 appears to be a convenient process for the production of 4,4'-dihydroxy biphenyl. Experiments on larger scale are in progress.



The autoxidation of 2,6-diisopropynaphthalene to mixtures of mono- and dihydroperoxide^{16,17} was utilised for the production of 2-hydroxy-6-isopropynaphthalene and of 2,6-dihydroxynaphthalene, which are interesting intermediates for the production of dyes, agrochemicals, drugs, liquid crystalline materials, and heat-resistant polymers. However, the drawbacks discussed above for other diisopropylaromatics, are also present in the oxidation of 2,6-diisopropynaphthalene. The formation of 2,6-dihydroxynaphthalene with high selectivity (>90%) was also reported by Olah and co-workers¹⁸ by hydroxylation of β -naphthol by H₂O₂ and superacid catalysis (eq 35). The practical application of this procedure is, however, limited by the use of 90% H₂O₂ in a large excess of HF-BF₃ at -50 °C and by the low conversions.



Thus, the approach involving 2,6-di(hydroxyisopropyl)-naphthalene, obtained in high yields according to eq 29, appears to be of interest. By the procedures of eqs 30 and 34 the corresponding diene and diphenol were obtained, but yields are somewhat lower, likely because these molecules are less stable than the derivatives in the biphenyl series. No attempt was made until now to improve yields by further investigation, for the main reason that diisopropylation of naphthalene by propene is less selective than the corresponding reaction with biphenyl;¹⁹ considerable amounts of 2,7-diisopropyl and minor amounts of other disubstituted isomers are also formed. This can affect the overall practical interest, due to the difficulty of isomer separation.

Conclusions

The aerobic oxidation of *p*-hydroxyacetophenone, catalysed by Mn(NO₃)₂ and Co(NO₃)₂, leads with high selectivity and under mild conditions to *p*-hydroxybenzoic acid, a useful monomer for LCPs; the presence of acetic anhydride protects the phenol as an ester group. The aerobic oxidation of 4,4'-diisopropylbiphenyl, catalysed by NHPI and Co(OAc)₂, always in mild conditions (40 °C and atmospheric pressure) in a suitable solvent, MeCN, leads in high yields to 4,4'-di(hydroxyisopropyl)biphenyl; temperature and solvent effects play a key role in determining the high selectivity of the oxidation. The benzylic diol is a useful intermediate for the synthesis of 4,4'-dihydroxybiphenyl, another important mono-

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mer for LCPs, and of 4,4'-di(isopropenyl)biphenyl, which can be used for the production of cross-linked polymers.

Experimental Section

4-Hydroxyacetophenone was a commercial product (Aldrich), 4,4'-diisopropylbiphenyl and 2,6-diisopropynaphthalene were supplied by Lonza S.p.A. $\text{Co}(\text{NO}_3)_2$, $\text{Co}(\text{OAc})_2$, $\text{Mn}(\text{NO}_3)_2$, and *N*-hydroxyphthalimide (NHPI) were also commercially available.

Synthesis of *p*-Hydroxybenzoic Acid by Aerobic Oxidation of *p*-Hydroxyacetophenone. A solution of 2.72 g (20 mmol) of 4-hydroxyacetophenone, 100 mg (0.4 mmol) of $\text{Mn}(\text{NO}_3)_2 \cdot 4 \text{H}_2\text{O}$ and 116 mg (0.4 mmol) of $\text{Co}(\text{NO}_3)_2 \cdot 6 \text{H}_2\text{O}$ in 50 mL of acetic acid and 10 mL of acetic anhydride was stirred for 8 h in oxygen atmosphere at 100 °C and ambient pressure. The solvents were distilled off, and 3.7 g of solid residue was obtained. It was dissolved in CH_2Cl_2 , filtered from the small amounts of metal salts, and analysed by GLC as *p*-acetoxymethyl benzoate after treatment with CH_2N_2 by using *p*-methoxymethyl benzoate as internal standard. *p*-Acetoxymethyl benzoate, 3.5 g (corresponding to 91%), was obtained. The crude *p*-acetoxymethyl benzoate gave, by flash chromatography on silica gel, the pure compound (mp 191–193 °C, lit.²⁰ 191–192 °C). Acid hydrolysis gave *p*-hydroxybenzoic acid (mp 215–217 °C, lit.²¹ 215–217 °C).

Aerobic Oxidation of Cumene, Catalysed by NHPI. Solutions of 2.40 g (20 mmol) of cumene, 326 mg (2 mmol) of NHPI, and 100 mg (0.4 mmol) of $\text{Co}(\text{OAc})_2 \cdot 4 \text{H}_2\text{O}$ were stirred under oxygen atmosphere at ambient pressure; temperatures, reaction times, and solvents (25 mL) are reported in Table 1. The solutions were analysed by GLC: unreacted cumene, cumyl alcohol, and acetophenone were the only reaction products; the only exception concerns the reaction in acetic acid, where a significant amount of phenol is also formed. Quantitative analysis was carried out by GLC using benzyl alcohol as internal standard. Conversions and selectivities are reported in Table 1.

Aerobic Oxidation of 4,4'-Diisopropylbiphenyl, Catalysed by NHPI. A solution of 4.77 g (20 mmol) of 4,4'-diisopropylbiphenyl, 652 mg (4 mmol) of NHPI, and 100 mg (0.4 mmol) of $\text{Co}(\text{OAc})_2 \cdot 4 \text{H}_2\text{O}$ in 25 mL of acetonitrile was stirred at 40 °C for 12 h under oxygen atmosphere at ambient pressure. The solvent was distilled off, and 6.4 g of solid residue was obtained. GLC analysis using cumyl alcohol as internal standard revealed the presence of 4.9 g of 4,4'-di(hydroxyisopropyl)biphenyl, corresponding to 90.7% yield. The pure product was separated by flash chromatography on silica gel and characterised by comparison with an authentic sample, obtained from 4,4'-diacetylbiiphenyl and

CH_3MgI , as reported¹⁴ (MS: m/z 270 (M^+), 255, 334, 195, 152, 76, 59, 43).

Aerobic Oxidation of 2,6-Diisopropynaphthalene, Catalysed by NHPI. The same procedure described above for 4,4'-diisopropylbiphenyl was utilised for 2,6-diisopropynaphthalene. A 92% yield of crude 2,6-di(hydroxyisopropyl)naphthalene was obtained by distillation of the solvent. The crude product was crystallised from $\text{EtOH}:\text{H}_2\text{O}$ (4:1 v/v) to give the pure product, mp 157–158 °C, lit.²² 156–158 °C. ^1H NMR: δ 1.61 (12 H, 4 CH_3), 7.56 (2 H aromatic, positions 3 and 7), 7.76 (2 H aromatic, positions 4 and 8), 7.88 (2 H aromatic, positions 1 and 5).

Synthesis of 4,4'-Diisopropenylbiphenyl. The procedure, described in ref 14, was utilised; it simply consisted of boiling 4,4'-di(hydroxyisopropyl)biphenyl in acetic anhydride solution for 6 h; 93% yield of 4,4'-diisopropylbiphenyl was obtained, in good agreement with the literature results.¹⁴

Synthesis of 2,6-Diisopropenyl-naphthalene. The same procedure described above for 4,4'-diisopropenylbiphenyl was utilised, starting from 2,6-di(hydroxyisopropyl)naphthalene. A 87% yield of 2,6-diisopropenyl-naphthalene was obtained, determined by GLC analysis. The compound was not known, and it was characterised by MS and NMR spectra. MS: m/z 208 (M^+), 193, 178, 165, 152, 139, 128, 115, 89, 76. ^1H NMR: δ 2.27 (6 H, 2 CH_3), 5.20 (2 H, vinyl), 5.54 (2 H, vinyl), 7.66 (2 H aromatic, positions 4 and 8), 7.78 (2 H aromatic, positions 3 and 7), 7.82 (2 H aromatic, positions 1 and 5).

Synthesis of 4,4'-Dihydroxybiphenyl. H_2SO_4 (0.15 mL, 3 mmol) was added dropwise to a mixture of 480 mg (2 mmol) of 4,4'-di(hydroxyisopropyl)biphenyl and 0.77 mL (9 mmol) of H_2O_2 (35%). The mixture was refluxed for 12 h and then extracted with CH_2Cl_2 . The CH_2Cl_2 solution was extracted with 5% aqueous NaOH. The basic aqueous solution was acidified with H_2SO_4 and extracted by ethyl acetate, obtaining 0.36 g of crude 4,4'-dihydroxybiphenyl, corresponding to 92% yield, evaluated by GLC analysis. The pure product was obtained by flash chromatography on silica gel and characterised by MS (m/z 186 (M^+), 157, 139, 128, 115, 93, 77, 63, 51) and comparison with a commercial sample.

Synthesis of 2,6-Dihydroxynaphthalene. The same procedure described above for 4,4'-dihydroxybiphenyl was used, starting from 2,6-di(hydroxyisopropyl)naphthalene. 2,6-Dihydroxynaphthalene was isolated in 48% yield and characterised by MS and ^1H NMR spectra. MS (m/z 160 (M^+), 131, 115, 103, 77, 63, 51); ^1H NMR: δ 7.07 (2H aromatic, positions 3 and 7), 7.13 (2H aromatic, positions 1 and 5), 7.56 (2H aromatic, positions 4 and 8), 8.35 (2H, OH).

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