Chinese Journal of Chemistry, **2004**, *22*, 487—491

Article

Catalytic Conversion of 2-Naphthol to 2-Hydroxy-1,4-naphthoquinone Under Mild Conditions

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2-Hydroxy-1,4-naphthaquinone (HNQ) was selectively synthesized from catalytic oxidation of 2-naphthol by molecular oxygen over tetra(4-methoxyl-phenyl)porphyrinate iron(III) chloride (TMOPPFeCl) catalyst in an alkali methanol solution under mild conditions. The influences of solvents, temperature, time, as well as amounts of catalysts and alkali were studied. The quantitative data show that 32.9% of 2-naphthol (0.093 mol/dm^3) was catalytically converted to HNQ with the selectivity of 100% at 323 K for 9 h over TMOPPFeCl catalyst (2.54×10^{-4} mol/dm^3) in alkali media (30 mL of methanol containing 2.5 mol/dm^3 of NaOH) by flowing molecular oxygen (flowing rate of 45 mL/min).

Keywords porphyrinate iron chloride, 2-naphthol, oxygen oxidation, 2-hydroxy-1,4-naphthoquinone

Introduction

2-Hydroxy-1,4-naphthoquinone (HNQ), existing in natural plants,[1,2] is popularly separated and purified as dye or pigment. Recent research results show that, with the function to prevent the formation of protein coenzyme of HIV-I, HNQ can inhibit HIV virus from copying and propagating,[3,4] HNQ's derivatives and dichloroallyl lawsone are also the inhibitor for RNA synthesis of cancer.[5] It is well known that there is a relationship between the side chain attached to HNQ and its toxic effects on several microorganisms.[6,7] Therefore, in the future, HNQ and its derivatives may be potentially useful for curing and as prophylactic medicines of AIDS and cancers.

HNQ was successfully synthesized by various chemical ways,[8-11] and several starting reactants are used, such as 2,3-epoxy-2,3-dihydro-1,4-naphthoquinone,[8] 1,2- or 1,3-dihydroxynaphthalene,[9,10] and 1- or 2-tetrolone.[11] Notably, these synthetic routes are generally complicated, and the oxidative states of all starting substances are higher than that of 1- or 2-naphthol. Meanwhile a relatively simple method such as catalytic conversion is seldom being sought.

More recently, it has been reported that metalloporphyrin catalysts with electron expelling groups display high selectivity (95%) and activity in catalytic oxidation of naphthol to HNQ (the HNQ yields from 1- and 2-naphthol are 40.2% and 57.2%, respectively) by hydrogen peroxide in an alkali at 0 ℃ for 1 h. Reaction time more than 1 h or increasing temperature both will increase the formation of phthalic anhydride which is a byproduct in this catalytic oxidation.[12]

Currently, more works are focused on the use of molecular oxygen for catalytic oxidation of hydrocarbons in the mild conditions because molecular oxygen is much cheaper than hydrogen peroxide.[13-15] For example, Thomas and co-workers[13] reported the oxidation of *n*-alkanes at the terminal carbon atoms with high selectivity using molecular oxygen in a liquid-phase reaction, and Sheldon and co-workers[14] reported the oxidation of alcohols to aldehydes and ketones in water solvent reaction.

Till now, 'Green Chemistry' becomes a popular concept in chemical research. Therefore, introducing molecular oxygen and air as oxidants in catalytic conversion exhibits more prominent significance for protecting the global environment.

We demonstrate here the catalytic oxidation of naphthol to HNQ by molecular oxygen over tetra (4-methoxyl-phenyl)porphyrinate iron(III) chloride (TMOPPFeCl) catalyst. Catalytic data show that the use of molecular oxygen completely avoids the over-oxidation of HNQ. The influences on the catalytic oxidation are discussed.

Experimental

Reagents

The metalloporphyrin catalysts were prepared ac-

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Received June 17, 2003; revised and accepted January 1, 2004.

cording to Adler's[16] methods. Oxygen with purity of 99.999% was from oxygen cylinder; methanol, ethanol, 1-propanol, 2-propanol, 1-butanol, glycol, 1- or 2-naphthol, and 2-hydroxy-1,4-naphthoquinone were purchased with purity higher than 99.99%, and other reagents all with purity of 99.9% were used without further purification.

Catalytic reactions

As a typical run, 0.40 g of 2-naphthol (or 1-naphthol, 2.8 mmol), 2.0 g of NaOH, and 2.0 mg of TMOPPFeCl was dissolved in 30 mL of MeOH at 323 K, followed by bubbling oxygen with rate at 45 mL/min. The color of the reaction solution was changing from straw yellow to bright orange gradually. Reaction products were determined by UV-vis method and the catalytic reaction was stopped after their absorption peaks at 452 nm reached the maximal value. The reaction mixture was distilled under vacuum for removing methanol. After adding of water, an orange solution was obtained. Metalloporphyrin catalyst was removed by filtrating. In present form, the product was sodium salt, which was converted into H-form by addition of HCl solution (1:1, *V/V*) and precipitated in the acidic aqueous solution. Pure buff HNQ product was prepared after filtrating and drying.

Instruments

The instruments used in this work are a GBC Cintra 10e spectrophotometer (Scan range from 350 nm to 700 nm with speed at 1000.0 nm/min; data interval is 1.280 nm, wavelength scan and absorbance, slit width: 1.5 nm, and sample concentration: 0.1—0.0001 mol/dm^3), a Nicolet FTIR 5-PC spectrometer (Slow scanning speed, resolution power: 4 cm^{-1}, 400—4000 cm^{-1}, KBr), a Trace 2000 GC-MS spectrometer [OV-17 column and SE-54 capillary column; 100—200 ℃, 5 ℃/min, injection temperature is 250 ℃. Nitrogen as carry gas with speed of 1.5 mL/min; chemical exciting source, *m/z* range: 0—300 *m/z*], a UNTY-400 NMR spectrometer (100.57 MHz, DMSO), a Shimadzu GC-15A chromatograph with CR 4A chromatpac recorder (SE-54 capillary column; injecting, column and detecting temperature are 200, 150, and 200 ℃, respectively), a Shimadzu LC-10A HPLC (Hypersit ODS 10 μ column with pressure of 7.9 MPa, liquid flow phase: H_2O_2/MeOH/MeCN (2*V*/1*V*/1*V*) with speed of 1 mL/min, injecting amount: 10 μL), and an X-4 microscopical melting point monitor.

Results and discussion

Characterization of reaction product

The oxidation product of naphthol shows buff powder with yield of 32.9% and selectivity of 100%, m.p. (192±0.5) ℃, UV-vis (NaOH aqueous solution) λ_{max}: 452, 286, 213 nm; MS (70 eV) *m/z* (%): 174. Anal. calcd for $C_{10}H_6O_3$: C 68.97, H 3.45; found C 68.78, H 3.47. m.p. datum is in good agreement with the reported value.[17] ^{1}H NMR and ^{13}C NMR of the product are the same as pure HNQ spectra and Sadtler Standard Spectra.[18] In the catalytic oxidation, all experimental data are the same as pure HNQ ones, and analysis results indicate that the oxidation product is 2-hydroxy-1,4-naphthoquinone (HNQ, lawsone),[18-22] the unique product in this catalysis.

Ordinarily, the quantitative analyses of organic substances such as 1- or 2-naphthol, and HNQ, were performed by means of GC method. The GC peaks appearing at t_R=0.641, 1.825 (1.902) and 2.068 min are attributed to ether, 1-naphthol (2-naphthol), and HNQ, respectively. HNQ is the only one product, which can be directly determined by UV-vis method since it shows very strong orange color in an alkali aqueous solution. In alkali condition, HNQ gives the form of a sodium salt (HNQNa), exhibiting a strong absorption at 452 nm (ε =2.809×10^3 dm^2/mol). Co-existing substances in the catalytic system, including NaOH, MeOH, 1- or 2-naphthol and alcohol solvents, have no absorption around 350—700 nm. Therefore the absorption of HNQNa at 452 nm can be directly used as the characteristic peak for analyzing HNQ quantitatively. An analytical error of HNQ between GC, or HPLC, and UV-vis method is smaller than 2%.

Influences on the catalysis

Influence of different metalloporphyrin catalysts:

The oxidative reaction of 2-naphthol conversion towards HNQ over metalloporphrin catalyst is as Scheme 1.

Scheme 1

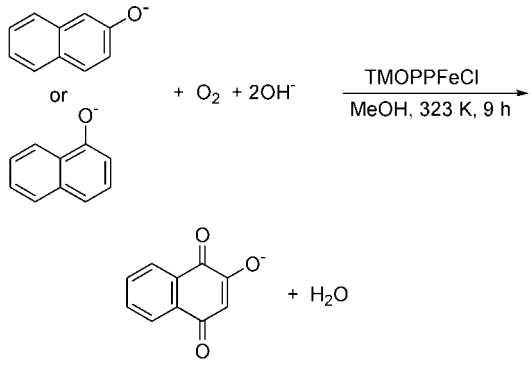

Table 1 Influences of different metalloporphyrin catalysts on the oxidation of 2-naphthol to produce HNQ

Side group	OCH_3	OCH_3	OCH_3	OCH_3	H	F
Center metal	Fe(III)	Mn(III)	Zn(II)	Co(II)	Fe(III)	Fe(III)
HNQ yield/%	13.16	4.64	—	—	10.64	5.05

$m_{Catalyst}$=2.0 mg; m_{NaOH}=2 g; 323 K; 3 h; V_{MeOH}=30 mL; V_{O_2} =6 mL/s; $m_{2\text{-naphthol}}$=0.4 g

Table 1 presents catalytic activities over various metalloporphyrin catalysts. Notably, metalloporphrins

with the same side groups, but with different center ions result in various catalytic activities significantly. For example, tetra(4-methoxy-phenyl)porphyrinate zinc(II) and cobalt(II) (TMOPPZn and TMOPPCo) show very low conversion, and no HNQ is detected. Tetra(4-methoxy-phenyl)porphyrinate manganese(III) chloride (TMOPPMnCl) shows relatively high activity, giving a yield of 4.64% of HNQ. And tetra(4-methoxy-phenyl)porphyrinate iron(III) chloride (TMOPPFeCl) shows the highest activity, exhibiting the highest yield of HNQ at 13.16%. These results are well consistent with those reported in previous work.[12]

Furthermore, we observed that the side groups also strongly influence the catalytic activity. For example, since the electron donating abilities of metalloporphyrin side groups being as $OCH_3 > H > F$, the catalytic activities display TMOPPFeCl > TPPFeCl > TFPPFeCl. Obviously, the catalytic activities are strongly depended on the electron donating ability. Possibly, the electron donating groups, such as methoxyl groups, can donate electron through conjugation to center metal to stabilize the catalytic intermediate of high valence oxygen-iron(V).[23]

Therefore, the best catalyst in this conversion is TMOPPFeCl, which is with the strongest electron donating side groups, methoxyls, and with center metal of iron(III).

Influence of the amount of TMOPPFeCl catalyst:

Figure 1 presents catalytic activities of different catalyst amounts. Along with the increasing of the amount of TMOPPFeCl, the conversion of 2-naphthol to produce HNQ was enhanced gradually. The experimental results show that when the amount of the catalyst is upwards of 6.0 mg (3.5×10^{-6} mol/dm^3), the highest yield of HNQ reached 12.71%.

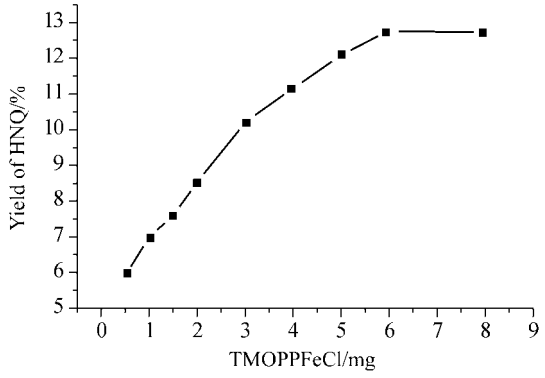

Figure 1 Influence of TMOPPFeCl catalyst amount (m_{NaOH}=2 g, 323 K, 3 h, V_{MeOH}=30 mL, V_{O_2} =0.072 mL/s, $m_{2\text{-naphthol}}$=0.4 g).

Influence of the amount of sodium hydroxide:

Figure 2 presents the influence of sodium hydroxide amount in the methanol solution. Alkali reacting medium is beneficial for both of decreasing the redox potential and promoting the organic reaction rate. In the catalytic oxidation of naphthol system, sodium hydroxide displays a very important role. Without sodium hydroxide, no HNQ can be detected by any determining methods, including GC, HPLC, even GC-MS method. Therefore, the conversion of naphthol to HNQ is also increased with the amount of NaOH in the reaction solution, until sodium hydroxide has reached its solubility. Along with NaOH amount changing from 0.2 to 3.0 g (from 0.17 to 2.5 mol/dm^3), the yield of HNQ is increased from 1.07% to 23.65%. When NaOH amount increases to 4.0 g, beyond its solubility in methanol solvent, the solution becomes too sticky to rapidly stir, which inhabits the oxidant oxygen to participate in the reaction adequately. Therefore, the yield of HNQ is descended when the amount of NaOH is more over its solubility.

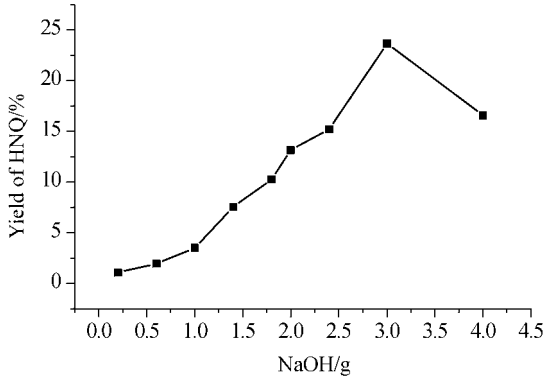

Figure 2 Influence of NaOH amount ($m_{TMOPPFeCl}$=2.0 mg, 323 K, 3 h, V_{MeOH}=30 mL, V_{O_2} =6.0 mL/s, $m_{2\text{-naphthol}}$=0.4 g).

Influences of oxygen, temperature and reacting time:

Figures 3, 4 and 5 indicate the influences of oxygen, reacting time and temperature, respectively. As the oxidant being in gas phase, increasing oxygen rate enhances to produce HNQ. When oxygen rate is controlled between 0.1 and 7.5 mL/s, the HNQ yield ranges from 11.11% to 14.71%. The oxidizing ability of molecular oxygen is weaker than that of hydrogen peroxide,

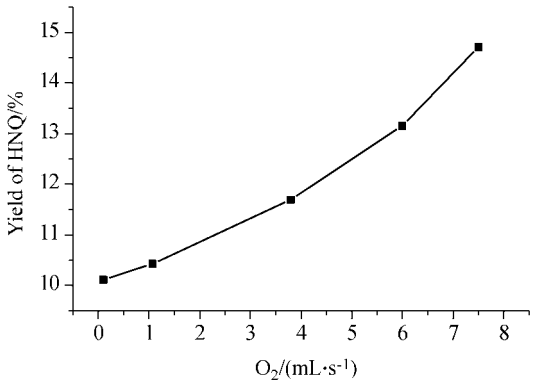

Figure 3 Influence of oxygen ($m_{TMOPPFeCl}$=2.0 mg, 323 K, 3 h, m_{NaOH}=2.0 g, V_{MeOH}=30 mL, $m_{2\text{-naphthol}}$=0.4 g).

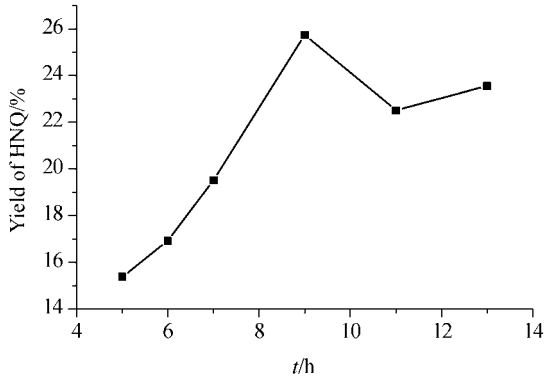

Figure 4 Influence of reacting time ($m_{TMOPPFeCl}$=2.0 mg, m_{NaOH}=2.0 g, 323 K, V_{MeOH}=30 mL, V_{O_2}=6.0 mL/s).

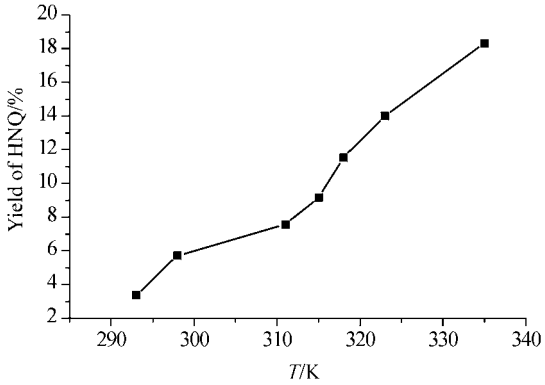

Figure 5 Influence of temperature ($m_{TMOPPFeCl}$=2.0 mg, m_{NaOH}=2.0 g, 3 h, V_{MeOH}=30 mL, V_{O_2}=6.0 mL/s, $m_{2\text{-naphthol}}$=0.4 g).

and the product HNQ can be not oxidized by molecular oxygen. Therefore no over oxidizing byproducts are detected by GC method.

High reaction temperature is also propitious to increase HNQ yield. After 9 h reaction at 323 K, the yield of HNQ reaches 25.75%. Over long reaction will reduce HNQ yield.

But over high leading in rate of oxygen, over high temperature and over long time reaction can bring the solvent methanol out of the reacting system, and make the reacting solution more sticky, cumbering contact between oxygen and the reaction solution, and as a result, cause the HNQ yield descending.

Selecting of reaction solution

Among all solutions including water, water dissoluble and insoluble organic solvents are examined in the catalytic reaction.

Owing to the insolubility of sodium hydroxide, in dichloromethane, chloroform, ether, benzene, or toluene media, after reaction, nearly no HNQ is detected by HPLC.

Although NaOH is soluble in aqueous solution, water is not a good reaction medium, since its strong polarity is unsuitable for HNQ formation and itself will prohibit the equilibrium shifting towards HNQ.

The HPLC analyses show more complicated chromatograms in acetone and ethanol reaction media during the formation of byproducts.

Both of GC and HPLC determinations show just two peaks in methanol medium, one is naphthol (t_R=1.72 min for 2-naphthol and t_R=1.69 min for 2-naphthol) and the other is HNQ (t_R=6.483 min). The experimental results indicate that, in the medium of methanol, the catalytic selectivity to produce HNQ is 100%. Therefore, methanol is the most suitable medium in the catalytic reaction, since it with both of dissolubility for NaOH and suitable polarity, the first factor accelerating reaction rate and the second one promoting HNQ formation.

Summarizing all influences, the optimizing conditions in the catalytic reaction are as below: when in 30 mL of methanol solution containing 3.0 g of NaOH, using 6.0 mg of TMOPPFeCl as catalyst (3.5×10^{-6} mol/dm^3) and 0.4 g of 2-naphthol (9.26×10^{-2} mol/dm^3) as reactant, while oxygen flow rate at 6.0 mL/s, after over 9 h reaction, the yield of HNQ can reach to 32.9% with the HNQ selectivity of 100% and catalyst conversion number of 16.12/min.

Under the same conditions, if the reactant 2-naphthol is displaced by 1-naphthol, just 20.6% of the reactant is converted to HNQ with the same selectivity and the catalyst conversion number is 10.09/min.

The different HNQ yields and catalyst conversion numbers indicate the reactants with different activities. In this oxidation, 1-naphthol is less active than its isomer 2-naphthol, since it must rearrange the molecular structure during HNQ formation while this rearrange for 2-naphthol is unnecessary. Therefore, the molecular structure rearranging may induce descending of the HNQ yield from 1-naphthol.

Other related questions

Under the optimizing conditions and after 6 cycles of catalytic oxidation, the activity of metalloporphyrinate iron(III) catalyst descends slightly, and the HNQ yield dropped from 32.9% to 22.6%. It is believed that catalyst losing in filtration processes results in the drop of HNQ yield.

We have tried to observe the active intermediate of metalloporphyrin with molecular oxygen by determination of UV-vis, IR and EPR in situ, respectively. After long time reaction with oxygen, no new signal appears in all spectra except the original characteristic peaks of metalloporphrin itself. Comparing with the system without metalloporphyrin catalyst, the catalytic one displays very high activity and selectivity towards forming HNQ. Therefore the metalloporphyrin indeed acts as active catalyst in this oxidation by some unknown way. The catalytic mechanism should be studied in more detail based on further more experimental evidences.

Conclusion

With metalloporphyrinate iron(III) as catalyst, in alkaline methanol solution and using molecular oxygen as oxidant, 2-naphthol is converted to 2-hydroxy-1,4-naph-

thol with high selectivity. Experimental results show special characteristics as below: **1**, the reaction goes on in the alkaline methanol solution. Without sodium hydroxide or substituting methanol by other solvent will decrease the conversion of naphthol and accelerate the formation of byproduct; **2**, HNQ, the single catalytic product, can be separated and determined easily; **3**, the catalysis is performed at low temperature; **4**, after reaction, catalyst is deposited from the system by adding large amount of water for reusing without decreasing of catalytic activity; and **5**, 2-naphthol as reactant is more active than its isomer 1-naphthol.

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(E0306178 ZHAO, X. J.)