Chemical model of oxidases. Cu^I-catalyzed oxidation of secondary alcohols by dioxygen

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Oxidation of secondary alcohols (2-propanol, 2-butanol, and cyclohexanol) by dioxygen, catalyzed by Cu^I and *o*-phenanthroline complexes, in the presence of alkali, was studied. The conditions under which oxidative dehydrogenation of secondary alcohols result in fast formation of ketones as the only primary oxidation products were found. Bis-phenanthrolinates $[Cu(phen)_2]^+$ are the active forms of the catalyst. The catalytic turnover number for complexes between copper(I) and *o*-phenanthroline is 1 to 2 s^{-1} at room temperature.

Kinetic regularities of the reaction are similar to those of the oxidation of alcohols in the presence of oxidases. The mechanism of the process is proposed, suggesting that the oxidation of secondary alcohols occurs *via* a concerted two-electron mechanism involving a stage of formation of the ternary complex $[O_2...Cu(phen)_2{}^+...{}^-OCHR^1R^2]$. It is significant for the oxidation mechanism that a hydrogen atom is transferred from the anionic form of a substrate to oxygen, which is confirmed by the value of the kinetic isotope effect $k_H/k_D = 2.1$.

Key words: oxidation by dioxygen, homogeneous catalysis, copper(I) phenanthrolinates, 2-propanol, models of oxidases, two-electron oxidation, biomimetics.

Oxidation of alcohols to aldehydes or ketones plays an important role in organic synthesis. Ruthenium[1—3] or copper[4—6] compounds are used, as a rule, in most promising catalytic systems of mild and selective oxidation of alcohols to carbonyl compounds by dioxygen. Copper compounds can be considered as the models of copper-containing oxidases, which play a substantial role in biological systems.[7]

The use of ruthenium- and copper-containing catalytic systems allows one to achieve a high selectivity in oxidation of primary and secondary alcohols to aldehydes and ketones (up to 98 % with respect to a substrate consumed). However, the activity of known catalytic systems, whose measure is the catalytic turnover numbers per catalyst species per second (t.n.), is several orders of magnitude lower than the activity of oxidases.

It has been shown in our previous works that in alkaline aprotic media copper(I) complexes with *o*-phenanthroline (phen) are capable of catalyzing oxidation of primary alcohols to aldehydes by dioxygen at temperatures close to room temperature[8,9] with rates that are several orders of magnitude higher than those of traditional radical chain oxidation and approach the rate of enzymatic oxidation. It seems that the reaction mechanism has many common features with the mechanism of alcohol oxidation by molecular oxygen in the presence of oxidases.[8] However, secondary alcohols almost do not undergo oxidation in strongly alkaline media in the presence of copper phenanthrolinates.[9]

In this work the conditions for highly efficient low-temperature oxidative dehydrogenation of secondary alcohols are established and the mechanism of their catalytic oxidation by molecular oxygen in the presence of copper phenanthroline complexes and bases is studied.

Experimental

Oxidation of secondary alcohols (2-propanol, 2-butanol, and cyclohexanol) was performed both in the absence of a solvent and in acetonitrile at 20—30 °C. 2-Propanol-d_8 was oxidized in acetonitrile.

Cu^I and Cu^{II} complexes with phen were prepared by dissolution of CuCl or $CuCl_2 \cdot 2H_2O$ and phen in secondary alcohols in the 1 : 4 molar ratio. When 2-propanol-d_8 was oxidized, CuCl and phen were dissolved in acetonitrile in the 1 : 15 molar ratio. Concentrations and compositions of Cu^I and Cu^{II} phenanthroline complexes were determined spectrophotometrically[10] (extinction coefficient of catalytically active Cu^I bis-phenanthroline complexes $\varepsilon = 7040\ M^{-1}\ cm^{-1}$ at λ = 430 nm corresponding to the absorption maximum (see Ref. 11).

Alkali were added to an alcohol solution containing Cu^I phenanthrolinate as granules or an alcohol solution of NaOH or KOH (0.5—1.0 mol L^{-1}). In the latter case, a concentrated alkaline solution was injected with a syringe into an oxidation cell attached to a gasometer. Oxygen absorption began immediately after injection of the alkaline solution. Granules of NaOH or KOH were added to a solution before stirring, and in this case the reaction started after stirring and dissolving some amount of the alkali.

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Reaction rates were controlled by the rates of dioxygen absorption, consumption of a base, and accumulation of ketones in the reaction medium. The concentration of ketones was determined by GLC on a Varian 3400 instrument (10 % polyethyleneglycol adipinate on Rysorb BLK, column 2 m in length).

Results and Discussion

Kinetic regularities of catalytic oxidation of secondary alcohols. It has been shown recently[6] that complexes of Cu^I with phen or 2,2′-dipyridyl (dipy) can catalyze oxidative dehydrogenation of primary and secondary alcohols by molecular oxygen in acetonitrile to form aldehydes or ketones as the main reaction products. Aromatic alcohols (benzhydrol) are oxidized at the highest rates, and oxidation rates of aliphatic secondary alcohols are the lowest. It is assumed that deprotonation of a substrate by bases (dipy or phen) is an important stage of the process. However, phen and dipy are weak bases [12] and cannot efficiently deprotonate alcohols. Even in the case of easily oxidized benzhydrol, oxidation rates higher than $2 \cdot 10^{-5}$ mol L^{-1} s^{-1} and values of t.n. > 3.10^{-3} s^{-1} can hardly be achieved. At the same time, we demonstrated earlier that the use of copper(I) complexes with phen and alkali as the cocatalysts makes it possible to oxidize primary alcohols to aldehydes with rates that are almost three orders of magnitude higher.[8,9] Such high differences in the rates of the processes in the presence and absence of alkali are caused mainly by different deprotonation degrees of alcohols.

Catalytic oxidation of primary alcohols in the presence of copper phenanthroline complexes and alkali[9] can be performed using secondary alcohols as inert solvents. For example, benzyl alcohol is oxidized to benzaldehyde in isopropyl alcohol solution with the selectivity close to 100 %.

The mechanism of oxidative dehydrogenation of primary alcohols suggested previously[9] did not allow us to explain such drastic differences in oxidation rates of primary and secondary alcohols. In this connection, we attempted to find conditions that make it possible to oxidize secondary alcohols in the presence of complexes between copper and phen.

Alkalinity of a medium is one of the main parameters, which determines the rate and selectivity of alcohol oxidation in the presence of copper phenanthrolinates. The effect of alkali on the rate and selectivity of oxidation of secondary alcohols was studied using both Cu^I and Cu^{II} phenanthroline complexes as the initial form of the catalyst.

When $[alkali]_0/[catalyst]_0 \approx 10$ (that corresponds to maximum oxidation rates of primary alcohols), after adding alkali to the solution the catalyst (Cu^I and Cu^{II} phenanthrolinates) is immediately hydrolyzed in 2-propanol solutions, forming a brown precipitate; no dioxygen absorption is observed.

At the same time, it was found that dioxygen is absorbed with very high rate even at 20 °C (Fig. 1, curve *1*), when the equimolar amount of KOH (or NaOH) is added to a solution of $[Cu(phen)_2]^+$ in 2-propanol.

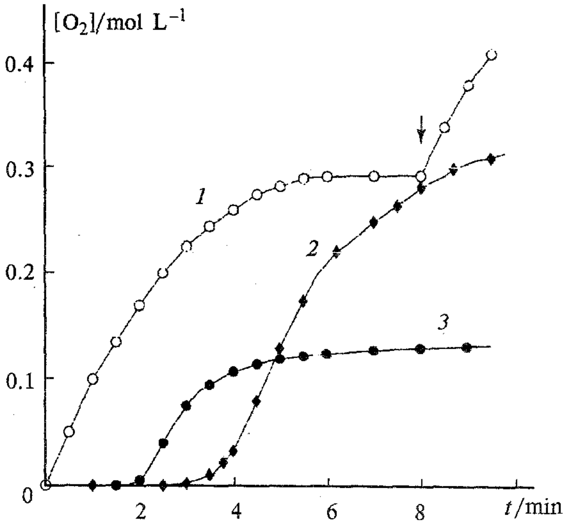


Fig. 1. Kinetic curves of dioxygen absorption during 2-propanol oxidation at 20 °C: *1*, $[Cu(phen)_2]^+ = 5 \cdot 10^{-3}$ mol L^{-1}, KOH = $5 \cdot 10^{-3}$ mol L^{-1} (instant when a new portion of alkali is added is indicated by the arrow); *2*, $[Cu(phen)_2]^{2+} = 5 \cdot 10^{-3}$ mol L^{-1}, KOH (granules) = 0.015 mol L^{-1}; *3*, $[Cu(phen)_2]^{2+} = 5 \cdot 10^{-3}$ mol L^{-1}, KOH (granules) = 0.030 mol L^{-1}.

It follows from the absorption spectra of the oxidized solutions in the visible region that when an alkali content in the system is low, the main portion of the catalyst exists as Cu^I bisphenanthroline complexes.

Acetone is the main product of the oxidation of 2-propanol under these conditions. The ratio between molar amounts of acetone formed and dioxygen absorbed is close to 2 according to the stoichiometric equation:

$$MeCH(OH)Me + 1/2\ O_2 = MeCOMe + H_2O, \qquad (1)$$

i.e., the selectivity of acetone formation with respect to dioxygen absorbed is close to 100 %.

Oxidation of 2-propanol ceases after complete neutralization of the alkali, which is related to either a slow (compared to the oxidation of alcohol) oxidation of acetone to acetic acid or to possible side reactions of direct oxidation of alcoholate ions to acids. Addition of an equimolar amount (with respect to the catalyst) of a new portion of the alkali (see Fig. 1, curve *1*) completely restores the rate of oxygen absorption. Fractional additions of the alkali make it possible to maintain a very high rate of oxidation of 2-propanol to acetone up to a content of acetone in the solution of >1.5 mol L^{-1}. Then the reaction rate decreases substantially due to accumulation of a considerable amount of water, which results in hydrolysis of the catalyst and in a decrease in the stationary concentration of catalytically active complexes $[Cu(phen)_2]^+$.

Under the conditions described, the alkali acts as the cocatalyst of oxidation, because its consumption is not greater than 1 mol per 100 mol of acetone formed.

Maximum oxidation rates for 2-butanol and cyclohexanol in the presence of Cu^I phenanthrolinates and equimolar amount of alkali are close to that for 2-propanol. However, consumption of alkali during oxidative dehydrogenation of these alcohols is 1 mol per 5 to 10 mol of ketones formed (methylethylketone and cyclohexanone, respectively). This is related to considerably higher oxidation rates of ketones to acids compared to that of acetone under the reaction conditions.[13,14]

The rate of dioxygen absorption and ketone accumulation linearly increases with the stationary concentration of $[Cu(phen)_2]^+$. The stationary concentration of copper(I) phenanthroline complexes increases under the conditions of oxidation of secondary alcohols with the concentration of free phen. An increase in the concentration of alkali results in an opposite effect: Cu^I phenanthroline complexes in strongly alkaline media are rapidly hydrolyzed to form the precipitate, which is not involved in the catalytic process. Therefore, oxidation of secondary alcohols is completely inhibited even at a five- to tenfold excess of alkali with respect to a catalyst.

Primary alcohols are oxidized at the highest rates in aprotic solvents (acetonitrile, dimethylformamide), when the nucleophilicity of alkoxide ions coordinated with Cu^I increases substantially, which results in an increase in the reactivity of alkoxide ions with respect to dioxygen.[8,9] Unlike oxidation of primary alcohols, the dilution of 2-propanol with acetonitrile exerts almost no influence on the reaction rate, which is related to compensation of an increase in the rate due to an increase in the nucleophilicity of alkoxide ions by a decrease in the stationary concentration of $[Cu(phen)_2]^+$ as a result of hydrolysis. With a content of 2-propanol in a mixture with acetonitrile of < 10 %, inactive copper compounds precipitate immediately after adding an equimolar amount of alkali to the solution.

The activity of copper(I) phenanthroline complexes in oxidative dehydrogenation of secondary alcohols is considerably higher than that of the majority of known catalysts and is close to the activity of such enzymes as oxidases. Under optimum conditions at 20—35 °C, the value of t.n. is 1—2 s^{-1}. For comparison, in the presence of one of the most active catalysts for oxidative dehydrogenation of alcohols in alkaline media, Ru^{III} complexes, 2-propanol is oxidized at 25 °C with the rate of ~15 t.n./days.[1] Thus, the activity of the $\{Cu^I...A^-...O_2\}$ system (where A^- is the anionic form of a substrate) is thousands of times higher than that for other known chemical systems.

Phenanthroline complexes of Cu^{II} also can be used as an initial form of the catalyst in the oxidation of 2-propanol in the presence of alkali, but in this case, the kinetic behavior of the system will be more complicated. For example, the addition of the equimolar amount of KOH or NaOH to the solution containing tris-phenanthroline complexes of Cu^{II} results, as observed previously, in the formation of $[Cu(phen)_2(OH^-)]^+$ complexes (see Ref. 10), and the solution remains neutral, *i.e.*, Cu^{II} phenanthrolinates act as one-base Lewis acids, which neutralize the alkali added, and no dioxygen absorption occurs.

With twofold excess of alkali with respect to Cu^{II} phenanthroline complexes the oxidation occurs with a small autoacceleration caused by the $Cu^{II} \rightarrow Cu^I$ transition. The induction period is the most pronounced when granulated alkali is used as the base (see Fig 1, curve *2*). At the initial moment, due to slow dissolution of the alkali and its neutralization by an excess of Cu^{II} complexes, the medium remains neutral, the catalyst exists in the two-valence state, and no dioxygen absorption is observed. When an amount of KOH dissolved is greater than that of the initial catalyst, bis-phenanthroline complexes of Cu^I are accumulated in the system (during several seconds the color of the solution changes from blue, which is typical of Cu^{II} complexes, to bright red with absorption maximum at 430 nm, which is related to the formation of $[Cu(phen)_2]^+$). The absorption of dioxygen begins after accumulation of rather high concentrations of Cu^I bis-phenanthrolinates and the alkali, which is not bound to copper complexes, and is responsible for deprotonation of secondary alcohols.

When a large excess of granulated alkali with respect to the catalyst, Cu^{II} phenanthroline complex, is used, the absorption of dioxygen also begins almost simultaneously with the transition of the catalyst to the one-valence state. Such a transition occurs somewhat faster than that in the case when a small amount of alkali is used due to an increase in the rate of KOH dissolution (see Fig 1, curve *3*). However, then a drastic retardation of the process occurs, caused by alkaline hydrolysis of Cu^I phenanthrolinates at high concentrations of alkali in the solution.

Oxidation of 2-propanol in the presence of primary and secondary alcohols. As mentioned above, primary alcohols are oxidized in 2-propanol in the presence of Cu^I phenanthroline complexes and alkali with a selectivity close to 100 % (see Refs. 8 and 9).

The study of the influence of additives of primary and secondary aliphatic alcohols on the rate of 2-propanol oxidation showed that the initial rate of 2-propanol oxidation in the presence of 2-butanol and cyclohexanol was almost unchanged (Fig 2, curves *1—3*). However, the process ceased due to neutralization of the medium considerably earlier than pure 2-propanol is oxidized. This is caused by the fact that oxidation rates of cyclohexanol and 2-butanol under conditions studied are comparable with the rate of 2-propanol oxidation, and the products of their oxidative dehydrogenation (methylethylketone and cyclohexanone) are oxidized, as shown previously,[13,14] to acids in the presence of copper phenanthrolinates and bases with higher rates than those in the case of acetone. It is likely that the differences in reactivity of acetone and ketones with CH_2 groups at

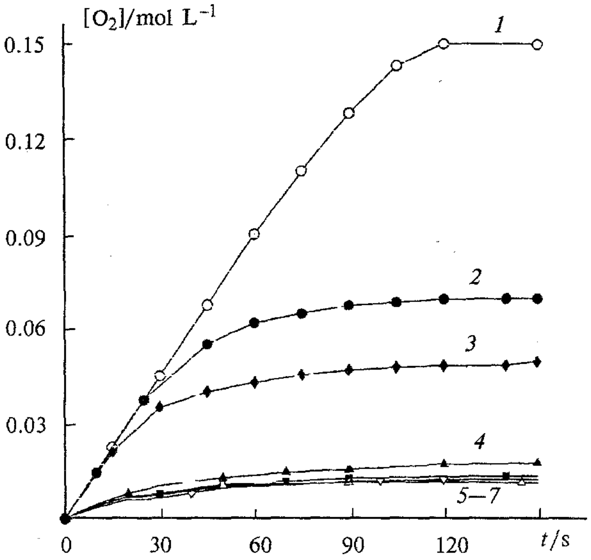


Fig. 2. Kinetic curves of O_2 absorption during 2-propanol oxidation without additives (*1*) and with addition of 5 vol. % of 2-butanol (*2*), cyclohexanol (*3*), ethanol (*4*), methanol (*5*), 1-propanol (*6*), and 1-butanol (*7*). $[Cu(phen)_2]^+ = 3 \cdot 10^{-3}$ mol L^{-1}, KOH $= 3 \cdot 10^{-3}$ mol L^{-1}, 30 °C.

α-positions to a carbonyl group in catalytic oxidation in alkaline media are related to substantial differences in stability of the corresponding carbanions formed in alkali solutions.[15]

At the same time, the additives of even small amounts of primary aliphatic alcohols (up to 5 vol. %) result in a drastic decrease both in the initial rate of dioxygen absorption, W_{O_2}, and the total amount of dioxygen consumed (see Fig 2, curves *4—7*). The cessation of 2-propanol oxidation in the presence of primary alcohols is related to fast neutralization of the medium due to predominant oxidation of primary alcohols accompanied by the formation of aldehydes, which undergo aldol condensation in alkaline media followed by fast oxidation of aldols to acids.

Table 1 presents data on a content of acetone in the solution after the complete neutralization of the added alkali and a content of acetone formed, Δ[MeCOMe], per mol of alkali consumed in 2-propanol oxidation in mass and in the presence of additions of 5 vol. % of primary and secondary aliphatic alcohols. It is seen that while the initial rate of dioxygen absorption during 2-propanol oxidation decreases only 3—4 times in the presence of primary alcohols (see Fig. 2), the yield of acetone with respect to alkali consumed decreases more than 15 times.

It has been shown previously[8] that the formation of adducts between RCH_2O^- alcoholate ions and Cu^I bis-phenanthrolinate plays the most important role in the mechanism of oxidative dehydrogenation of primary alcohols. It is likely that secondary alcohols are oxidized *via* the formation of similar adducts. It can be imagined that a high efficiency of inhibition of 2-propanol oxidation by small additives of primary alcohols is related to an efficient solvation of Cu^I phenanthroline complexes by primary alcohols and to considerably higher stability constants of adducts formed between $[Cu(phen)_2]^+$ and alcoholate ions formed by primary alcohols compared to secondary alcohols. Thus, inhibition of 2-propanol oxidation is caused by the predominant oxidation of alcoholate ions of primary alcohols to aldehydes, which, although occurring at rates lower than the rate of 2-propanol oxidation, results in fast neutralization of the medium.

Table 1. Effects of additives (5 vol. %) of primary and secondary aliphatic alcohols on 2-propanol oxidation

Alcohol added (5 vol.%)	Δ[MeCOMe] /mol L^{-1}	$\frac{\Delta[MeCOMe]}{\Delta[KOH]}$
Without additives	0.29	96.6
2-Butanol	0.13	43.3
Cyclohexanol	0.09	30.0
Methanol	0.02	6.7
Ethanol	0.03	10.0
1-Propanol	0.02	6.7
1-Butanol	0.02	6.7

Note. $[Cu(phen)_2]^+_0 = 3 \cdot 10^{-3}$ mol L^{-1}, KOH $= 3 \cdot 10^{-3}$ mol L^{-1}, 30 °C.

Kinetic isotope effect in 2-propanol oxidation. To study the kinetic isotope effect, the kinetics of oxidation of 2-propanol and 2-propanol-d_8 in acetonitrile were compared. Experiments were carried out with a concentration of copper complexes of $3 \cdot 10^{-3}$ mol L^{-1} and a considerable excess of free *o*-phenanthroline ($[CuCl]_0/[phen]_0 = 15$) for stabilization of catalytically active Cu^I bis-phenanthrolinate.

According to the data of spectrophotometry, in the oxidation of both 2-propanol and 2-propanol-d_8, the concentration of Cu^I bis-phenanthrolinates before adding KOH was close to $3 \cdot 10^{-3}$ mol L^{-1}, *i.e.*, almost all catalyst was in the form of Cu^I. In the course of the reaction, the concentration of catalytically active Cu^I complexes changed by not more than 10 % in both cases.

The kinetic isotope effect k_H/k_D determined from the ratio of the rates of dioxygen absorption during oxidation of 2-propanol-h_8 and -d_8 was found to be equal to 2.1 and retained close to 2 during the reaction, including the period after adding a fresh portion of alkali.

Mechanism of catalytic 2-propanol oxidation. Analysis of the experimental data obtained shows that Cu^I bis-phenanthrolinates are catalytically active forms of copper phenanthroline complexes.

The catalytic turnover number per Cu^I bis-phenanthrolinate complex is 1—2 s^{-1} under optimum conditions at 20—35 °C, which is close to that of enzyme-catalyzed oxidation of organic substances by molecular oxygen.

The fact that the values of kinetic isotope effects and regularities of oxidation of secondary alcohols coincide with those obtained previously for oxidation of primary alcohols[15] catalyzed by Cu^I complexes allows one to assume that oxidation of substrates of the both classes occurs *via* similar mechanisms.

Formation of the adduct between Cu^I bis-phenanthrolinates and alkoxide ion, $\{Cu^I(phen)_2...^-OCHR^1R^2\}$, is the first stage of oxidative dehydrogenation of alcoholate ions. When the alkalinity of a medium is high, such an adduct undergoes fast consequent transformations probably involving the second alcoholate ion, as observed in the case of ruthenium phenanthrolinates,[16] to form a catalytically inactive brown precipitate during several seconds. Formation of the precipitate is accelerated as the donating ability of alcoholate ions increases, for example, when secondary alcohols are diluted with aprotic solvents, such as acetonitrile, dioxane, DMF, *etc.* In aprotic solvents the catalyst is deactivated at a lower alkalinity of a medium.

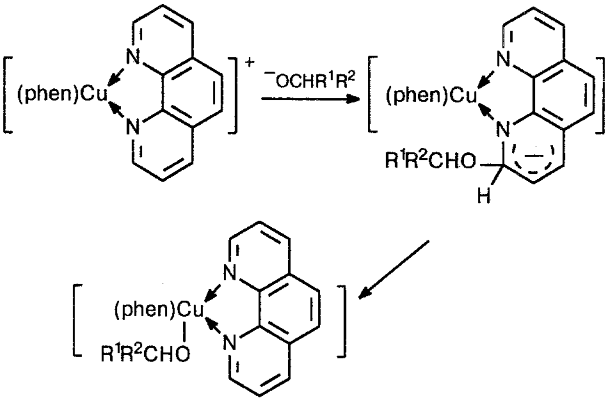
It could be assumed that coordinatively unsaturated complexes $[Cu(phen)]^+$ are active particles that are responsible for oxidative dehydrogenation of 2-propanol. However, according to data of UV analysis, all the copper exists in one-valence state in the presence of a large excess of *o*-phen ($[o\text{-phen}]/[CuCl_2] = 15$). The following condition is fulfilled:

$$[Cu(phen)] + [Cu(phen)_2] = [Cu]_0$$

Since the stability constant of Cu^I bis-phenanthrolinates (see Ref. 12) is not lower than 10^7—10^8 mol^{-1} L, the stationary concentration of Cu(*o*-phen) complexes should not be higher than 10^{-8}—10^{-9} mol L^{-1}. When the oxidation rate W is $\sim 10^{-3}$ mol L^{-1} s^{-1}, the number of catalytic acts in the process of oxidative dehydration of secondary alcohols per such a particle (t.n.) should be 10^5—10^6 per second, which seems improbable for reactions involving molecular oxygen as an oxidant.

It is evident that coordinative saturated $[Cu^I(phen)_2]^+$ complexes participate in the formation of an adduct with an alkoxide ion according to the scheme suggested previously for reactions between ruthenium[16] and iron[17] phenanthrolinates and various anions (Scheme 1).

Scheme 1



The alkoxide ion attacks the molecule of coordinated *o*-phenanthroline to position 2 (9), and then the anion reacts with the Cu^+ cation to form a pentacoordinated adduct. The efficiency of the attack to C(2) depends on the nature of a dianion and decreases in the series $OEt^- > OMe^- \gg OH^- \gg CN^-$ for ruthenium phenanthrolinates (see Ref. 16).

The obtained values of the kinetic isotope effect for catalytic oxidation of $i\text{-}C_3H_8O^-$ ($k_H/k_D \sim 2$) are a forcible argument in favor of the reaction proceeding *via* a stage of transfer of a hydride ion from the coordinated alkoxide ion to O_2 followed by one-stage formation of acetone as the main reaction product.

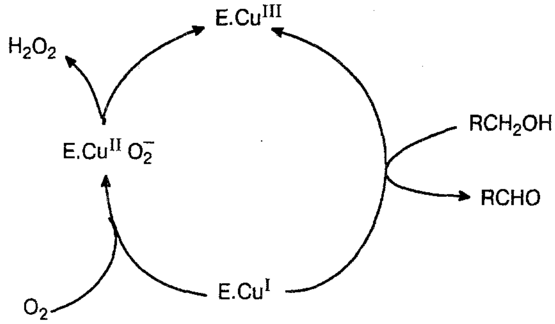
The transfer of hydride ions from alcoholate anions to several hydrogen acceptors is rather popular both in chemical and biological systems. The transfer of a hydride ion to molecular oxygen is suggested for noncatalyzed oxidation of alcohols in strongly alkaline aprotic media.[18] A hydride ion is readily accepted by molecular oxygen in the processes of catalytic oxidation in alkaline media, which is confirmed by low values of $\Delta G^{\#}$ found for oxidation of cyclohexanol in the presence of Ru^{III} (see Ref. 19).

The transfer of a hydride ion from alcohols to aliphatic and aromatic ketones are efficiently catalyzed by ruthenium complexes $RuCl_2(PPH_3)_3$.[20,21] The presence of alkali results in an increase by several orders of magnitude in the rate of 2-propanol dehydrogenation due to generating more nucleophilic (compared to 2-propanol) alkoxide ions, which can effectively attack the ruthenium complex that is responsible for dehydrogenation.

A distinctive feature of catalytic dehydrogenation of alcohols in alkaline media in the presence of Cu^I phenanthrolinates compared to those described in the literature is reaction rates that are much higher in our system (t.n. ~1—2 s^{-1}). For example, when molecular oxygen is used as the oxidant, t.n. is $(2—3)\cdot 10^{-4}$ s^{-1} (see Refs. 1 and 6) in oxidation of alcohols to carbonyl compounds in the presence of ruthenium complexes or copper dipyridyl complexes. When Ru^{III} complexes as the oxidants and ketones as the acceptors of hydride ions are used, t.n. = 0.25 can be achieved (see Ref. 20). Thus, molecular oxygen is the most active electron acceptor for catalysis by $[Cu(phen)_2]^+$ complexes in an alkaline medium, which allows one to speak about a basically new catalytic system of catalytic dehydrogenation of alcohols using O_2 as the oxidant, and the activity and selectivity of this system are close to those of enzymatic systems.

The kinetic behavior of the system studied is similar to that of galactosooxidase, whose active center contains, as known, a Cu^+ ion on which alcohol groups of a substrate are dehydrogenated.[22] The analysis of the mechanism of action of galactosooxidase and chemical models involving the $\{Cu^I—alcohol—O_2\}$ system assumes[6,23] that the first stage of the process is the reaction between Cu^I complexes and O_2 accompanied by the electron transfer to form O_2^- and Cu^{II} ions, and it is postulated that the active species responsible for dehydrogenation of alcohol groups is the Cu^{III} complex (see Scheme 2), which oxidizes the alkoxyl group to the carbonyl group:

Scheme 2



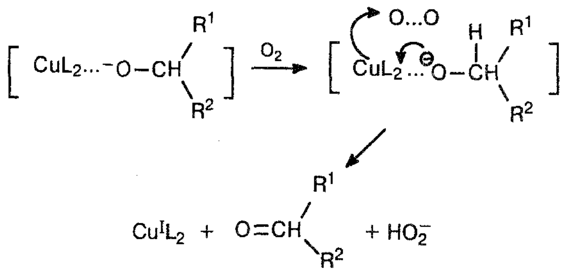
It is assumed[22] that reactions involving Cu^{III} complexes are rather common in chemical and biological systems, and difficulties in identification of this particle are related to a high reactivity and, hence, a low steady-state concentration of Cu^{III} complexes, in particular, due to a high rate of oxidation of ligands by Cu^{III} ions.

However, a high stability of *o*-phenanthroline, which is not consumed under oxidation conditions even after several thousands of turnovers, casts doubt on the possibility of participation of both Cu^{III} complexes and $O_2^{\cdot -}$ radical ions in the process, because the latter readily react with coordinated molecules of *o*-phenanthroline resulting in their deep destruction.[24]

Kinetic regularities of oxidation of 2-propanol and other secondary alcohols in the presence of $[Cu(phen)_2]^+$ and alkali can be easily explained in terms of a synchronous reaction mechanism, whose limiting stage is the transfer of the hydride ion from the coordinated alkoxide anion to the O_2 molecule (Scheme 3) to form the peroxide ion and ketone. Addition of hydrogen peroxide shows that H_2O_2 disproportionates to oxygen and water at a high rate and exerts no effect on either the rate or the degree of transformation of alcohol.

A direct one-stage transfer of a singlet hydride ion to oxygen followed by formation of the peroxide anion and ketone is impossible due to the violation of the spin conservation rule in such a process. However, participation of a catalyst, Cu^I complexes, in the process of transfer of electrons and proton from the coordinated alkoxide anion to the O_2 molecule can remove the spin forbiddance for reactions of this type, which is formally presented in Scheme 3.

Scheme 3



It is known that from the thermodynamic viewpoint oxygen is one of the strongest two- or four-electron oxidants. One-electron reduction of oxygen is energetically unfavorable,[25] which explains the relatively low rates and the selectivity of such one-electron processes involving $^3O_2$, and the formation of free radicals as active intermediates, which are typical of the overwhelming majority of processes of liquid-phase oxidation. We believe that the catalytic system suggested is one of the first examples of simple chemical systems, for which synchronous two-electron reduction of oxygen is highly probable. This can be confirmed by extremely high rate constants for reactions involving O_2 at room temperatures, which were not described for any other catalytic systems, and an anomalously high stability of the catalyst, excluding any possibility of participation of free radicals in the overall mechanism of the process.

The experimental data obtained allow one to assume that two-electron reduction of dioxygen is a factor that determines the high reactivity of active centers of enzymes in several enzymatic processes involving O_2 as the oxidant, in particular, in reactions catalyzed by oxidases.

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References

1. R. R. Gagne and D. N. Marks, *Inorg. Chem.*, 1984, **23**, 65.
2. J.-E. Bäckvall, R. L. Chowdhury, and U. Karlsson, *J. Chem. Soc., Chem. Commun.*, 1991, 475.
3. G. -Z. Wang, V. Adreasson, and J.-E. Bäckvall, *J. Chem. Soc., Chem. Commun.*, 1994, 1037.
4. M. Munakata, S. Nishibayashi, and H. Sakamoto, *J. Chem. Soc., Chem. Commun.*, 1980, 219.
5. P. Capdevielle, P. Audeberi, and M. Maumy, *Tetrahedron Lett.*, 1984, **25**, 39, 4400.
6. P. Capdavielle, D. Sparfel, J. Baranne-Lafont, Nguyen Kim Cuong, and M. Maumy, *J. Chem. Research (S)*, 1993, 10; *J. Chem. Research (M)*, 1993, 170.
7. N. Kitajiama and Y. Moro-oka, *Chem. Rev.*, 1994, **94**, 737.
8. A. M. Sakharov and I. P. Skibida, *J. Molec. Cat.*, 1988, **48**, 157.
9. A. M. Sakharov and I. P. Skibida, *Kinet. Katal.*, 1988, **29**, 110 [*Kinet. Catal.*, 1988, **29** (Engl. Transl.)].
10. A. M. Sakharov and I. P. Skibida, *Dokl. Akad. Nauk SSSR*, 1980, **251**, 155 [*Dokl. Chem.*, 1980, **251** (Engl. Transl.)].
11. R. J. P. Williams, *J. Chem. Soc.*, 1955, No. 1—2, 137.
12. W. R. McWhinnie and J. D. Miller, *Adv. in Inorg. Chem. and Radiochem.*, 1969, **12**, 135.

13. A. M. Sakharov and I. P. Skibida, *Oxidation Comm.*, 1979, **1**, 113.
14. A. M. Sakharov and I. P. Skibida, *Izv. Akad. Nauk SSSR, Ser. Khim.*, 1980, 523 [*Bull. Acad. Sci. USSR, Div. Chem. Sci.*, 1980, **29**, 344 (Engl. Transl.)].
15. I. P. Skibida and A. M. Sakharov, *Ros. Khim. Zh.*, 1995, **39**, 14 [*Mendeleev. Chem. J.*, 1995, **39** (Engl. Transl.)].
16. R. D. Gillard, L. A. P. Kane-Maguire, and P. A. Williams, *J. Chem. Soc., Dalton. Trans.*, 1977, No. 10, 1039.
17. M. J. Blandamer, J. Burgess, and D. L. Roberts, *J. Chem. Soc., Dalton. Trans.*, 1978, 1086.
18. A. A. Grinfel'd, G. A. Artamkina, and I. P. Beletskaya, *Izv. Akad. Nauk SSSR, Ser. Khim.*, 1984, 1567 [*Bull. Acad. Sci. USSR, Div. Chem. Sci.*, 1984, **33**, 1438 (Engl. Transl.)].
19. M. M. Taqui Khan, *Indian J. Technology*, 1992, **30**, 127.
20. R. L. Chowdhury and J.-E. Bäckvall, *J. Chem. Soc., Chem. Commun.*, 1991, 1063.
21. G-Z. Wang and J.-E. Bäckvall, *J. Chem. Soc., Chem. Commun.*, 1992, 337.
22. G. A. Hamilton, P. K. Adolf, J. de Jersey, G. C. DuBois, G. R. Dyrkacz, and D. Libby, *J. Am. Chem. Soc.*, 1978, **100**, No. 6, 1899.
23. P. Capdevielle, P. Audebert, and M. Maumy, *Tetrahedron Lett.*, 1984, **25**, 4397.
24. O. S. Fedorova and V. M. Berdnikov, *Izv. Akad. Nauk SSSR, Ser. Khim.*, 1979, 745 [*Bull. Acad. Sci. USSR, Div. Chem. Sci.*, 1979, **28**, No. 4 (Engl. Transl.)].
25. R. D. Jones, D. A. Summerville, and F. Basolo, *Chem. Rev.*, 1979, **79**, 139.

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