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Correlation between Regiospecific Dioxygen Incorporation into 2,6-Di-*tert*-butylphenols and Their Redox Potential

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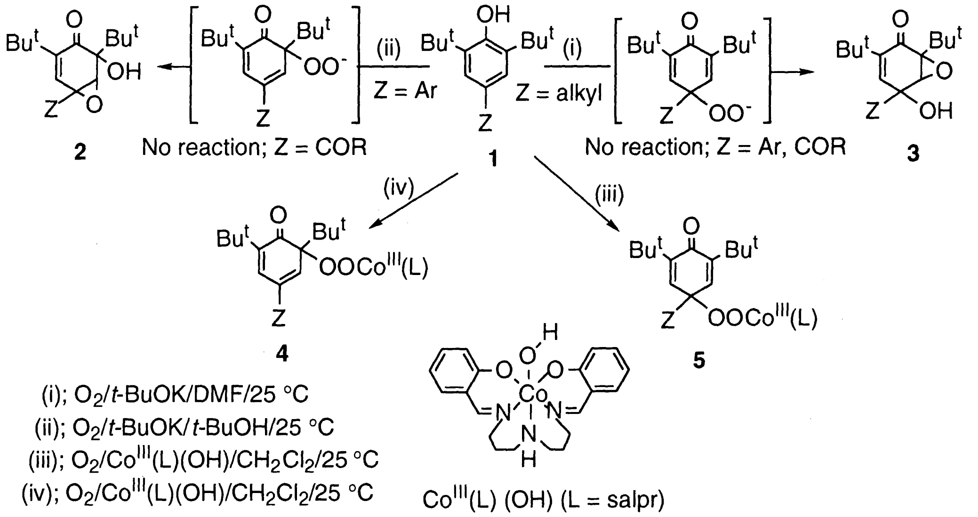
The position of O_2 incorporation into 2,6-di-*tert*-butylphenols in the presence of Co(salpr) is correlated to redox potential E^o (mV) of phenolate anion/phenoxy radical couple: $E^o > -645$, *ortho* position; $E^o < -650$, *para* position. No phenoxy radical intermediate is involved for the oxygenation of the phenolate anion with $E^o > -645$ Å mV.

In our previous studies on the *t*-BuOK and Co^{III}(salpr)(OH) promoted oxygenation of 2,6-di-*tert*-butylphenols (**1**), it has been clarified that the position of dioxygen incorporation is regulated by the nature of the substituent at 4-position as well as the reaction conditions (Scheme 1):$^{1)}$ the oxygenation of **1** (Z = alkyl) with *t*-BuOK in *N,N*-dimethylformamide (DMF), where the phenolate anion is in a free state, results in exclusive dioxygen incorporation into the *para* position finally to give epoxy-*p*-quinols (**3**) (Z = alkyl), whereas under these conditions phenols **1** (Z = Ar, COR) are not reactive. However, phenols **1** (Z = Ar) can undergo oxygenation with *t*-BuOK in *t*-BuOH, where the phenolate anion is associated with K^+, resulting in the exclusive dioxygen incorporation into the *ortho* position to give **2** (Z = Ar). Phenols bearing an electron-withdrawing group (**1**; Z = COR, CN, etc) are no longer susceptible to the *t*-BuOK promoted oxygenation system, but in the presence of Co^{III}(salpr)(OH) in CH_2Cl_2 exclusively to give **4**. The regiospecificity for the



Scheme 1.

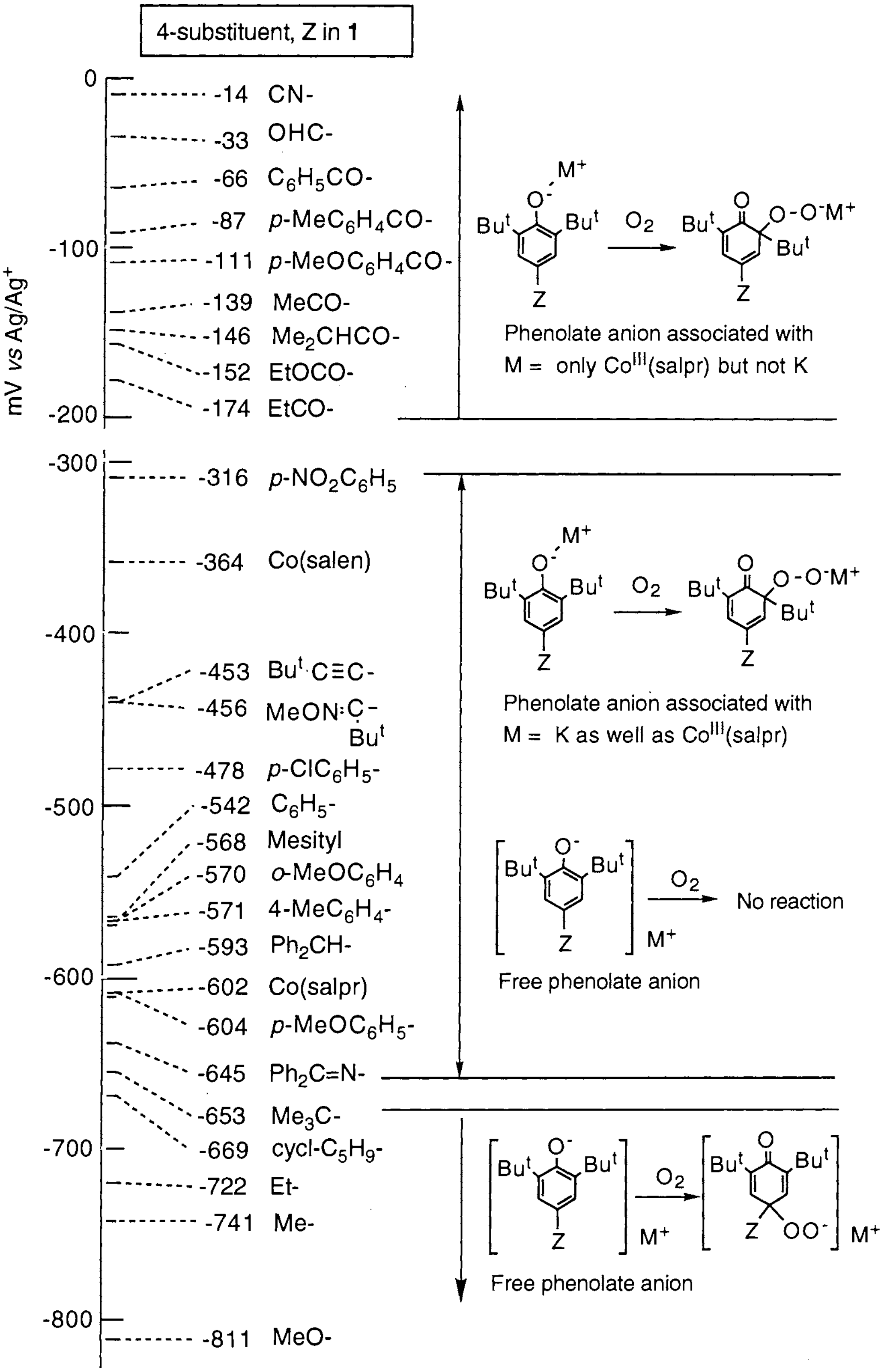


Fig. 1. Formal potential of $1^-/1\bullet$ redox couple for 1. Conditions: 0.1 M NBu_4PF_6 in DMF. E^o: mean value of oxidation and reduction peak potentials, which are obtained at scan rates v = 50-200 mV/s.

dioxygenation of phenols **1** in the O_2/*t*-BuOK/*t*-BuOH system[2, 3] is the same as that in the O_2/Co^{III}(salpr)(OH)/CH_2Cl_2 system.[4 - 6]

We now find that the regiospecificity for O_2 incorporation into **1** is well correlated to their formal potential (E^o) of **1**$^-$/**1**• redox couple: the *ortho* dioxygenation takes place for **1** with E^o > -645 mV, whereas the *para* dioxygenation for **1** with E^o < -650, and that no phenoxy radical intermediate is involved for the oxygenation of phenolate anion **1**$^-$ with E^o > -645 mV.

Formal potential E^o of 2,6-di-*tert*-butylphenolate anions (**1**$^-$). The formal potential (E^o) of **1**$^-$/**1**• redox couple have been determined by means of cyclic voltammetry (CV) of **1** in DMF containing-BuOK. The results are summarized in Fig. 1 together with the CV data of Co(salen) and Co(salpr). In all cases examined, quasi-reversible CV curves (ΔE = 60 - 130 mV) were obtained. Oxidation and reduction currents were almost the same indicating the reversible one-electron redox couple of **1**$^-$/**1**•. As seen from Fig. 1, the E^o values of **1** (Z = alkyl) are below -654 mV, those of **1** (Z = aryl) are between -650 and -300 mV, and those of **1** (Z = COR, CN) are above -200 mV. These data are in accord with the electronegativity of the groups. Interestingly, all phenolate anions **1**$^-$ whose E^o values are above -650 mV do not undergo dioxygenation in DMF. In other words, these phenolate anions are not susceptible to oxygenation in a free state, but in an associated form with counter cation K$^+$ or [Co^{III}]$^+$. Further, when the E^o value of **1**$^-$ reaches more positive than -200mV, the oxygenation is possible only when associated with [Co^{III}]$^+$.

Mechanism of dioxygen incorporation. Sheldon and Kochi[7] have discussed the possibility of involvement of phenoxy radical intermediate in the oxygenation of **1** with Co(salpr). As the E^o value of Co(salpr) is more positive than that of **1**$^-$ (Z = alkyl) (Fig. 1) and the oxygenation of **1**• (Z = alkyl) is faster than that of **1**$^-$ (Z = alkyl),[8] it is reasonable to consider that the oxygenation of Co^{III}(salpr)(**1**$^-$) (Z = alkyl) involves **1**• (Z = alkyl) as the intermediate, where O_2 is always incorporated into the para position of **1**. On the other hand, from the data shown in Fig. 1, the equilibrium constant for the electron transfer equilibrium between [Co^{III}(salpr)]$^+$ and **1**$^-$ (Z = COMe) giving rise to Co^{II}(salpr) and **1**• (Z = COMe) is calculated as about 1 X 10^{-8}: concentration of **1**• (Z = COMe) is about 1 X 10^{-4}%. Actually, very weak EPR signals for **1**• (Z = COMe) (a triplet due to the rig protons) was detected from a solution of [Co^{III}(salpr)(**1**$^-$) (Z = COMe)] in

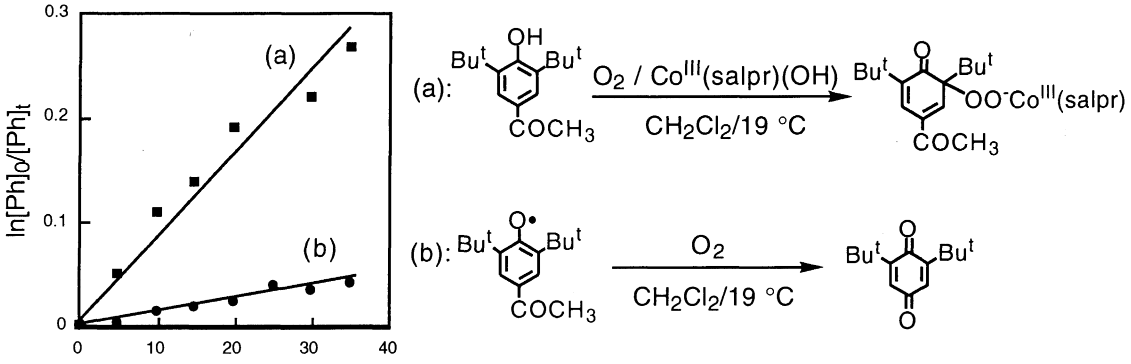
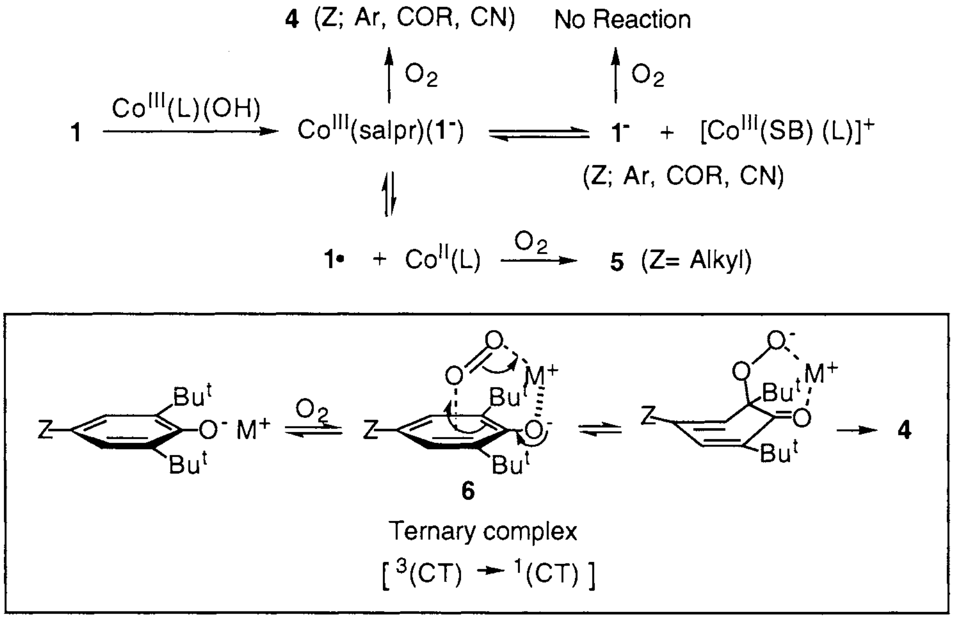


Fig. 2. Time course and product for the oxygenation of **1** (Z = CN) (0.1 M) with Co^{III}(salpr)(OH) (0.1 M) and of **1**• (0.1 M) in CH_2Cl_2 (10 ml).

CH_2Cl_2. The oxygenation of Co^{III}(salpr)(**1**$^-$) (Z = COMe), derived from the reaction of **1** (Z = COMe) with Co^{III}(salpr)(OH), in CH_2Cl_2 was faster than that of **1**• (Z = COMe) in CH_2Cl_2 (Fig. 2). Furthermore, the



Scheme 2.

oxygenation of **1**• (Z = COMe) gave 2,6-di-*tert*-butyl-p-benzoquinone as the sole product. These results clearly indicate that no radical intermediate is involved in the oxygenation of Co^{III}(salpr)(**1**$^-$) (Z = COMe) in CH_2Cl_2, contrary to the discussion by Sheldon and Kochi. Since no oxygenation of Co^{III}(salpr)(**1**$^-$) (Z = COMe) takes place in DMF, where Co^{III}(salpr)(**1**$^-$) (Z = COMe, CN) is dissociated to [Co^{III}(salpr)]$^+$ and **1**$^-$ as judged by CV, the association form of Co^{III}(salpr)(**1**$^-$) is essential for the oxygenation taking place. Similar results were obtained with Co^{III}(salpr)(**1**$^-$) (Z = Ar).

Thus, the oxygenation process of **1** can be summarized as depicted in Scheme 2, and it should be reasonable to assume a ternary complex (**6**) involving **1**$^-$, O_2, and [Co^{III}]$^+$ as the transition state, which undergoes intersystem crossing under influence of Lewis acidity of [Co^{III}]$^+$, for the nonradical process.

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