## Study of the Reaction of 3,6-Di-*tert*-butyl-o-benzoquinone with Organozinc and Organocadmium Compounds

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**Abstract**—The effect of substituents in the reactions of 3,6-di-*tert*-butyl-o-benzoquinone with organozinc and organocadmium compounds, leading to three types of products: 3-alkyl-6-*tert*-butyl-o-benzoquinones, 4-alkyl-3,6-di-*tert*-butyl-o-benzoquinones, and 2-alkoxy-(or 2-phenoxy)-3,6-di-*tert*-butylphenols. Correlation analysis gave evidence to show that the first- and second-type products are formed by nucleophilic 1,2- and 1,4- addition, while substituted phenols result from single-electron transfer.

Keywords: o-quinone, organometallic compound, correlation analysis, polarization effect

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Two mechanisms were proposed for reactions of quinones with organometallic compounds. The first is heterolytic, specifically, nucleophilic addition to unsaturated conjugated ketones to form either 1,2-adduct by the C=O bond or 1,4-adduct by the conjugated double bond [1]. The second mechanism is homolytic, and it involves single-electron oxidation of the organometallic compound with quinone, followed by ion-radical recombination to form substituted phenols and, possibly, 1,2-adducts [2].

According to [3], reactions of organic compounds of Zn, Cd, and Hg with sterically hindered o-quinones at low temperatures occur by a single-electron oxidation scheme. In the reactions performed at a higher temperature, nucleophilic addition products were found along with single-electron transfer (SET) products [4, 5]. In later research, too, no common view of the mechanism of reactions of organometallic compounds with guinones has been developed. Mc Kinley et al. [6] argued in favor of the SET mechanism to form both 1,2-adducts and hydroquinone (a reduction product) for reactions of 1,4-benzoquinone with organolithium and organomagnesium compounds. Aponick et al. [7] found no other products but 1,2adducts (quinols) in reactions of 1,4-benzoquinone with various organocadmium compounds, whereas Shahidzadeh and Ghandi [8] found hydroquinones along with quinols in the same reactions.

Apparently, in reactions of organic compounds of group IIB metals with quinones both mechanisms are operative. To gain a deeper insight into the mechanism of these reactions, we performed correlation analysis of the effect of different electronic factors on the yield of the reaction products. The development of excess charges on the reaction center in the transition state, associated with the formation of an activation complex, induces dipoles in substituents and gives rise to the polarization effect [9]. Therefore, in the case of a nucleophilic addition, one can expect an essential polarization effect of substituents. As to a radical addition, the product yield should be controlled by electron-transfer processes [10].

In the present work, in addition to the known classical inductive, resonance, and steric effects of substituents, in the correlation analysis of the effect of different electronic factors on the yields of reactions of organozinc and organocadmium compounds with quinones we took account of the polarization effect that enhances with increasing excess charge on the reaction center.

To find out the effect of substituents in the organometallic compounds on the composition of their reaction products with 3,6-di-*tert*-butyl-o-benzoquinone (1), we took the following compounds: Me<sub>2</sub>Zn(Cd), Et<sub>2</sub>Zn(Cd),  $Pr_2Zn(Cd)$ ,  $i-Pr_2Zn(Cd)$ ,  $t-Bu_2Zn$ , and





 $Ph_2Zn(Cd)$ . All reactions were performed in THF at 1 : 1 reagent ratios. In the course of all reactions of quinone **1** with alkylated organometallic compounds, ESR signals of *o*-semiquinone derivatives of Zn and Cd were detected [5] (Scheme 1).

Abakumov et al. [4] showed on the example of the reactions of quinone 1 with methyl derivatives of Zn and Cd that the primary 1.2- and 1.4-adducts are organometallic compounds 2 and 3; after mild hydrolysis with acetic acid the latter convert into 3,6di-tert-butyl-2-hydroxy-2-methylcyclohexa-3,5-dien-1-one and 3,6-di-tert-butyl-2-hydroxy-4-methylcyclohexa-2,5-dien-1-one. The rearrangement of the organometallic 1,2-adduct at a temperature higher than -10°C gives rise a 3-tert-butyl-6-methylpyrocatechol derivative which is oxidized to form 3-tert-butyl-6methyl-o-benzoquinone 4. Thus, the yields of the 2hydroxycyclohexadiene derivative and guinone 4 in the reaction with Me<sub>2</sub>Zn at 0°C are 75.0 and 1.1% and at 30°C the yields are 40.8 and 31.1%, respectively. In the case of ethyl-, propyl-, and isopropyl-substituted Zn and Cd compounds, from the reaction mixtures after hydrolysis in the presence of HCl followed by oxidation with a weakly alkaline solution of potassium ferricvanide we isolated and characterized by elemental analysis and IR and <sup>1</sup>H NMR spectroscopy three types of products: 3-alkyl-6-tert-butyl-o-benzoquinones 4, 4-alkyl-3,6-di-tert-butyl-o-benzoquinones 5, and 2-alkoxy-3,6-di-tert-butylphenols 6. Unlike reactions with methylated organometallic compounds, where the organometallic 1,2-adduct underwent no transformations at low temperatures, organometallic

compounds 2 with other alkyl substituents already at  $-60^{\circ}$ C rearrange into 3-alkyl-substituted quinones 4.

In the reaction with *t*-Bu<sub>2</sub>Zn analysis was performed immediately after hydrolysis of the reaction mixture. The main reaction products were 3,4,6-tri-*tert*butyl-2-hydroxycyclohexa-2,5-dien-1-one (1,4-adduct) and 2-*tert*-butoxy-3,6-di-*tert*-butylphenol. Because of the thermal instability of *t*-Bu<sub>2</sub>Cd, we could not react it with quinone **1**. The only product of the reactions of quinone **1** with diphenylzinc and diphenylcadmium in the temperature range in study isolated after corresponding work-up was phenoxyphenol **6**. The reaction products were analyzed by liquid chromatography (see Table 1).

As seen from the data in Table 1, the ratio of the 1,4- and 1,2-adducts increases in going from methylto *tert*-butyl-substituted organometallic compounds and is almost independent on the nature of the metal at low temperatures. Presumably, this phenomenon is associated with the steric and electronic effects of alkyl substituents. Table 2 lists the inductive  $\sigma_I$ , resonance  $\sigma_{\rm R}$ ,  $\sigma_{\rm R}^+$ , and  $\sigma_{\rm R}^-$ , polarization  $\sigma_{\alpha}$  [9], and steric  $E_{\rm s}$  [11] constants of the studied substituents. The  $\sigma_R^+$  and  $\sigma_R^$ constants are quantitative characteristics of the resonance effect of substituents on the reaction centers bearing a positive or a negative charge, respectively. The studied reactions proceed with high rates and form products almost immediately after the reagents have been mixed. Therefore, to first approximation, we assumed that the product yields (Table 1) can be used as a measure of the rate of formation of these products.

To assess the electronic and steric effects of substituents on the reaction rates, we employed correlation

	T, ℃		Nucleophili	Single-electron transfer, %			
R		1,2-Nu				1,4-Nu	
		R <sub>2</sub> Zn	R <sub>2</sub> Cd	R <sub>2</sub> Zn	R <sub>2</sub> Cd	R <sub>2</sub> Zn	R <sub>2</sub> Cd
Me	0	76.1		24.4			
	30	71.9		22.6		1 >	
Et	0	4.4	9.3	6.5	11.5	92.6	80.6
	30	6.3	16.4	9.3	14.0	81.2	69.9
	60	7.9	23.3	11.7	19.2	71.6	55.3
Pr	0	4.8	10.3	7.8	12.9	83.6	77.2
	30	5.7	17.3	9.1	14.8	80.0	68.5
	60		23.8		20.9		49.2
<i>i</i> -Pr	0	9.8	12.7	25.8	31.2	62.9	55.3
	30	12.4	18.6	28.4	38.9	57.8	43.2
	60	13.1	20.6	37.0	51.2	49.7	27.6
<i>t</i> -Bu <sup>a</sup>	0	2.4		45.2		52.4	
	30			62.4		36.2	
	60			70.7		26.5	

Table 1. Product ratios of the reactions of 3,6-di-*tert*-butyl-o-benzoquinone with alkyl derivatives of zinc and cadmium after hydrolysis and oxidation

<sup>a</sup> Analysis was performed after hydrolysis of the reaction mixture.

analysis. Apparently, the 1,4-/1,2-adduct ratios are determined by the ratio of the rate constants of their formation. For the alkyl substituents in the organozinc and organocadmium compounds we deduced the linear equation (1) relating the logarithm of the 1,4-/1,2-adduct ratio log (1,4-Nu/1,2-Nu) with the polarization constants  $\sigma_{\alpha}$ .

$$log (1,4-Nu/1,2-Nu) = -1.95 - 2.02\Sigma\sigma_{\alpha},$$
(1)  
(0.26) (0.23)  
$$S_{\rm V} = 0.14, r = 0.962, n = 8.$$

Here and hereinafter, in parentheses under the free term and the coefficients we give the standard errors of their determination. Since the studied organometallic compounds contain by two substituents, the equations all include sums of two parameters.

The correlation with the steric constants of the alkyl substituents on Zn and Cd only is fairly poor.

$$log (1,4-Nu/1,2-Nu) = -0.13 - 0.50\Sigma E_s, (2) (0.09) (0.08)$$

$$S_{\rm Y} = 0.19, r = 0.935, n = 8.$$

The linear correlation between log (1,4-Nu/1,2-Nu) and the resonance constants  $\sigma_R^+$  of the substituents attached to a positively charged reaction center is no

more than a trend, whereas with the resonance constants  $\sigma_R^-$  no correlation was obtained at all.

There are strong reasons to suggest that in our case a multiparameter correlation analysis [12] will provide more information. The corresponding correlation equation takes form (3).

$$P = P_0 + (a_1 \pm S_1) \cdot x_1 + (a_2 \pm S_2) \cdot x_2 + \dots + (a_m \pm S_m) \cdot x_m.$$
(3)

Here *P* is the property being correlated [for example, log (1,4-Nu/1,2-Nu)];  $x_1$ ,  $x_2$ , ...,  $x_m$ , variables (in our case,  $\sigma_I$ ,  $\sigma_R$ ,  $\sigma_R^+$ ,  $\sigma_R^-$ ,  $\sigma_\alpha$ , and  $E_S$ );  $a_1$ ,  $a_2$ , ...,  $a_m$ , coefficients; and  $S_1$ ,  $S_2$ , ...,  $S_m$ , standard deviations for the corresponding coefficients. Equation (3) includes

Table 2. Electronic and steric constants of substituents

R	$-\sigma_{I}$	$-\sigma_R$	$-\sigma_R^+$	$-\sigma_{R}^{-}$	$-\sigma_{\alpha}$	$-E_S$
Me	0.05	0.12	0.26	0.13	0.35	0
Et	0.05	0.10	0.25	0.14	0.49	0.08
Pr	0.05	0.10	0.25	0.14	0.54	0.31
<i>i</i> -Pr	0.03	0.12	0.25	0.12	0.62	0.48
<i>t</i> -Bu	0.07	0.13	0.19	0.14	0.75	1.43
Ph	-0.12	0.13	0.30	0.10	0.81	2.31



Linear correlation between the polarization constants of alkyl substituents and the 1,4-/1,2-adduct ratios in the reactions of organozinc compounds with 3,6-di-*tert*-butyl-*o*-benzoquinone.

the sample volume *n* (in our case, this is the number of different substituents, for example, n = 5, if there are five substituents Me, Et, Pr, i-Pr, and t-Bu on the Zn atom), approximation standard error  $S_{\rm Y}$ , and the socalled corrected correlation coefficient r. In such an equation, compared to any other equations, the correlation coefficient r is maximal, the error  $S_{\rm Y}$  is minimal, and the coefficients  $a_1, a_2, \dots, a_m$  are statistically significant. The latter fact implies that the coefficients  $a_1, a_2, \dots a_m$  all are higher than their corresponding standard deviations  $S_1, S_2, \dots S_m$  ( $a_m/S_m >$ 1). It should be noted that the sample volume n = 5 is enough to calculate a three-parameter equation (for example,  $x_1$ ,  $x_2$ ,  $x_3 = \sigma_I$ ,  $\sigma_R$ , and  $\sigma_\alpha$ ), and at n > 5, a four-parameter equation can be calculated, in which  $x_i$ can be, for example,  $\sigma_{I}$ ,  $\sigma_{R}^{+}$ ,  $\sigma_{\alpha}$ , and  $E_{S}$ . In our case, the most general four-parameter equation with the variables  $\sigma_{I}$ ,  $\sigma_{R}$  ( $\sigma_{R}^{+}$ ,  $\sigma_{R}^{-}$ ),  $\sigma_{\alpha}$ , and  $E_{S}$  should take the following form:

$$P = P_0 + a_1 \Sigma \sigma_1 + a_2 \Sigma \sigma_R(\sigma_R^+, \sigma_R^-) + a_3 \Sigma \sigma_\alpha + a_4 \Sigma E_s.$$
(4)  
(S\_0) (S\_1) (S\_2) (S\_3) (S\_4)

The three-parameter Eq. (5) including the resonance  $\sigma_{\rm R}^+$ , polarization  $\sigma_a$ , and steric  $E_S$  effects on the yields of the reaction products works in the best way for R<sub>2</sub>Zn (R = Me, Et, Pr, *i*-Pr, *t*-Bu) and R<sub>2</sub>Cd (R = Et, Pr, *i*-Pr).

$$log (1,4-Nu/1,2-Nu) = 2.14 + 7.58\Sigma\sigma_{R}^{+} - 1.85\Sigma\sigma_{a} + 0.27\Sigma E_{S}, (5)$$

$$(0.76) \quad (1.60) \qquad (0.23) \qquad (0.11)$$

$$S_{Y} = 0.06, r = 0.994, n = 8.$$

The  $\sigma_{R}^{+}$ ,  $\sigma_{\alpha}$ , and  $E_{S}$  are statistically significant. The polarization effect plays an important role in nucleophilic addition, which is evidenced, in particular, by a low relative standard error  $100 \times S_{2}/a_{2} = 100\% \times 0.23/1.85 = 12\%$ . With the data for organozinc compounds at 0°C exclusively, the three-parameter correlation becomes excellent.

$$\log (1,4-\text{Nu}/1,2-\text{Nu}) = 2.33 + 8.11\Sigma\sigma_{\text{R}}^{+} - 1.98\Sigma\sigma_{\alpha} + 0.33\Sigma E_{s}, (6)$$

$$(0.07) \quad (0.15) \qquad (0.02) \qquad (0.01)$$

$$S_{\text{Y}} = 0.004, r = 1.000, n = 5.$$

When the resonance constant  $\sigma_R^+$  in Eq. (5) is replaced by  $\sigma_R$  or  $\sigma_R^-$ , the correlation coefficient decreases from 0.99 to 0.97, and the  $\sigma_R$  or  $\sigma_R^-$  parameters become statistically insignificant.

The 1,4-/1,2-adduct ratio in the reactions of organozinc compounds with quinone 1 is almost temperatureindependent. The figure shows the linear dependences (r = 0.97) of the logarithm of this ratio on polarization constants for all the organozinc compounds at 0, 30, and 60°C (11 points from Table 1).

The effect of alkyl substituents [Eqs. (5) and (6)] gives evidence showing that products 2 and 3, as well as their derivatives 4 and 5 are formed by a nucleophilic mechanism. The donor-acceptor interaction of quinone 1 with organometallic compound, preceding the nucleophilic reaction, creates additional positive charges  $\delta$ + on the reaction centers in the 2 and 4 positions with respect to the quinone oxygen involved in reaction, thereby activating substituent R.



Therefore, in the transition states leading to products **2** and **3**, the resonance effect of substituent R is described by the  $\sigma_R^+$  constants which relate to its conjugation with the positively charged reaction center. An important contribution comes from the polarization effect. The substituent constants  $\sigma_a$  have a clear physical meaning and are based on ab initio quantum-chemical calculations [12]. The polarization effect relates to ion–dipole interaction of the charge on the reaction center with the dipole induced by this charge in substituents R. The energy of this ion-dipole interaction is known [9] to be proportional to  $1/d^4$ , where d is the ion-to-dipole distance. Therefore, the polarization effect on 1,2-addition is stronger compared to 1,4-addition.

Let us now focus on single-electron transfer. This reaction can result in the formation of three species in the solvent cage: semiquinone radical anion, alkyl (aryl) metal cation, and alkyl(aryl) radical [14]. The reaction centers in this case are the radical anion oxygens bearing the negative charge.



The logarithms of the yields of the single-electron transfer products 2-alkoxy- and 2-phenoxy-3,6-di-*tert*butylphenols (SET, %) in the reactions of quinone **1** with organozinc compounds at 30°C are excellently correlated to substituent parameters by a four-parameter equation (7), where  $\sigma_{I}$ ,  $\sigma_{R}^{-}$ ,  $\sigma_{\alpha}$ , and  $E_{S}$  are respectively the inductive, resonance (conjugation with a negatively charged reaction center), polarization, and steric constants of the substituents (Me, Et, Pr, *i*-Pr, *t*-Bu, and Ph).

$$log (SET) = -9.8 + 9.8\Sigma\sigma_{\rm I} - 27.3\Sigma\sigma_{\rm R} - 5.3\Sigma\sigma_{\rm u} + 0.99\Sigma E_{S}, (7)$$
(0.6) (0.6) (2.1) (0.2) (0.05)
$$S_{\rm Y} = 0.06, r = 0.997, n = 6.$$

It should be noted that if the resonance constant  $\sigma_R^$ is replaced by  $\sigma_R$ , the correlation coefficient decreases to 0.979, and the relative standard error in the coefficient at  $\sigma_R$  increases from 8 to 22%. No correlation takes place, when  $\sigma_R^-$  is replaced by  $\sigma_R^+$  (a constant that characterizes conjugation of substituents with a positively charged reaction center).

The results of correlation analysis provide convincing evidence showing that the mechanism of formation of substituted phenols 6 cardinally differ from the mechanism of formation of products 4 and 5. Unlike the nucleophilic pathway, when the charge on the reaction centers is positive, the reaction centers in the radical anion formed by electron transfer bear a negative charge. The fact that the yield of singleelectron transfer products much decreases with increasing reaction temperature (Table 1) is one more evidence in favor of concurrent occurrence of two processes: heterolytic and homolytic.

Thus, in the reactions of 3,6-di-tert-butyl-obenzoquinone with organozinc and organocadmium compounds, two different mechanisms are operative. The 1,2-/1,4-adduct ratio depends, along with steric, on the polarization and resonance  $\sigma_R^+$  (conjugation with a positive reaction center) constants of substituents R in  $R_2Zn$  and  $R_2Cd$ , which confirms a nucleophilic (heterolytic) mechanism of formation of these products. 2-Alkoxy- and 2-phenoxy-3,6-di-tertbutylphenols form in the studied reaction by a hemolytic mechanism via a semiquinone radical anion intermediate. Accordingly, the resonance interaction in the reactions involving single-electron transfer is described by the resonance constants  $\sigma_{R}^{-}$  which characterize conjugation with a negatively charged reaction center.

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