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MECHANISM OF CATALYTIC ALKYLATION OF 2,6-DI-*tert*-BUTYLPHENOL BY METHYL ACRYLATE

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Abstract. The determining factor of the reaction of 2,6-di-*tert*-butylphenol with alkaline metal hydroxides is temperature, depending on which two types of potassium or sodium 2,6-di-*tert*-butyl phenoxides are formed with different catalytic activity in the alkylation of 2,6-di-*tert*-butylphenol with methyl acrylate. More active forms of 2,6-Bu^t₂C₆H₃OK or 2,6-Bu^t₂C₆H₃ONa are synthesized at temperatures higher than 433 K and represent predominantly monomers of 2,6-di-*tert*-butyl phenoxides producing dimers on cooling.

Keywords: phenol, phenoxide, 2,6-di-*tert*-butylphenol, methyl acrylate, Michael reaction, kinetics.

1. Introduction

Phenoxides based on sterically hindered phenols and alkali metals are used in the synthesis and industrial production of a number of compounds applied in the production of antioxidants [1].

The shielding of the reaction center by the *tert*-butyl groups gives rise to the specific properties inherent in sterically hindered phenoxides, which are related to negative charge delocalization in the six-membered ring and the formation of a coordination bond of the metal cation with the oxygen atoms and carbon atoms of the six-membered ring. These features are responsible for the ability of potassium (**1**) and sodium (**2**) 2,6-di-*tert*-butylphenoxides to form supramolecular structures as contact or solvent-separated ion pairs and dimers [2]. Similar structures based on alkali metal cations and radical anions have been studied previously by EPR [3]. The above data suggest that a nonsolvated cation may be formed in a matrix comprising 2,6-di-*tert*-butylphenol (**3**), methylacrylate (**4**), and catalytic amounts of monomer **1** or **2**. The course of alkylation of phenol **3** with methyl acrylate in the presence of catalytic amount of monomer **1**

or **2** differs from that in the presence of the corresponding phenoxide dimers (associates).

2. Experimental

PMR ¹H spectra were recorded on a Bruker WM-400 instrument (400 MHz) in DMSO-d₆. Molecular weights were determined by the thermoelectric method using a cell described previously and calculated by the formula: $M = (k_g M_s / 100(t_1 - t_2))$, where g is a weighed sample (g) per 100 g of solvent (2–3%), k is the coefficient of the instrument and thermistors, M_s is the molecular weight of a standard sample, and $t_1 - t_2$ is the value equivalent to the temperature change in the cell filled with a sample solution by the potentiometer scale. The temperature in the thermostat was 355 K. Kinetic data were obtained by liquid chromatography of reaction mixtures (Bruker LC-31 chromatograph, IBM Cyano column, hexane – isopropyl alcohol ethyl acetate (8:1:1) mixture as eluent, rate 0.4 ml·min⁻¹).

2.1. Sodium 2,6-di-*tert*-Butylphenoxide (**2**)

A. A flask was filled with **3** (20.6 g, 0.1 mol) and heated in an argon flow to 463 K, and granulated NaOH (1.4 g) was added. After 10 min crystals that formed were separated by high-temperature filtration under argon and washed with *n*-octane heated to 383–388 K until no 2,6-Bu^t₂C₆H₃OH was found in the mother liquor.

Residues of the solvent were separated in vacuo at 393–403 K to obtain **2** (5.3 g, 93.5%), which was placed under argon into a flask heated to 393–403 K. NMR ¹H, δ : 1.30 (s, 18 H); 5.58 (t, 1 H, J = 6 Hz); 6.58 (d, 2 H, J = 6 Hz). PMR ¹H spectrum of 2,6-di-*tert*-butylphenol (for comparison), δ : 1.37 (s, 18 H); 3.48 (s, 1 H); 6.74 (t, 1 H,

$J = 8$ Hz); 7.06 (d, 2 H, $J = 8$ Hz). Found: $M_{min} = 234$. Calc. for $2,6\text{-Bu}^t_2\text{C}_6\text{H}_3\text{ONa}$: $M = 228.96$.

B. A flask was filled with **3** (20.6 g, 0.1 mol) and heated in an argon flow to 463 K, and granulated NaOH (1.4 g) was added. After 10 min the reaction mixture as a suspension was cooled to ~ 293 K, and heptane (50 ml) was added. The precipitate was filtered off and washed with heptane until no **3** was found in the washing solutions to obtain 4.9 g ($\sim 88\%$) of dimer **2**; $M_{max} = 458$.

2.2. Methyl 3-(-3,5-di-*tert*-butyl- 4-hydroxyphenyl) Propionate (**5**)

A Methyl acrylate (2.5 ml, 0.03 mol) was added in an argon flow to a mixture of **2** (method **A**) and **3** (4.88 g, 0.01 mol) at 388 K. After 30 min the reaction mixture was cooled to ~ 293 K, 10 % HCl was added to neutral pH, and the product was extracted with hexane. The compound **5** was obtained in a yield of 5.66 g (96 %), m.p. 439 K.

B. Granulated KOH (0.11 g, 0.002 mol) was added in an argon flow **3** (20.6 g, 0.1 mol) heated to 463 K. After 10 min the reaction mixture was cooled to 403 K, and methyl acrylate (11 g, 0.13 mol) was added. After the reactants were mixed, the temperature of the reaction mixture decreased to 383 K. After 25 min the content of the product in the reaction mixture was 98 mol %.

C. Methyl acrylate (11 g, 0.13 mol) was added in an argon flow at 383 K to a mixture of **3** (20.6 g, 0.1 mol) and **2** (0.488 g, 0.002 mol) synthesized by method **B**. After 25 min the content of the product in the reaction mixture became 15 mol %, while after 3 h it reached 72 %. Similarly, when **1** (0.46 g, 0.002 mol) synthesized by method **B** was used, the product yield after 3 h became 86 %.

2.3. Influence of Solvent Additives on the Catalytic Alkylation of **3** with Methyl Acrylate in the Presence of **2**.

Granulated NaOH (0.12 g, 0.002 mol) was added to **3** (20.6 g, 0.01 mol) at 463 K in an argon flow. After 10 min, the reaction mixture was cooled to 408 K, and methyl acrylate (11.2 g, 0.13 mol) and DMCO (0.2 ml) were added. The reactions with additives HMPA, DMF, MeCN and Diglime were carried out similarly.

3. Results and Discussion

In this work we found that with a nearly equimolar mixture of **3** and **4**, the catalytic alkylation in the presence of 1.5–3 mol % of monomer **1** or **2** proceeds at higher rates than those known previously (in the presence of dimer **1** or **2**) [2–5] and gives the alkylation product methyl 3-(3,5-di-*tert*-butyl-4-hydroxyphenyl)propionate

(**5**), in up to 98 % yield. The formation of the monomer species was supported by thermoelectric measurements of the molecular weights of phenoxides **1** and **2** at 388 K. The kinetic studies for this reaction in the range of 382–403 K showed that the pattern of the kinetic curve does not depend on the reaction temperature (Fig. 1), which may imply a tunneling effect in the catalytic alkylation mechanism.

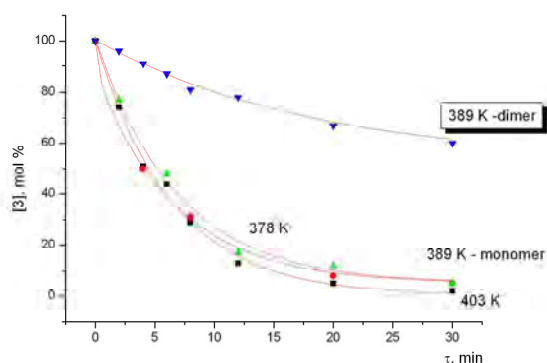
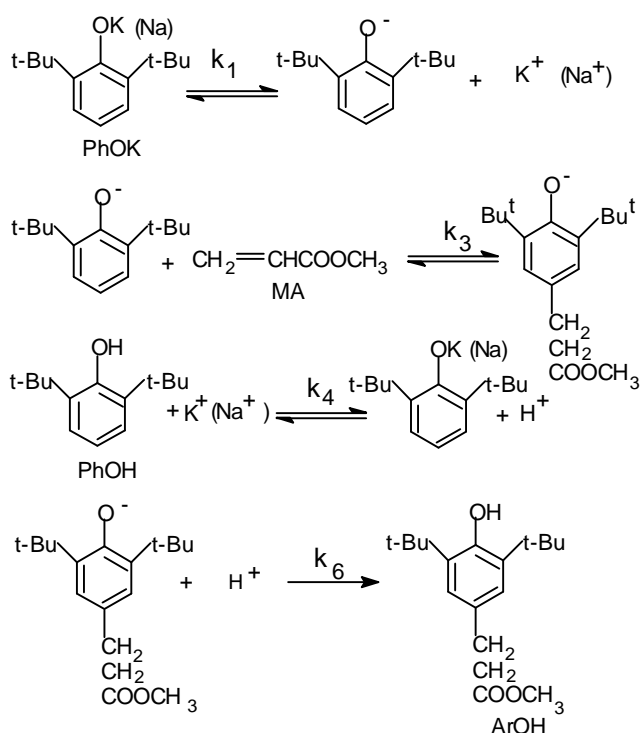


Fig. 1. Temperature dependence of the kinetics of the reaction of phenol **3** with methyl acrylate in the presence of **1**: $[\mathbf{3}]_0 = 3.29$; $[\mathbf{4}]_0 = 3.75$; $[\mathbf{1}]_0 = 0.108 \text{ mol}\cdot\text{l}^{-1}$; the dots correspond to the experiment

The monomer of phenoxide **1** is formed upon the reaction of phenol **3** with potassium hydroxide at 453–473 K. On cooling to 293 K, the monomer is converted into dimer **1**. In the experiment a mixture of **1** and **3** was cooled to 408–393 K and compound **5** was simultaneously added. This gave a reaction mass in which phenoxide **1** or **2** was mainly uniformly distributed throughout the mixture of phenol **3** and acrylate **4** and the reaction between these compounds proceeded under steady-state conditions in a thermostat without stirring the reactants.

By sampling the reaction mixture during the process and analyzing the samples by liquid chromatography, the contents of **3**, **5** and dimethyl-(3,5-di-*tert*-butyl-4-hydroxybenzyl)glutarate (**6**) in the reaction mixture were determined. The yield of **6** in the experimental series did not exceed 1 %. Fig. 1 shows also the kinetic data for the reaction of phenol **3** with methyl acrylate in the presence of catalytic amounts of dimer **1**, which coincide with published data [2]. The kinetics of the alkylation of phenol **3** with methyl acrylate depends on the ratio of **3** to **4**, the presence of polar or proton-containing solvent additives, and other factors that can affect the catalyst properties. When the initial **3** to **4** ratio is nearly equimolar and **1** or **2** is present in catalytic amounts, the reactions take place between **1** (**2**) and **3** and between **1** (**2**) and **4** to give the alkylation products **5** and **6** and methyl acrylate oligomers. When the ratio $\mathbf{4}:\mathbf{3} > \mathbf{3}$, the yield of alkylation product **5** decreases to 10–15 %. Presumably, with excess methyl acrylate, the reaction

matrix properties change and the nonassociated cations enter the bulk and react with methyl acrylate to give oligomers. In a binary reactions mass consisting of phenoxide **1** in methyl acrylate solution, oligomerization predominates. This gives an oligomer with a molecular mass of > 10000 containing a phenolic fragment. Based on the foregoing, a scheme of the catalytic alkylation of 2,6-di-tert-butylphenol with methyl acrylate was proposed. In terms of this scheme, mathematical modeling was carried out using the experimental kinetic data for various initial concentrations of **3**, **4**, and **2**.



Scheme 1

The modeling was carried out using a computer program for reaction kinetics based on the solution of a set of differential equations. The kinetic scheme consists of three blocks (table). The first block {reactions (1)-(6)} includes the steps of formation of the alkylation product **5** (the numbers of the constants correspond to the numbers of reactions in the table).

The second block contains two reactions, resulting in product **6** and methyl acrylate oligomer. The third block is related to the inhibition caused by the reaction of the metal cation with the solvent additive (the formation of an associated cation, a crown ether-type complex, or dimmer associated). The stimulating influence of polar solvents in bimolecular addition is known [6].

However, in this case, polar solvents have an adverse effect on the catalytic alkylation which is

manifested as a decrease in the consumption rate of phenol **3** and a decrease in the yield of **5** (Fig. 2).

Table 1

Rate constant for the elementary steps of the catalytic alkylation of 2,6-di-tert-butylphenol (3**) by methyl acrylate (**4**) in the presence of sodium 2,6-di-tert-butylphenoxide (**2**)**

Reaction	No.	k
$\text{PhONa} \rightarrow \text{PhO}^- + \text{Na}^+$	(1)	$4.5 \cdot 10^{-2} \text{ s}^{-1}$
$\text{PhO}^- + \text{Na}^+ \rightarrow \text{PhONa}$	(2)	$1 \cdot 10^{-2} \text{ l} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$
$\text{PhO}^- + \text{MA} \rightarrow \text{ArO}^-$	(3)	$1.8 \cdot 10^{-3} \text{ l} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$
$\text{Na}^+ + \text{PhOH} \rightarrow \text{PhONa} + \text{H}^+$	(4)	$1.5 \cdot 10^{-1} \text{ l} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$
$\text{PhONa} + \text{H}^+ \rightarrow \text{Na}^+ + \text{PhOH}$	(5)	$5 \cdot 10^{-2} \text{ l} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$
$\text{H}^+ + \text{ArO}^- \rightarrow \text{ArOH}$	(6)	$7 \cdot 10^{-1} \text{ l} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$
$\text{Na}^+ + \text{MA} + \text{MA} \rightarrow \text{Na}^+ 2\text{MA}$	(7)	$3 \cdot 10^{-4} \text{ l}^2 \cdot \text{mol}^{-2} \cdot \text{s}^{-1}$
$\text{PhO}^- + \text{MA} + \text{MA} \rightarrow \text{ArO}^-$	(8)	$1 \cdot 10^{-5} \text{ l}^2 \cdot \text{mol}^{-2} \cdot \text{s}^{-1}$
$\text{ArO}^- + \text{H}^+ \rightarrow \text{ArOH}$	(9)	$7 \cdot 10^{-1} \text{ l} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$
$\text{Na}^+ + \text{MeCN} \rightarrow \text{Na}^+ \text{MeCN}$	(10a)	$5 \cdot 10^{-3} \text{ l} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$
$\text{Na}^+ + \text{HMPA} \rightarrow \text{Na}^+ \text{HMPA}$	(10b)	$2.2 \cdot 10^{-2} \text{ l} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$
$\text{Na}^+ + \text{DMF} \rightarrow \text{Na}^+ \text{DMF}$	(10c)	$4.2 \cdot 10^{-2} \text{ l} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$
$\text{Na}^+ + \text{DMSO} \rightarrow \text{Na}^+ \text{DMSO}$	(10d)	$6.4 \cdot 10^{-2} \text{ l} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$
$\text{Na}^+ + \text{Diglyme} \rightarrow \text{Na}^+ \text{Diglyme}$	(10e)	$6.1 \cdot 10^{-1} \text{ l} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$

MeCN is acetonitrile; HMPA is hexamethylphosphoramide; DMF is dimethylformamide; DMSO is dimethyl sulfoxide; Diglyme is dimethoxyethane

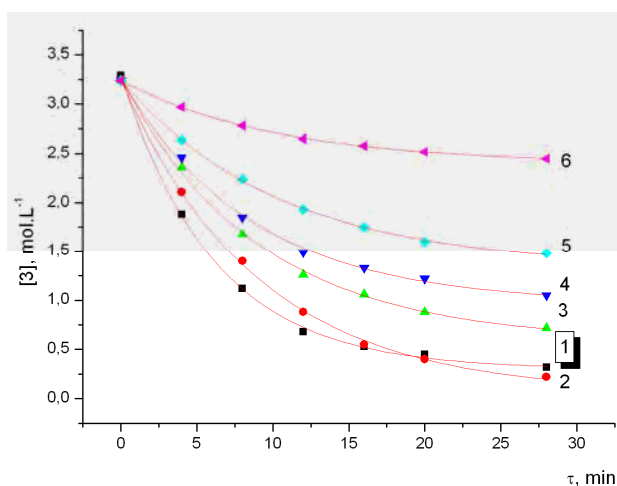


Fig. 2. Kinetics of reaction of phenol **3** with acrylate (**4**) in the presence of phenoxide **2** and solvent additives (solvent, $\text{mol} \cdot \text{l}^{-1}$) at 383 K: no solvent (1); MeCN, 0.24 (2); HMPA, 0.22 (3); DMF 0.21, (4); DMSO, 0.23 (5) and diglyme, 0.19 (6). $[\mathbf{3}]_0 = 3.26\text{--}3.28$; $[\mathbf{4}]_0 = 3.5\text{--}3.6$; $[\mathbf{2}]_0 = 0.1 \text{ mol} \cdot \text{l}^{-1}$; the curves show the calculation data and the dots correspond to the experiment

This fact is at variance with the classical mechanism; however it is consistent with the ion chain mechanism because the formation of a nonassociated metal cation implied regeneration of the catalyst (**1 or 2**). In the series of solvents studies, dimethoxyethane is most efficient additive, having an inhibiting effect due to formation of a crown ether-type complex (cation trap).

4. Conclusions

Thus, experimental data are consistent with the possibility of the ion chain mechanism in the catalytic alkylation of 2,6-di-*tert*-butylphenol with methyl acrylate in the presence of potassium and sodium 2,6-di-*tert*-butylphenoxide monomers.

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МЕХАНІЗМ КАТАЛІТИЧНОГО АЛКІЛУВАННЯ 2,6-ДІ-ТРЕТ.-БУТИЛФЕНОЛУ МЕТИЛАКРИЛАТОМ

Анотація. Показано, що температура є вирішальним чинником реакції взаємодії 2,6-ді-трет.-бутилфенолу з гідроксидами лужних металів, залежно від якої утворюються два типи калієвих або натрієвих 2,6-ді-трет.-бутил фенолоксидів з різною каталітичною активністю. Синтезовано більш активні форми 2,6- $\text{Vi}^t_2\text{C}_6\text{H}_3\text{OK}$ або 2,6- $\text{Vi}^t_2\text{C}_6\text{H}_3\text{ONa}$ при температурах, вищих за 433 K, і це, головним чином, мономери 2,6-ді-трет.-бутилфеноксидів, які утворюють димери при охолодженні.

Ключові слова: фенол, феноксид, 2,6-ді-трет.-бутилфенол, метилакрилат, кінетика.