

## Interactions of Phenols with Lewis Acids: XVIII.\* Tautomerism of Methylated Phenols

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**Abstract**—The tautomeric state of methylated phenols was evaluated experimentally and by quantum-chemical calculations. The values of  $\Delta H_t$  and  $K_t$  are presented.

The phenol-cyclohexadienone rearrangement may be regarded as a particular case of keto-enol tautomerism [2–4]. In the review [2] are summarized the factors leading to stabilization of cyclohexadienones. It was established that one among these factors is the presence of alkyl substituents attached to the ring (best of all, *ortho-tert-butyl*). The lack of quantitative data prevents the estimation of contribution from separate components into the phenol tautomerism. This study aims to fill in this gap by an example of methylated phenols.

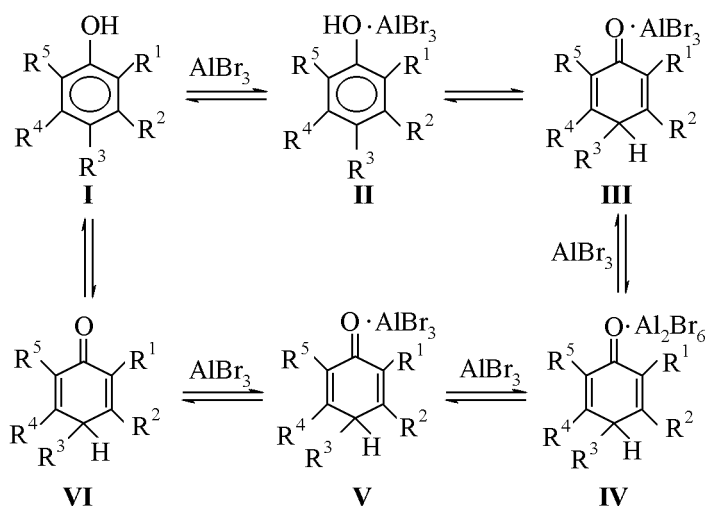
In a series of studies [5–8] an interaction of phenols and cyclohexadienones with strong Lewis acids was established with the use of UV, IR, and

NMR spectroscopy that in the presence of two molar equivalents of  $\text{AlBr}_3$  arose complexes of the same composition and structure. This fact may be used to calculate the enthalpy ( $\Delta H_t$ ) and tautomerism constants ( $K_t$ ). Actually, if exists the process described in Scheme 1, then a certain complex can be obtained by two different ways, and it conforms to Hess' law [equation (1)].

$$\Delta H_{1,2} + \Delta H_{2,3} + \Delta H_{3,4} = \Delta H_{1,6} + \Delta H_{6,5} + \Delta H_{5,4} \quad (1)$$

Let us take  $\Delta H_{6,5} + \Delta H_{5,4} = \Delta H_{7,9}$ , since  $\Delta H_{1,2} + \Delta H_{2,3} + \Delta H_{3,4} = \Delta H_{1,4}$ , and  $\Delta H_{1,6} = \Delta H_t$ , then  $\Delta H_{1,4} = \Delta H_t + \Delta H_{7,9}$  and we therefrom obtain  $\Delta H_t = \Delta H_{1,4} - \Delta H_{7,9}$ .

Scheme 1.



\* For communication XVII, see [1].

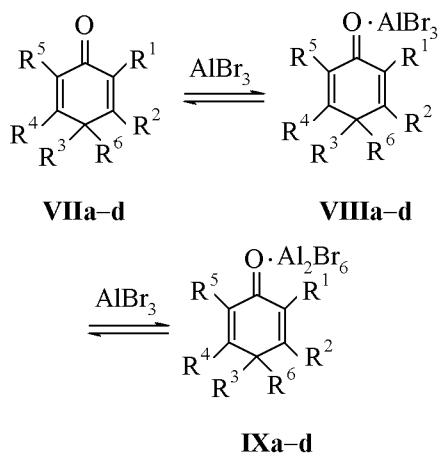
Experimental and calculated values of enthalpy  $\Delta H_t$  (kJ mol<sup>-1</sup>) and constants of tautomeric equilibrium  $K_t^a$  for methylated phenols

| Phenol                      | $\Delta H_t$ |                               | $K_t$                 |                               |
|-----------------------------|--------------|-------------------------------|-----------------------|-------------------------------|
|                             | experimental | calculated (MP <sub>2</sub> ) | experimental          | calculated (MP <sub>2</sub> ) |
| Phenol                      | 71.4         | 70.7                          | 2.5–10 <sup>-13</sup> | 3.3–10 <sup>-13</sup>         |
| 3-Methylphenol              | 68.4         | 69.7                          | 8–10 <sup>-13</sup>   | 5–10 <sup>-13</sup>           |
| 3,5-Dimethylphenol          | 66.2         | 67.9                          | 2–10 <sup>-12</sup>   | 1–10 <sup>-12</sup>           |
| 2-Methylphenol              | –            | 61.4                          | –                     | 1.4–10 <sup>-11</sup>         |
| 2,3-Dimethylphenol          | 56.2         | 58.9                          | 1.2–10 <sup>-10</sup> | 4–10 <sup>-11</sup>           |
| 2,3,5-Trimethylphenol       | 55.4         | 58.0                          | 1.6–10 <sup>-10</sup> | 6–10 <sup>-11</sup>           |
| 2,6-Dimethylphenol          | –            | 44.6                          | –                     | 1.3–10 <sup>-8</sup>          |
| 2,3,5,6-Tetramethylphenol   | 42.4         | 43.6                          | 3–10 <sup>-8</sup>    | 1.9–10 <sup>-8</sup>          |
| 2,3,4,5,6-Pentamethylphenol | 34.8         | 40.7                          | 7–10 <sup>-5</sup>    | 6–10 <sup>-8</sup>            |

<sup>a</sup> The  $K_t$  values given in the table were calculated with the value of  $\Delta S_t$  –1.2 J K<sup>-1</sup> [10].

Thus to evaluate the  $\Delta H_t$  value it is necessary to measure the formation enthalpy of triple complexes of phenols  $\Delta H_{1,4}$  and cyclodienones  $\Delta H_{6,5}$  with Al<sub>2</sub>Br<sub>6</sub> and insert these values into equation (1). The  $\Delta H_{1,4}$  values for the methylated phenols **I** are given in [7].

By calorimetric titration of substituted cyclohexadienones **VIIa–d** we found that only small variations exist in the formation enthalpies of complexes **IXa–d**. Therefore we took for  $\Delta H_{7,9}$  a constant value of 158.3 kJ mol<sup>-1</sup>.



**a**, R<sup>1</sup> = R<sup>2</sup> = R<sup>3</sup> = R<sup>4</sup> = R<sup>5</sup> = R<sup>6</sup> = CH<sub>3</sub>; **b**, R<sup>1</sup> = R<sup>2</sup> = R<sup>3</sup> = R<sup>4</sup> = R<sup>5</sup> = CH<sub>3</sub>, R<sup>6</sup> = CHCl<sub>2</sub>; **c**, R<sup>1</sup> = R<sup>3</sup> = R<sup>5</sup> = CH<sub>3</sub>, R<sup>6</sup> = CHCl<sub>2</sub>; **d**, R<sup>1</sup> = CH<sub>3</sub>, R<sup>6</sup> = CHCl<sub>2</sub>.

If into equation (1) instead of  $\Delta H_{6,4}$  value is inserted  $\Delta H_{7,9}$ , we should obtain in first

approximation the values  $\Delta H_t$  for the series of methylated phenols (see table).

As seen from the table, the  $\Delta H_t$  value gradually decreases with increasing number of the methyl groups bonded to the ring from 68.4 (for 3-methylphenol) to 34.8 kJ mol<sup>-1</sup> (for pentamethylphenol).

For *ortho*- and *meta*-methylated phenols exists a linear correlation between  $\Delta H_t$  and Hammett's  $\sigma$ -constants. The enthalpy of tautomeric transformation for unsubstituted phenol (71.4 kJ mol<sup>-1</sup>) was obtained by extrapolation according to equation (2).

The estimation of enthalpy of the tautomeric processes in the phenol series may be used as criterion for quantum-chemical calculations. In particular, calculation of  $\Delta H_t$  values by MO SCF procedure [9] show that phenol structure is more stable than that of 2,5-cyclohexadienone by 94.2 kJ mol<sup>-1</sup>, and the calculation by optimized OHF procedure with MP<sub>2</sub> corrections gives a value 42.5 kJ mol<sup>-1</sup> [10].

It turned out that calculations using MP<sub>2</sub> afforded  $\Delta H_t$  values very close to experimental results. The biggest deviation was observed for the tautomerism enthalpy of pentamethylphenol, and it amounted to ~6 kJ mol<sup>-1</sup>.

According to quantum-chemical calculations the stability of the keto form of methylated phenols should decrease in the series *ortho*-*meta*-*para*-cresol. Maximum stabilization of 2,5-cyclohexadienones is achieved in the presence of *ortho*-methyl groups (1CH<sub>3</sub> 10–13 kJ mol<sup>-1</sup>), the effect of *meta*-methyls is less pronounced (1CH<sub>3</sub> 3–4 kJ mol<sup>-1</sup>), and the appearance of a *para*-methyl group destabilizes the

keto form. The higher stability of the ortho-alkylated 2,5-cyclohexadienones is confirmed by numerous examples cited in review [2].

However we should mention some discrepancies between the values of cyclohexadienones stability obtained by calculations, from calorimetry, and NMR spectra of the complexes of the keto form. For instance, from the NMR spectra [4, 5] follows that among 2,6-dimethyl- and 3,5-dimethyl-2,5-cyclohexadienones the most stable is 3,5-dimethyl-2,5-cyclohexadienone since in the presence of 2 mol equivalents of  $\text{AlBr}_3$  the keto form complex from 2-methylphenol forms by half, and 3-methylphenol totally transforms into the keto complex under these conditions [4, 5]. The inconsistency of the calculated and spectral data presumably arises because these complexes by the structure are rather oxybenzenium ions than 2,5-cyclohexadienones, and the stabilizing contribution of methyls in these structures is different.

The constants of equilibrium between methylated phenols and keto forms were estimated from the general thermodynamic equilibrium (at  $\Delta S_t$   $-1.2 \text{ J K}^{-1}$  [10]). In the table are given the numerical values of the constants of tautomeric equilibrium obtained from the experimental data and quantum-chemical calculations. As seen, the constants gradually grow from  $2.5 \times 10^{-13}$  for phenol to  $7 \times 10^{-7}$  for pentamethylphenol. It turned out, that two meta-methyl groups stabilize the keto form approximately 5-fold, whereas the effect of two *ortho*-methyl groups is greater by nearly four orders of magnitude, and the exhaustive

methylation of phenol results in stabilization  $2.8 \times 10^6$  times.

We like to mention in conclusion that thermochemical experiment and quantum-chemical calculations provide a possibility to estimate and predict with high probability the thermodynamic parameters of the phenol-cyclohexadienone tautomerism for phenols of the benzene series.

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