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Modeling of the aniline with nitrobenzene reaction by PM6 method

T.A. Klimova, V.V. Bochkarev*, L.S. Soroka

National Research Tomsk Polytechnic University, 30 Lenina av., Tomsk, 634050, Russia

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Abstract

Modeling of the aniline with nitrobenzene reaction was carried out by PM6 method with tetramethylammonium hydroxide. Calculated data prove that the stage of transfer of hydride ion from the *p*-σ-complex to the acceptor, i.e. nitrobenzene or 4-nitrodiphenylamine determines the rate of aniline with nitrobenzene condensation. Herein, intermolecular transfer mechanism that has lower activation energy is the most likely one if compared with intramolecular mechanism. It is shown that tetramethylammonium cation can form ionic and ion-dipole complexes with the components of the reaction mixture and its field influences the distribution of electron density in the reactants and their reactivity.

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Keywords: aniline; nitrobenzene; 4-nitrodiphenylamine; 4- nitrosodiphenylamine; condensation; mechanism; modeling; PM6 method.

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1. Introduction

The condensation of aniline with nitrobenzene serves as an example of aromatic nucleophilic substitution of hydrogen. Upon the research of nitrobenzene with anilin-d_5 reaction, Stern M.K. et al.[1] have proposed the mechanism of condensation of nitrobenzene with aniline in strongly basic media. In anhydrous highly polar solvents, a very active nucleophile, anilide-ion **P1**, is generated from aniline under tetraalkilammonium hydroxide (TMA-OH). The attack of anilide-ion on nitrobenzene molecule mostly happens in *para*-position and leads to the formation of anionic *p*-σ-complex **P2** (Fig. 1). The attack of anilide-ion in the ortho-position of nitrobenzene leads to the formation of phenazine **P3**. Authors suppose that further transformations of **P2** are connected with the oxidation-reduction process of hydride ion abstraction with two possible mechanisms. The intramolecular mechanism of

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* Corresponding author. Tel.: +7-382-260-6120.
E-mail address: walery_w_b@mail.ru

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elimination and transfer of hydrogen with a σ-complex **P2** nitrogroup leads to the formation of 4-nitrosodiphenylamine (4-nitrodiPhAm) **P4** salt. The intermolecular mechanism of the process with nitrobenzene nitrogroup leads to the formation of 4-nitrodiphenylamine salt (4-nitrosodiPhAm) **P5.**

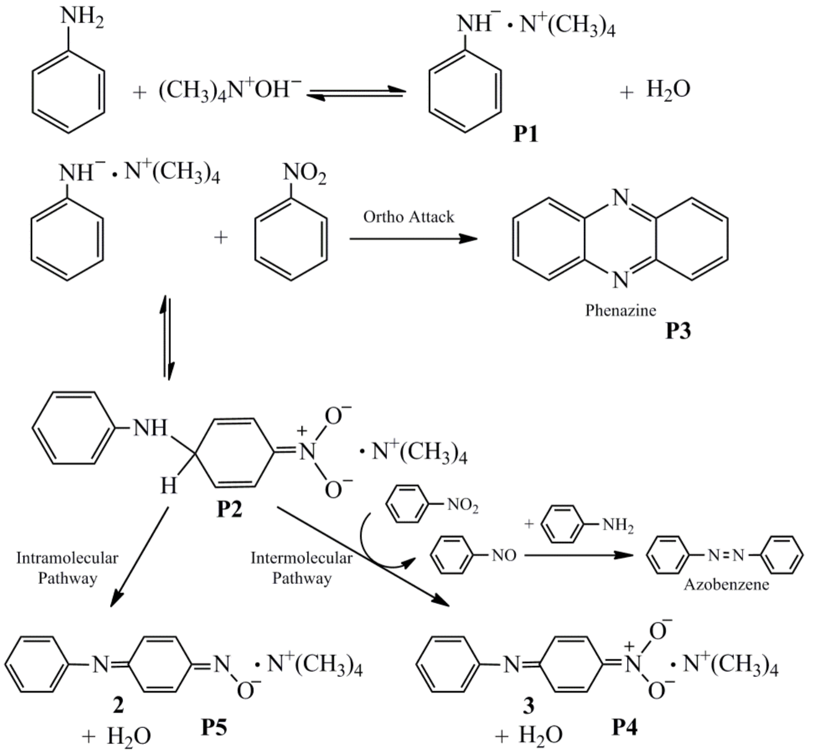

Fig.1. Mechanism of nitrobenzene with aniline condensation reaction.

The nucleophilic substitution in nitroarenes with the formation of anionic σ-complex is proved by the data acquired by Orlov V.Yu. et al.[2] using quantum-chemical calculations Zheng Ya-Jun, Ornstein R.L.[3], Glukhovtsev M.N. et al.[4], Fernandez I. et al.[5] and in the experiments carried out by Danikiewicz W. et al.[6] in reactions with carbanions in vapor phase.

Ayyangar N.R. et al.[7] registered that in the reaction of acetanilide with nitrobenzene a nitrogroup from the initial nitroarene or its σ-complex is involved in hydrogen oxidation substituting. It was noted in the reaction of benzamide acetanilide with nitrobenzene by Stern M.K. and Cheng B.K.[8]. The peculiarity of these reactions is the absence of external oxidant. Either the initial reagent, i.e. nitrobenzene, or a nitrogroup of the σ-complex can participate in the oxidation-reduction process of hydride ion abstraction from σ-complex **P2.** This study views modeling the reaction of aniline with nitrobenzene over TMA-OH to reveal the rate-determining stage of the process and to compare the acquired results with experimental data.

2. Methods of Calculation

Quantum-chemical calculations were carried out using the following software: ChemBio3D Ultra V. 12.0.2.1076[9] and MOPAC2012[10]. Geometrical parameters (i.e. bond length, angles of valence and torsion angles) that determine the position of atoms in relation to one another and to the reaction center were improved according to the standard procedure. The optimization of geometrical parameters of transition states was carried out according to the standard TS-procedure[10].

We performed experimental calculations using various methods with the following software: MOPAC2012 and ChemBio3D Ultra to choose methods of calculation and modeling acid-base interaction. We used the interaction of hydroxide ion with aniline with the formation of anilide-ion and water as a test reaction. The calculated values of reagent and products formation enthalpy are in table 1.

Table 1. Calculated and experimental data on the enthalpies of reagents and products formation, $\Delta H^{\circ}_{f}(298)$, the reaction enthalpies, kJ/mol

Substance	MNDO	AM1	PM3	PM6	3-21G	Experimental data
$C_6H_5NH_2$(g)	90.43	85.42	88.78	89.38	347.37	86.86[11]
OH^-(g)	-24.17	-59.08	-73.23	-138.21	26.14	-143.20[12]
$C_6H_5NH^-$(g)	57.25	80.64	59.56	54.80	306.15	83.65[13]
H_2O(g)	-255.01	-247.90	-223.55	-227.21	67.11	-241.84[11]
ΔH_r (298)	-264.01	-193.60	-179.54	-123.58	-0.26	-101.85

As it can be seen from the data given, the least disagreement between experimental and calculated data is for PM3 and PM6 methods. The ab initio method with 3-21G parameterization shows the biggest deviations of calculated values from experimental data and, thus, cannot be used for the modeling of acid-base interaction. Considering that PM6 method correctly simulates the enthalpies of both neutral substances (H_2O) and ions (OH^-) formation, we used semi empirical PM6 method for further calculations.

3. Results and discussion

3.1. Reaction of aniline with tetramethylammonium hydroxide

Reactive system: $C_6H_5NH_2 + (CH_3)_4N^+OH^-$ (R1) → $C_6H_5NH^- + (CH_3)_4N^+$ (P1) + H_2O.

When aniline approaches TMA-OH, an ion-dipole complex (IDK1) is formed as the energy of the system reduces. Further approaching of OH^- with an atom from aniline H NH_2-group leads to stretching of N-H bond and its opening. The transition state TS1 occurs with the following distances between atoms: N…H – 1,386A; H…O – 1,206A. The energy of reaction activation is E_1 = 39.49 kJ/mol. The opening of N-H bond and addition of a proton to OH^- comes amid the formation of an ion-dipole complex (IDK1a). For example, the removal of water molecule from reaction products because of its solvation by solvent molecules is connected with the system energy increase (P1…H_2O). The P1 reaction product is an ion complex of anilide-ion and tetramethylammonium cation (ΔH_f = 269.76 kJ/mol). Tetramethylammonium cation is located over the plane of anilide-ion benzene ring, at the same time the distance between the nitrogen atom $(CH_3)_4N^+$ and the ring plane is 3.983A. The reaction energy diagram is in fig. 2.

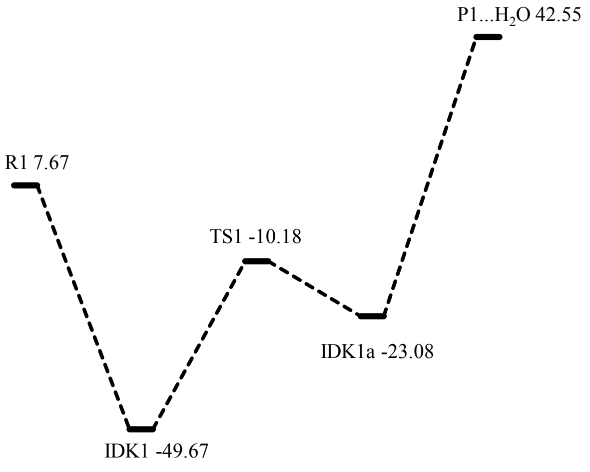

Fig. 2. Changing of enthalpy of reactive system formation (kJ/mol) during the reaction $C_6H_5NH_2 + (CH_3)_4N^+OH^- \rightarrow C_6H_5NH^- + (CH_3)_4N^+ + H_2O$

3.2. Reaction of ionic complex of anilide-ion…tetramethylammonium hydroxide with nitrobenzene

Reactive system: $C_6H_5NH^- + (CH_3)_4N^+$ (P1) $+C_6H_5NO_2 \rightarrow$ *p*-σ-complex (P2).

When P1 approaches nitrobenzene (NB), an ion-dipole complex (IDK2) is formed as the energy of the system reduces, as $\Delta H°_f$ of the reactive system is 347.14 kJ/mol with endless elimination of reagents. TMA cation is oriented towards NB nitrogroup, its field increasing particle negative charge of oxygen atoms. This leads to the reduction of electron density of C atom, which is in *p*-position towards nitrogroup by 0.0083 units in comparison with the initial NB. Thus, TMA cation activates NB molecule for nucleophilic attack with anilide-ion. The distance between atoms in IDK2: $(CH_3)_4N^+…NO_2C_6H_5$ – 4.724A; $(CH_3)_4N^+…NH^-C_6H_5$ – 3.376A; C atom in *p*-position NB…$NH^-C_6H_5$ – 5.550A; $\Delta H°_f$ – 267.33 kJ/mol.

Further approaching of $C_6H_5NH^-$ and NB leads to the formation of *p*-σ-complex (P2). The transition state TS2 occurs with the following distances between atoms: N7…C14 – 2.315A; C14…H23 – 1.093A; $\Delta H°_f$ − 295.11 kJ/mol. The energy of reaction activation is E_2 = 27.78 kJ/mol. The P2 reaction product has the following properties. The bonds length is N7…C14 – 1.519A; C14…H23 – 1.124A; the angle of valence is N7…C14… H23 – 104.8°; $\Delta H°_f$ – 164.79 kJ/mol. The P2 product is an ionic complex between the *p*-σ-complex and TMA cation (ref. fig.3) with partial charge transfer of 0.0413 charge unit.

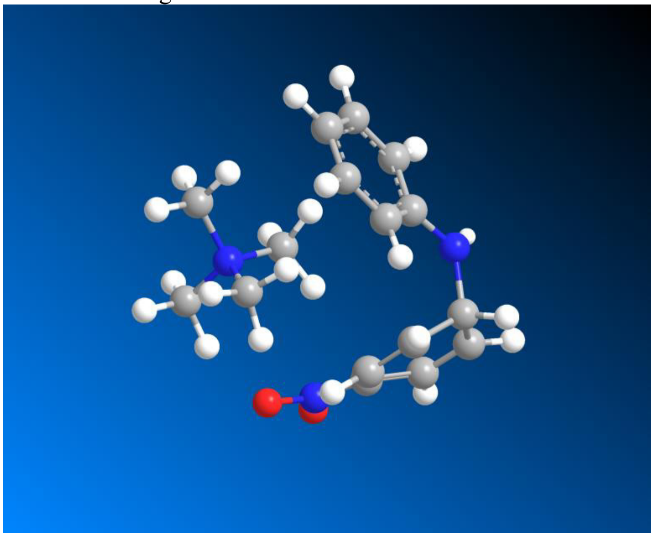

Fig. 3. Calculated geometry of the product of anilide-ion with nitrobenzene interaction over TMA cation.

3.3. Intermolecular transfer of hydride ion from the p-σ-complex

According to numerous patent data[14], the elimination of hydride ion can occur under various oxidants. These oxidants can be external, i.e. air oxygen, hydrogen peroxide, $KMnO_4$ etc. They can also be internal which means that they are in the reactive system, i.e. nitrobenzene and 4-nitrodiPhAm. This work studies the latter case of hydride ion elimination under NB and 4-nitrodiPhAm, as it is the most common for industrial process implementation.

The reaction of *p*-σ-complex and NB interaction goes through two stages. On the first stage, there is the transfer of hydride ion from *p*-σ-complex to NB molecule with the formation of $C_6H_5N(OH)O^-$ anion and 4-nitrodiPhAm. On the second stage, there is the transfer of a proton from 4-nitrodiPhAm to $C_6H_5N(OH)O^-$ OH-group with simultaneous water elimination. The products of this reaction are the ionic complex of anion 4-nitrodiPhAm…TMA cation, nitrosobenzene and water.

Similarly, the reaction of *p*-σ-complex and 4-nitrodiPhAm interaction goes through two stages. On the first stage, there is the transfer of hydride ion to 4-nitrodiPhAm molecule with the formation of $C_6H_5NHC_6H_4N(OH)O^-$ anion and 4-nitrodiPhAm. On the second stage, there is the transfer of a proton from 4-nitrodiPhAm to

$C_6H_5NHC_6H_4N(OH)O^-$ OH-group with simultaneous water elimination. The products of this reaction are the ionic complex of anion 4-nitrodiPhAm… TMA cation, nitrosodiPhAm and water.

On the first stage, the profile of way reaction was determined by deviation of two variables, i.e. distances C14…H23 and H23…O29. It was suggested that when NB nitrogroup or 4-nitrodiPhAm (O29 atom) approach the departing hydrogen atom (H23 atom) there is simultaneous stretching of the splitting bond C14…H23. The transition state TS3 is localized according the standard TS procedure.

4-NitrodiPhAm can show acidic properties. According to the data acquired by Bochkarev V.V. et al.[15], the value of pK_a 4-nitrodiPhAm in water solutions is 4.40. This means that any anion can be proton acceptor in the reactive system, including the $C_6H_5N(OH)O^-$ or $C_6H_5NHC_6H_4N(OH)O^-$ anion. On the second stage, the profile of way reaction was determined by deviation of two variables i.e. distances N7…H13 and H13…O29. It was suggested that under $C_6H_5N(OH)O^-$ or $C_6H_5NHC_6H_4N(OH)O^-$ anion stretching of the N7…H13 bond takes place with simultaneous formation of a new H13…O29 bond, which leads to the formation of water, nitrosobenzene (nitrosodiPhAm) and 4-nitrodiPhAm anion molecules. The transition state TS4 is localized according to the standard TS procedure. The results are in table 2.

Table 2. Calculated values of formation enthalpies of reagents and products of intermolecular transfer of hydride ion, $\Delta H^\circ_f(298)$, kJ/mol

Description	Distance, A					$\Delta H^\circ_f(298)$
	C14…H23	H23…O29	N7…H13	H13…O29	O29…N30	
Reaction P2 + NB → P4 + C_6H_5NO + H_2O						
P2…NB	1.127	-	1.023	-	1,235	242.24
IDK3	1.127	9.718				173.25
TS3	1.451	2.019				271.29
4-nitrodiPhAm + $C_6H_5N(OH)O^-$ + $(CH_3)_4N^+$	3.075	0.996	1.089	2.985	1.462	112.51
TS4			2.099	1.015	1.813	162.59
P4 + C_6H_5NO + H_2O	4.022	0.948	1.873	1.004	6.879	113.49
Reaction P2 + 4-nitrodiPhAm → P4 + nitrosodiPhAm + H_2O						
P2…4-nitrodiPhAm	1.125	-	1.027	-	1.223	333.10
IDK3a	1.126	9.268				259.35
TS3a	1.289	1.303	1.025	4.217	1.254	380.67
4-nitrodiPhAm + $C_6H_5NHC_6H_4N(OH)O^-$ + $(CH_3)_4N^+$	3.620	0.991	1.032	4.703	1.474	234.92
TS4a			2.045	1.012	1.805	296.00
P4 + nitrosodiPhAm + H_2O	3.382	0.96	3.535	0.969	4.015	183.32

The energy of P2 + NB → P4 + C_6H_5NO + H_2O reaction activation on the first stage is 98.04 kJ/mol and on the second stage is 50.07 kJ/mol.

The energy of P2 + 4-nitrodiPhAm → P4 + nitrosodiPhAm + H_2O reaction activation on the first stage is 121.32 kJ/mol and on the second stage is 61.07 kJ/mol.

3.4. Intermolecular transfer of hydride ion in p-σ-complex

Intramolecular transfer of hydride ion in *p*-σ-complex from *n*-position to the nitrogroup can occur in several ways. This work studies several implementation variations of this process. This includes simultaneous transfer of hydrogen atoms on the ring and to the oxygen atom in the nitrogroup by means of hydride shifts and further elimination of O OH^- under TMA cation (with E_4 = 886 kJ/mol). Another variation is simultaneous transfer of hydrogen atoms on the ring with the formation of *o*-σ-complex to the oxygen atom in the nitrogroup by means of hydride shifts and further elimination of OH^- under TMA cation (with E_4 = 675 kJ/mol). There is also a variation, which includes asynchronous transfer of hydrogen atoms on the ring with sequential formation of *m*-σ-complex and *o*-σ-complex to the oxygen atom in the nitrogroup by means of hydride shifts and further elimination of OH^{-} under TMA cation (with E_4 = 333 kJ/mol). The last possible variation is direct transfer of hydride ion to the oxygen atom in the nitrogroup and further elimination of OH^{-} under TMA cation (with E_4 = 273 kJ/mol). It can be seen that all the proposed variants have very high energy of activation and are quite unlikely because of that.

Experimentally observed formation of a mixture of nitrosodiPhAm and 4-nitrodiPhAm products during the condensation of aniline with NB can be explained by the fact that the stage of hydride ion transfer is carried out only by intermolecular mechanism over NB and 4-nitrodiPhAm. These deviations have relatively low energy of activation, i.e. 98.04 and 121.32 kJ/mol respectively, and they are close to the value of experimentally found condensation energy of activation, i.e. E_a = 71.0 kJ/mol.

4. Summary

The results of this study confirm that the stage of hydride ion transfer from *p*-σ-complex to acceptor (nitrobenzene or 4-nitrodiPhAm) determines the rate of condensation of aniline with nitrobenzene over tetramethylammonium hydroxide. Intermolecular transfer mechanism, which has lower energy of activation, is more likely than intramolecular mechanism.

The catalyst is actively involved in the condensation of aniline with nitrobenzene. It activates initial reagents and intermediates and stabilizes products. It mechanism is the following: tetramethylammonium cation can form ionic and ion-dipole complexes with the reaction mixture components and can influence the distribution of electron density in reactants and their reactivity with its field.

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