ABSTRACT

of the dissertation submitted for the degree of Doctor of Philosophy (PhD) in the specialty «6D060600 – Chemistry»

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EPR spectroscopic and quantum-chemical study of the kinetics of fast protolytic reactions in non – aqueous solutions of acids and bases

General Description of the Work. The dissertation thesis is devoted to studying the mechanisms and kinetics of fast protolytic reactions occurring between organic acids and bases in non-aqueous solutions, utilizing EPR spectroscopy and quantum chemical modeling methods. Stable semiquinone radicals, specifically 3,6-di-tert-butyl-2-hydroxyphenoxyl, interacting with various organic acids and bases in a toluene medium, were used as model objects. These radicals served as spin probes for the highly sensitive evaluation of proton transfer and exchange rate constants.

Obtaining experimental and theoretical data allows for a deeper understanding of intermolecular proton transfer mechanisms, including potential two-step processes accompanied by preliminary electron transfer. Alternative mechanistic pathways, such as hydrogen atom transfer (HAT) and proton-coupled electron transfer (PCET), were considered, with an emphasis on their applicability to non-aqueous acid-base systems.

Based on kinetic data obtained by the EPR method, calculations were performed using the Bell–Limbach model, which allowed for a quantitative description of proton exchange in the "acid–radical" system under non-aqueous organic environment conditions. This approach enabled a deeper characterization of charge and mass transfer processes, as well as the refinement of the energetic parameters of the reactions.

The work combines experimental and theoretical methods, including physicochemical analysis, quantum chemical modeling, and interpretation of spectroscopic data, making it a significant contribution to the development of the modern theory of proton transfer and acid-base interactions in organic systems.

Relevance of the Work. One of the main areas of physical chemistry is the study of protolytic reactions. This is of crucial importance for understanding the nature of acid-base interactions occurring in various non-aqueous media. The mechanisms of proton transfer and exchange in non-aqueous media remain insufficiently studied. Their characteristics depend on solvation effects, the dielectric permittivity of the medium, and the ability of the solvent to form hydrogen bonds as well as molecular and ionic complexes.

In non-aqueous media, protolytic reactions often proceed through short-lived intermediate states that are difficult to investigate using conventional methods. Modern experimental and theoretical approaches, namely dynamic EPR spectroscopy and density functional theory (DFT), provide unique opportunities for

an in-depth investigation of proton-transfer mechanisms and quantum tunneling effects in protolytic reactions involving stable radicals in anhydrous systems.

At present, one of the relevant areas of physicochemical analysis is the application of the Bell-Limbach model to the analysis of kinetic data on proton transfer. This approach provides deeper insight into the mechanisms of protolytic reactions, particularly by allowing the contribution of quantum tunneling effects to proton-transfer processes observed at low temperatures to be determined.

Aim of the Research. The aim of the dissertation thesis is to predict the mechanisms of fast intermolecular acid-base reactions in organic solvents, utilizing EPR spectroscopy and quantum chemical modeling methods.

Research Objectives:

- To develop a general mechanism of two-channel proton transfer and exchange involving semiquinone radicals;
- To upgrade the software for simulating dynamic EPR spectra to calculate the kinetics of protolytic reactions between acids/bases and 3,6-di-*tert*-butyl-2-oxyphenoxyl;
- To analyze kinetic data to evaluate quantum tunneling effects;
- To perform quantum chemical modeling of the mechanism and assess the reactivity of organic systems and their complexes.

Research Methods: The methods of this work involve the experimental and theoretical study of the kinetics and mechanisms of fast protolytic reactions between stable semiquinone radicals and organic acids and bases in non-aqueous media.

Experimental measurements were carried out in the Spectroscopy Laboratory of the Karaganda Buketov National Research University, which is equipped with RE-1306 radiospectrometer featuring temperature-control system, setups for vacuum purification, free radical generation, as well as equipment for the synthesis and storage of reagents. To simulate theoretical EPR spectra, a specialized computational program written in Fortran was applied, allowing for the numerical processing of experimental data, spectral line shape simulation, and calculation of the kinetic parameters of the reactions under study. Based on the kinetic data obtained via EPR spectroscopy, the contributions of quantum tunneling to proton transfer processes were calculated using the Bell–Limbach model.

For quantum chemical modeling, modern licensed software packages Gaussian 2016 (USA) and Firefly v.8.2.0 were utilized. Based on density functional theory (DFT) and multi-configuration correlation methods, the mechanisms of proton transfer were investigated, the energetic parameters of the reactions were calculated, and the characteristics of the electronic structure and the nature of intermediate states in the studied molecular systems were established.

Main Points to be Defended.

1. The dual protolytic nature of the stable semiquinone radical 3,6-di-tert-butyl-2-oxyphenoxyl has been confirmed. It is governed by ultrafast homolytic hydrogen atom transfer processes, which determine its ability to participate in both acidic and basic protolytic interactions.

2. A theoretical-kinetic approach for the analysis of time-dependent EPR signals of radical spin probes has been developed. It is based on a modified Bloch equation and implemented as a Fortran computational program, enabling quantitative description of the kinetics of fast protolytic processes in non-aqueous media.

3. The participation of proton quantum tunneling in fast protolytic reactions of dicarboxylic acids in toluene was demonstrated through analysis of experimental data within the Bell–Limbach model.

4. Quantum-chemical studies of "radical I – acid" systems using DFT and multiconfigurational correlation methods (MCSCF/CAS, XMCQDPT) allowed identification of proton transfer stages and showed that in 3,6-di-tert-butyl-2-oxyphenoxyl–acid systems, the hydrogen atom transfer (HAT) mechanism is predominantly realized.

Characteristics of the main research results:

1. The conducted comprehensive study confirmed the high efficiency of the dynamic EPR spectroscopy method for investigating fast protolytic reactions in non-aqueous media. The use of oxyphenoxyl radicals, specifically 3,6-di-*tert*-butyl-2-oxyphenoxyl (I), allowed for the detection of changes during proton exchange with high temporal resolution and the determination of kinetic reaction parameters.

2. For the first time, experimental data were obtained on the interaction of the stable radical I with a series of dicarboxylic acids of various structures in non-polar toluene medium. The characteristics of the proton-donor ability of these acids in non-aqueous conditions were established, demonstrating the high sensitivity of the EPR method to weak intermolecular interactions.

3. Theoretical modeling of double proton transfer (DPT) in radical–acid systems using DFT and the Bell–Limbach model showed that accounting for dispersion and correlation effects is essential for reliably reproducing experimental activation energies. The Hydrogen Atom Transfer (HAT) mechanism was confirmed as the primary pathway in such systems.

4. Calculations of potential energy profiles and reaction path analysis using the IRC method confirmed the symmetric nature of the intermolecular hydrogen bond and the absence of significant geometric rearrangements during DPT, aligning with the predictions of the Bell–Limbach model.

5. A quantum chemical investigation of the interactions between semiquinone radicals and aliphatic dicarboxylic acids revealed patterns of hydrogen bond weakening with increasing carbon chain length and the introduction of OH-groups or multiple bonds, as well as an increase in the energy barrier in more polarizing solvents.

6. Structural factors influencing dimerization energy were established: an increase in the number of methylene groups enhances hydrogen bonding, while unsaturation and electron-active substituents weaken it. Analysis of HOMO–LUMO energy gaps allowed for the assessment of the electronic stability of the investigated complexes.

7. DFT investigation of radical-substituted benzoic acids in complexes with radical I demonstrated qualitative agreement between the calculated and experimental data characterizing the reaction mechanism and the relative energetics of the studied systems. Accounting for the solvent effect using the PCM method allowed its influence to be evaluated without explicit modeling of toluene molecules; therefore, the calculated results are considered as a qualitative characterization of the processes. The distributions of spin density, charges, and dipole moments are consistent with the HAT mechanism.

8. The specialized Fortran program developed by the author for simulating dynamic EPR spectra demonstrated practical significance in calculating proton exchange rates and tautomeric transitions, expanding the analytical toolkit for protolytic processes in organic systems.

9. The results obtained significantly deepen the understanding of acid-base interaction mechanisms in non-aqueous media, confirm the universality and sensitivity of EPR spectroscopy as a method for studying radical chemistry, and open new prospects for the design of functional materials and catalysts based on the control of proton transfer.

Scientific Novelty of the Research. The work provides new results that are of decisive importance for understanding the theory of proton transfer in non-aqueous media, as well as for the methodology of utilizing EPR spectroscopy and quantum chemical modeling in studies of protonation processes:

- Analytical studies were carried out to analyze the mechanisms and kinetics of the reactivity of stable semiquinone radicals proceeding via a two-channel protonation mechanism;

- The mechanism of rapid proton transfer and exchange between the stable semiquinone radical 3,6-di-tert-butyl-2-oxyphenoxyl and various organic acids, including dicarboxylic and substituted benzoic acids, as well as a range of bases, was experimentally and theoretically demonstrated using EPR spectroscopy and quantum-chemical methods;

- A dedicated Fortran program was developed for simulating dynamic EPR spectra and calculating kinetic parameters of intermolecular proton transfer reactions and tautomeric transitions in radical systems;

- For the first time, calculations were performed within the Bell–Limbach model to determine the contribution of quantum tunneling effects in proton transfer processes;

- Using the Firefly-8.2.0 program, electron-adiabatic potential energy curves were constructed for the radical I–oxalic acid system. The calculations were carried out using the MCSCF method in a full active space and supplemented by energy correlation calculations using the XMCQDPT method;

- The potential energy profile of the double proton transfer reaction in 3,6-di-tert-butyl-2-oxyphenoxyl–dicarboxylic acid systems was calculated using the DFT method (B3LYP/6-31+G(d,p));

- Quantum-chemical calculations using the B3LYP method showed that the energy of intermolecular hydrogen bonds depends on the structure of dicarboxylic

acids. An increase in the number of methylene groups leads to an increase in dimerization energy, whereas double bonds and substituents have the opposite effect. The energy gap between frontier molecular orbitals increases with elongation of the carbon skeleton and decreases in unsaturated and substituted compounds;

- In the study of complex formation between a semiquinone radical and aliphatic dicarboxylic acids, a weakening of hydrogen bonds was observed along the homologous series, which is related to the structure of the acids. For example, in maleic acid systems, an increase in the polarizing ability of the solvent leads to an increase in activation parameters, indicating strengthening of the hydrogen bond in the complex;

- In the 3,6-di-tert-butyl-2-oxyphenoxyl–substituted benzoic acids system, density functional theory (DFT) was applied for the first time in a comprehensive approach combining TS, QST3, and IRC methods with PCM and CPCM solvent models. This allowed an accurate description of the influence of the reaction pathway and medium on proton transfer processes;

- In the radical I — o-NBA system, analysis of charge distribution, dipole moment, electrostatic potential, and spin density confirmed the hydrogen atom transfer (HAT) mechanism. The obtained results demonstrate the effectiveness of DFT modeling in studying proton exchange dynamics.

Significance of the Obtained Research Results.

The results obtained in the dissertation thesis possess significant scientific and practical value for the development of physical chemistry, chemical kinetics, radiospectroscopy, and quantum chemistry.

The scientific significance of the research is determined by the comprehensive experimental and theoretical study of the mechanisms of fast protolytic reactions in non-aqueous media involving stable semiquinone radicals. The obtained results expand fundamental conceptions regarding proton transfer processes, the regularities of acid-base interactions, and the role of quantum tunneling in liquid-phase protonation reactions. Based on the kinetic data from EPR spectroscopy and quantum chemical calculations, the characteristics of reaction courses in various non-aqueous solvents were established, and the energetic parameters and mechanisms of intermediate state formation were revealed.

The scientific and practical efficiency of the research lies in the possibility of utilizing the thoroughly studied 3,6-di-tert-butyl-2-hydroxyphenoxyl radical as a spin probe in analytical, physical, and organic chemistry. The developed approaches, including spectra simulation using specialized Fortran-based software, allow for the quantitative determination of the protonation rate constants of various acids and bases, as well as the prediction of the characteristics of acid-base interactions in non-aqueous environments.

The practical significance of the work is related to the potential application of the obtained results in developing new methods for studying the reactivity of organic and biologically active compounds, modeling natural and chemical-technological processes, and creating sensor systems and auxiliary materials sensitive to changes in the protonation medium. The acquired data can be utilized to predict the acid-base

properties of substances in non-aqueous solutions and to design new functional materials.

Alignment with the directions of science development or state programs:

The research direction corresponds to the specialized scientific field "Fundamental and applied research in mathematics, mechanics, astronomy, physics, chemistry, biology, computer science, and geography." This field is included in the priority direction "Intellectual Potential of the Country."

The personal contribution of the author consists in the direct execution of experimental work within the framework of the dissertation research, processing of the obtained results, their interpretation, and the formulation of scientific conclusions, as well as in the preparation of scientific articles and presentations for the publication of the research results. The works are published in the following scientific papers:

1. S.N. Nikolskiy, F.Zh. Abilkanova, Kurmanova, A.F., Rakhim R. R. Proton Exchange Between 3,6-Di-Tert-Butyl-2-Hydroxyphenoxyl and Dicarboxylic Acids Studied by Electron Spin Resonance Spectroscopy and Density Functional Theory Calculations // CHEMPHYSCHEM. – 2025. – Vol. 26(20). – P. e202500306. DOI: https://doi.org/10.1002/cphc.202500306. [IF (2025) = 2.2 (Q3)]. - Investigation of the kinetics, mechanism, and energetic characteristics of intermolecular proton exchange between 3,6-di-tert-butyl-2-hydroxyphenoxyl radical and dicarboxylic acids using dynamic EPR spectroscopy and quantum chemical calculations in a non-aqueous medium.

2. Kurmanova, A.F., Abilkanova, F.Zh., Pustolaikina, I.A., & Nikolskiy, S.N. (2023). DFT Study of Intermolecular Proton Exchange with Some Derivatives of Benzoic Acids. Eurasian Journal of Chemistry, 111(3), 143-151. https://doi.org/10.31489/2959-0663/3-23-14 - Theoretical investigation of the mechanism and dynamics of intermolecular proton transfer in complexes of substituted benzoic acids with the 3,6-di-tert-butyl-2-hydroxyphenoxyl radical utilizing density functional theory methods to establish the nature of proton exchange and determine the active reaction mechanism.

3. Kurmanova, A.F., Abilkanova, F.Zh., Rakhimzhanova, A.S., & Pustolaikina, I.A. (2022). DFT Study of Complexation Reactions Involving Dicarboxylic Acids: Hydrogen Bonds, Influence of Solvent Nature. Bulletin of the University of Karaganda – Chemistry, 106(2), 43-51. https://doi.org/10.31489/2022Ch2/2-22-21 - Quantum chemical investigation of the protolytic properties of several dicarboxylic acids, their capacity for dimerization and complexation with the 3,6-di-tert-butyl-2-hydroxyphenoxyl semiquinone radical, as well as the study of the influence of acid structure and solvent nature on the energetic and kinetic parameters of proton transfer reactions.

4. Stadnik, I.L., Abilkanova, F.Zh., Kudryavtseva, Ye.V., Nikolskiy, S.N., & Masalimov, A.S. (2022) ESR-Study of the Proton Exchange with Aliphatic Amino Acids in Toluene. Bulletin of the University of Karaganda – Chemistry, 106(2), 69-76. https://doi.org/10.31489/2022Ch2/2-22-15 - Investigation of the kinetics and energetic parameters of intermolecular proton exchange between the 3,6-di-tert-

butyl-2-hydroxyphenoxyl radical and aminocaproic acid isomers via dynamic EPR spectroscopy in a non-aqueous medium.

5. S.N. Nikolskiy, F.Zh.Abilkanova, A.S. Golovenko, I.A. Pustolaikina, A.S. Masalimov. Investigation of intermolecular proton exchange of 3,6-di-tert-butyl-2-oxyphenoxyl with N-phenylanthranilic acid by ESR spectroscopy method // Bulletin of the Karaganda University. Chemistry Series. – 2020. – Vol. 2(98). – P. 35-41. https://doi.org/DOI 10.31489/2020Ch2/35-41 - Investigation of the kinetics of intermolecular proton exchange between the 3,6-di-tert-butyl-2-hydroxyphenoxyl radical and N-phenylanthranilic acid by dynamic EPR spectroscopy combined with computer simulation of spectra to determine the kinetic and activation parameters of the reaction in a non-aqueous medium.

6. Nikolskiy S.N., Abilkanova F.Zh., Katbashev A.Ye., Masalimov A.S. Semiquinone-type spin probes: Materials of the International Scientific and Practical Conference "Science, Education, and Production under the Fourth Industrial Revolution", – Karaganda: KarSU Publishing House, 2018. - P. 494-497. - Investigation of the application possibilities of semiquinone-type spin probes for studying acid-base interactions and fast proton exchange processes by EPR spectroscopy.

7. Nikolskiy S.N., Katbashev A.Ye., Abilkanova F.Zh., Tur A.A., Masalimov A.S. Protolytic capacity of some amines: PROCEEDINGS of the International Scientific and Practical Conference "Integration of Science, Education, and Production – the Basis for Implementing the Plan of the Nation" (Saginov Readings No. 10) June 14-15, 2018. Part VII, - Karaganda: KSTU Publishing House, 2018. - P. 119-120. - Investigation of the protolytic capacity of certain amines and evaluation of their acid-base properties by EPR spectroscopy using a semiquinone spin probe.

8. Abai S. Masalimov, F.Zh. Abilkanova, Sergey N. Nikolskiy, Rakhim R. Rachimov. The mechanism of the fast protolytic acid-base reactions in solutions: XIth EFEPR Conference, 1-5 September 2019, Bratislava (Slovakia). – P. P46 URL: https://efepr2019.conference.fchpt.stuba.sk/book-high-res.pdf - Investigation of the mechanisms of fast protolytic acid-base reactions in solutions using EPR spectroscopy and quantum chemical analysis methods.

The main provisions of this dissertation work were presented in peer-reviewed journals recommended by the Committee for Quality Assurance in the Sphere of Science and Higher Education of the Republic of Kazakhstan, where 4 articles were published. As confirmation of the relevance of the ongoing research, 1 article was published in international peer-reviewed journals indexed in the Web of Science and Scopus databases. Additionally, 3 abstracts were co-authored, published at international conferences in both near and far abroad, based on the results of the dissertation objectives.