Computer Simulations in Condensed Phases: from Basic Principles to Applications

Summary of the main results

The year-to-year summaries of the results were collected in the period closing reports. Here, instead of repeating the same summaries, we give a collection of the results topic by topic.

1. Condensed Phase Molecular Dynamics Simulations

In the first project we planned to investigate different interaction potentials for alkali and halide ions. This work is part of the first major area of the original proposal, the development of new, efficient alkali-halide potentials. Here we started examining alkali halide force fields, searching for reasonable and acceptable compromises in terms of the form of the potential vs. the ability of the model to reproduce available experimental data. In particular, we investigated the role of polarization in pure states (melting temperatures, density of melts, internal energy and density of crystals) and in aqueous solutions (coordination). We found that while in the first case polarization as a result of the symmetric or almost symmetric environment is less important, in the second case, especially for very polarizable anions, the polarization plays a crucial role. We also found that for certain properties the polarization of the ions is a useless extra cost of the calculation without noticeable benefit of accuracy but for other systems the polarization plays an important role whatever the reality of the merely dipolar interaction. If one studies aqueous solutions of these ions, neglect of polarization leads to incorrect results. To devise more realistic ion potentials multi-polar polarization or some clever and cheaper technique should be used. A search for a simplified method which goes beyond the dipolar polarization must be welcomed. Nevertheless, we experience reluctance in the scientific community to move away from the point charges and Lennard-Jones nonpolarizable models. Despite knowing shortcomings of these models, most importantly the low dielectric constant, their simplicity and presence in pre-coded packages rules out the 5–8 times slower but more realistic model. For instance, it has been shown that the triplet and quadruplet water clusters for SPC, SPC/E and TIP3P charge distribution, contrary to measurements and quantum chemical calculations, are fully planar. This planar character prevails in ambient water because these models contain much more planar triplet arrangements than models with TIP4P geometry. The manuscript on this subject was published in the Journal of Molecular Liquids in 2020.

In the second study of the development of new, efficient alkali-halide potentials, we found the following: Alkali and halide ions are seemingly simple chemical particles: spheres with plus or minus charges of 1 esu. There is, however, a large set of properties impossible to predict by this simple model. Molecular simulation is a suitable tool to test the performance of different models trying to grasp numerous features of these ions in solid, liquid, or gas phases, in pure state or solvated. While the internal energy and density of the crystal and the melt can be estimated by different models with acceptable accuracy, the melting temperature is a more elusive property being highly sensitive to fine details of the interactions. In this work we devised a set of potentials where the fit is carried out for the internal energy and density of ambient crystals with accurate melting temperatures. The ions have non-polarizable Gaussian charges with r-6 attraction and exponential repulsion. We presented the results and discussed the difficulties of the process in our paper that was published in the Journal of Molecular Liquids in 2021.

In the next study we try to re-establish the pairwise combination of repulsions fulfilling the requirement of accurate energy, density and melting temperature. We applied a simpler combination rule for an exponential function, square root both of the pre-exponentials and the arguments. The repulsion of cations was fixed for all combinations. The size difference of cations did not allow covering the entire set with identical anion parameter values. We could create two separate groups were the anion repulsion was also constant. The sodium–potassium and the rubidium-cesium pairs used the same anion parameters. Exceptions are fluorides, we had to use individual anion parameters for K+, Rb+, and Cs+. For lithium the fluoride used the same parameters as in the case of sodium. For other anions of Li+, however, they had to use different anion parameters from that of Na+. While fluoride deficiency can be attributed to the inadequacy of the form of functions applied, problems of the lithium halides, namely, the nonadditive character of their radii for large anions, is physical. We describe the fitting process and present the results. We presented the results and discussed the difficulties of the process in our paper that was published in the Journal of Molecular Liquids in 2022.

In the last study of the series, the self-diffusion coefficient of water in aqueous solutions of alkali halides at different concentrations was studied using the polarizable BK3 model of water. As ion potentials, initially the alkali halide force field fitted to this water potential by the solvation free energy, ion-water clusters as well as, for the purpose of crosschecking, to the ambient crystal energy and density were investigated. It was found that the strength of attraction between the central ion and the water molecules in the hydration shell is stronger than in reality, which manifests itself in the reduced mobility of water. For small ions, this discrepancy is small. By omitting the dipolar polarization of larger ions, the estimates could be improved. Similarly, increasing the size of the anions within reasonable limits also enhances the results but the structural breaking effect is insufficient. If the relative permittivity of water is smaller than that measured experimentally, typically ionic charges in non-polarizable water models can be decreased to recover the correct semi-macroscopic Coulomb energy. Since our polarizable water model reasonably estimates the relative permittivity, smaller ionic charges were used to quantify the differences in the strengths of ion-water attraction. Our estimates of self-diffusion in aqueous solutions by varying the concentration of ions are presented and discussed for LiCl, NaCl, NaBr, NaI, RbF and RbI. We published these results in the Hungarian Journal of Industry and Chemistry in 2023.

We also had a loosely related liquid simulation study that were connected to the development of potentials. This study concerns bulk condensed phase simulations with the final goal of extending the investigations to anisotropic environments, such as interfaces. Here, instead of performing purely classical simulations, we performed ab initio molecular dynamics simulations of neat water, and studied the effects of an asymmetric environment on the electronic properties of a water molecule in liquid water. The analysis was based on ab initio molecular dynamics simulations of liquid water at 300 and 350 K using the BLYP-D3 functional. We made the following observations. (1) The electronic density of states (DOS) and the net molecular charge are more affected by the asymmetry of the water molecule's H-bond surroundings than by the number of H-bonded neighbors. The reverse is true for the dipole moment. (2) For all three properties, a 3-coordinated water molecule is more perturbed by accepting two H-bonds and donating one than by donating two and accepting one. (3) This order is not maintained in the calculated XES spectrum, which is less straightforward to interpret in terms of structure-property relationships than the DOS spectrum. Our manuscript on this problem was published in the Journal of Molecular Liquids in 2020.

2. Quantum Molecular Dynamics Simulations of Charge Transfer Processes

The second part of the proposal focuses on quantum molecular dynamics simulations of charge transfer processes in molecular clusters. Here, we successfully finished two projects that investigate excess electrons in methanol and ammonia clusters. These studies are strongly connected to the previous NKFIH grant of the principal investigator. We performed a series of ab initio molecular dynamics simulations to investigate the physical properties of small methanol cluster anions, $[(CH_3OH)_n]^-$, (n = 8 – 32). The excess electron was attached to neutral clusters that were prepared to accommodate the electron in interior cavity states or surface bound states. The computed initial binding energies of the electrons to these clusters indicate appealing similarity to the experimentally observed vertical detachment energies. The tendency of the interior state clusters parallels that of the clusters with strong electron binding in the experiments, while the simulated unrelaxed surface state anions are similar to the observed weakly bound species. This assignment is consistent with a previous identification based on hybrid quantum-classical simulations. The time evolution of the cluster anions suggest that interior state electrons slowly move to and relax on the surface, in excess electronic states that appear significantly more stable than the experimentally assigned putative surface states. Based on this result we predict the existence of relaxed surface state isomers of small methanol cluster anions. Our manuscript on this problem was published in the Physical Chemistry Chemical Physics in 2018.

Next, we assessed the stability of various size $(\mathrm{NH_3})_n^-$ ammonia cluster anions up to n = 32 monomers using a combination of quantum chemical calculations and molecular dynamics simulations. We found that the smallest clusters (n = 3 – 8) bind the electron in non-branched hydrogen bonding chains in dipole bound states. The VDE increases with size from a few meV up to ~200 meV. We located the first branched hydrogen bonding cluster that binds the excess electron at n = 7. For larger (n = 8 – 32) clusters we generated cold, neutral clusters by semiempirical and ab initio molecular dynamics (AIMD) simulations, and added an extra electron to selected neutral configurations. VDE calculations on the adiabatic and the relaxed anionic structures suggest that the n = 12 - 32 neutral clusters weakly bind the excess electron. Electron binding energies for these clusters (~ 100 meV) appear to be significantly weaker than extrapolated from experimental data. The observed excess electron states are diffuse and localized outside the molecular frame (surface states) with minor (~1%) penetration to the nitrogen frontier orbitals. Stable minima with excess electron states surrounded by solvent molecules (cavity states) were not found in this size regime. A conference talk on the solvated electron cluster project was given at 12th European Conference on Computational and Theoretical Chemistry (EUCO-CTC 2019). Our manuscript on the physical properties of small ammonia cluster anions was published in the Journal of Chemical Physics in 2019.

In another, related work, we investigated excess electron solvation dynamics in $(\mathrm{NH_3})_n^-$ ammonia clusters in the n = 8 – 32 size range by performing finite temperature molecular dynamics simulations. In particular, we focused on three possible scenarios. The first case is designed to model electron attachment to small neutral ammonia clusters ($n \leq$ ~10) that form hydrogen bonded chains. The excess electron is bound to the clusters via dipole bound states, and persists with a VDE of ~160 meV at 100 K for the n = 8 cluster. The coupled nuclear and electronic relaxation is fast (within ~100 fs), and takes place predominantly by intermolecular librational motions and the intramolecular umbrella mode. The second scenario illustrates the mechanism of excess electron attachment to compact, cold, neutral clusters of medium size ($8 \leq n \leq 32$). The neutral clusters show increasing tendency with size to bind the excess electron on the surface of the clusters in weakly bound, diffuse, highly delocalized states. Anionic relaxation trajectories launched from these initial states provide no indication for excess electron stabilization for sizes $n < 24$. Excess electrons are likely to autodetach from these clusters. The two largest investigated clusters ($n = 24, 32$) can accommodate the excess electron in electronic states that are mainly localized on the surface, but may be partly embedded in the cluster. In the last 500 fs of the simulated trajectories the VDE of the solvated electron fluctuates around ~200 meV for $n = 24$, and ~500 meV for $n = 32$, consistent with the values extrapolated from the experimentally observed linear VDE – $n^{-1/3}$ trend. In the third case, we prepared neutral ammonia cluster configurations, including an $n = 48$ cluster, that contain possible electron localization sites within the interior of the cluster. Excess electrons added to these clusters localize in cavities with high VDEs up to 1.9 eV for $n = 48$. The computed VDE values are considerably higher than the experimentally observed photoelectric threshold energy for the solvated electron in bulk ammonia (~1.4 eV). Molecular dynamics simulations launched from these initial cavity states strongly indicate, however, that these cavity structures exist only for ~200 fs. During the relaxation the electron leaves the cavity and becomes delocalized, while the cluster loses its initial compactness. Our manuscript on the quantum molecular dynamics simulations of small ammonia cluster anions was published in the Journal of Physical Chemistry B in 2020.

At this point we had several failed, semi-failed and stalled projects. For example, we started quantum molecular dynamics simulations of bulk ammoniated electrons. This work is a natural extension of our previous work on ammoniated electron clusters. Recently we have performed the initial steps of the simulation by creating initial configurations for the simulations. In these steps, $n = 33$, and $n = 65$ ammonia molecules were placed in a cubic simulation box and preliminary, long (~ ns timescale) classical molecular dynamics simulations were performed to generate models of the bulk liquid. These trajectories are further propagated by DFT based quantum molecular dynamics simulations at ~250 K temperature. We then remove a single ammonia molecule from the center of the simulation box, and add an extra electron to the system. These simulations would model the bulk ammoniated electron. But we have had a longstanding, serious problems with the bulk structure of the ammonia. In our simulations we were unable to generate liquid like structures, the ammonia would tend to crystallize at all physically meaningful temperatures. We still do not understand the reason for this failure. In addition, the simulation of the negatively charged system proved to be too costly for the more realistic bulk model we considered consisting $n = 64$ ammonia molecules and an extra electron. This part of the project has also been stalled due to hardware limitations. We, however, decided that we will finish the project even if it will be clearly after the end of the present proposal. Now we are restarting our efforts to have our simulations performed on the new Debrecen supercomputer (Komondor) that has been operational since the Fall of 2023.

We similarly failed to develop a new one electron-based electron – water molecules pseudopotential based on high level quantum chemistry calculations on various size water cluster anion configurations. The original plan was to develop the pseudopotential in association with the polarizable BK3 water model. Here, successive and time-consuming iterations of the potential fitting and quantum chemistry calculations did not result in converging the vertical detachment energy of the hydrated electron and, in general, better description of the hydrated electron system.

Due to these latest failures on the solvated electron field, we extended our quantum molecular dynamics simulations for proton transfer processes. Using Path Integral Molecular Dynamics simulations, we examined isomerization paths involving collective proton transfers in $[H_2O]_5$ and $[H_2O]_8$ clusters at cryogenic conditions. The computer simulation results presented in this paper provide new insights about combined effects from solvation and nuclear quantum fluctuations on the mechanisms that drive collective proton transfers in small water clusters. In particular, we focused attention on the characteristics of free energy barriers and relative stabilities of reactants and products. In the exchange of donor-acceptor hydrogen bond roles along cyclic moieties, the explicit incorporation of quantum tunneling introduces important modifications in the classical free energy profile, corresponding to compressions of O-O distances and to nuclear tunneling of the light protons. Solvation effects promote a moderate polarization of the cyclic structures and a partial loss of concertedness in the collective modes, most notably, at the onset of tunneling. Still, the latter effects are also sufficiently strong to promote the stabilization of ion pairs along classical trajectories. Contrasting, the explicit incorporation of nuclear quantum fluctuations bring charge separation, leading to stable $[H_3O]^+[OH]^-$ ion pairs, marginally stable. As such, the latter states could be also regarded as short-lived intermediate states along the exchange reactive path. Our manuscript on the quantum molecular dynamics simulations of small protonated water clusters was published in the Journal of Physical Chemistry B in 2020.

After a two-year-delay, we continued the proton transfer project investigating the proton transfer dynamics in the protonated methanol-water system. Here, we dramatically changed our concept of developing the necessary potential energy surface. The investigated potential energy surface is now based on neural network potentials. This change of the approach has taken significant amount of time due to learning the technique, and, in particular, experimenting with and developing the method of training set generation, training of the neural network, and applying the developed potential in actual molecular dynamics simulations. But now we are ready to show using a sophisticated, combined, neural network-based umbrella sampling molecular dynamics that the proton protonates the methanol molecule if only one water molecule is present in the complex, but the interaction of a methanol with a hydrogen bonded water dimer changes the free energy surface significantly, leading to the stabilization of the excess proton basically at the midpoint of the interacting water and methanol molecules. This work is very near completion, and we plan to submit our manuscript on the problem within a few weeks.

We also mention that we started a new project in 2023 on proton transfer processes modeling the proton transfer in the protonated water-glycine system.

The success of the application of neural network potential redirected our attention to the hydrated and ammoniated electron problem. After experimenting extensively with neural networks, we now seem to be able to generate reliable neural network potentials for the ammoniated electron and for the hydrated electron, as well. Although this change of the approach has taken significant amount of time, we now believe that we can successfully tackle our previously failed projects above. In fact, these two projects are under way, simulating molecular dynamics of ammoniated electron and hydrated electron clusters based on neural network potentials. We predict that at least one paper of these two projects is expected for publication is 2024.

We also made significant progress in a project that we started in 2022 and examined the effect of quantization on classical molecular dynamics trajectories by the method developed by Madarász and his co-workers. Here, we investigated the effect of trajectory quantization on the computed absorption spectrum of water cluster anions and the bulk hydrated electron. Our results strongly suggest a slight shift of the maximum of the absorption bands with a significant broadening upon quantization. The quantum corrections nicely improve the agreement of the classical simulations with experimental data. The manuscript of these latest results has been completed and we submitted it for publication in the Journal of Chemical Theory and Computation.

3. Large Biomolecules in Complex Condensed Phase Environment: Photosynthetic Systems

As a significant change relative to the original research plan, we turned our attention toward the simulations of photosynthetic systems. This project basically trivially fits in the original ideas and directions of the proposal, in that here we attempt to investigate a biologically important system embedded in a complex condensed phase environment. But instead of using classical density functional theory to describe the environment surrounding the chemically relevant, and quantum mechanically (QM) treated chlorophyll molecules, we applied classical atomistic (MM) description of the bath.

As a preliminary study, we have already performed a theoretical investigation on the dynamics of the distribution of the excitation energies of chlorophylls (Chls) in the CP29 complex of spinach and the effect of the surrounding such as protein molecules, carotenoids and water molecules. The spectral calculations have been performed with a reasonable quantum chemical method (B3LYP/def2-TZVP) using the TD-DFT method, while various dynamical calculations have been done using a combination of QM, MM and QM/MM techniques. Figure 1 illustrates the complexity of the investigated system.

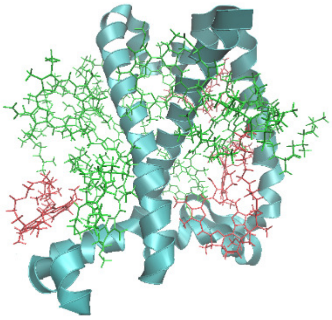

Figure 1 Protein-pigment complex of CP29 in spinach without showing carotenoid molecules and thylakoid membrane, red and green colour represent Chl-b and Chl-a respectively.

We have drawn several clear conclusions from this study. First of all, we found that in a given configuration the excitation energies of the individual chlorophylls were found to be to a reasonably good approximation independent of the presence of the surrounding biomolecules. Nevertheless, the energy gaps fluctuate significantly during the dynamics, since they strongly depend on the instantaneous structure of the pigments. These structures, in turn, are determined by the fluctuating environment. The two effects, that of the static and dynamic interactions with the environment should be evaluated and carefully analyzed. We also performed preliminary calculations on the absorption spectrum of the CP29 complex, a characteristic signature of the light absorption step in photosynthesis. We anticipate that the dominant spectral features originating from multiple pigments can be understood in terms of the contributions from the individual chlorophyll molecules, a reasonable basic approximation we plan to use in our future studies. In addition, by analyzing the electron distributions of the molecular orbitals and identifying the pigment molecules that are involved in the excitation, we were able to map the order of the chlorophyll molecules that are excited as one increases the energy of the incident radiation. In principle, if we sample the dynamics of the complex (and its pigments) and compute the necessary physical quantities (i.e. oscillator strengths), we may be able to predict which pigment (or pigments) absorb the photon initially, and how the whole process of excitation energy transfer begins.

Motivated by these preliminary results we would like to extend our investigations to all basic aspects of the initial events of photosynthesis, focusing on the operation of the antenna part, the operation of the reaction center and the coupling between these subunits. These processes include basic photochemical absorption of photons, energy transfer processes, energy relaxation mechanisms, and electron and, in general, charge transfer processes.

We are optimistic about our presently available results and their publication in the near future.

4. Chemometry

As another significant change relative to the original research plan, we also turned our attention toward chemometry. Although this project does not trivially fit in the original ideas and directions of the proposal, we made significant efforts in this direction, as well. These investigations became a natural part of our efforts to understand fundamental questions of modelling that are in the very heart of the present project. Especially, since we turned our attention to machine learning techniques, identification of interpretable models by evaluating clusters of data, and, in particular, hidden layer neutrons became an unavoidable scientific challenge. In fact, the following studies are loosely connected to all three major areas of our original proposal. First, we investigated the allocation dependence of validation and design of experiment optimality parameters by modifying the pattern of the independent variables. They were scanned from a center-like to corner-like positions and fixed design of experiment settings were checked, too. The response variable was modelled with multivariate linear regression. The calculations were performed on simulated data in two and 4-dimensional independent variable spaces and on datasets of power plant and QSAR studies. Our results showed that almost all parameters evaluating validation or design of experiment optimality could be tuned by intentionally increasing the number of samples taken close to the edges of the variable domain. We got strong rank correlation among most of the parameters. It coincides well with the primary aim of design of experiment to obtain validatable models, where design of experiment is performed before the model building, or even before the experiments, and validation takes place after the model building. Our manuscript on this problem was published in Chemometrics and Intelligent Laboratory System in 2020.

In our second chemometric study, we still focus on model validation. Previously we calculated the sample size dependence of different validation models using a few datasets. To get well justified results, we extended the number of the datasets up to 13. The results have been published in fit of multivariate linear curves. We observed that R2 and related internal parameters were misleading as they overestimated the goodness-of-fit of models at small sample size. Cross-validation metrics showed correct trends. It was possible to scale the leave-one-out and the leave-many-out results close to identical by correcting the degrees of freedom of the models. y and x-randomized validation parameters were calculated and the methods provided close to identical results. We suggest to use the simplest methods in both cases. The external parameters followed correct trends with respect to the sample size, but their sensitivity differed. We plotted the Roy-Ojha metrics in 2D and we colored them with respect to other external parameters to provide an easy classification of models. The rank correlations were calculated between the performance parameters. Up to a sample size goodness-of-fit and robustness were distinguishable, but above a certain sample size the parameters were redundant. The external-internal pairs were weakly correlated. Our data show that all the three aspects of validation are necessary at small sample sizes, but the internal check of robustness is not informative above a given sample size. Our paper on this problem was published in SAR and QSAR in Environmental Research in 2021.

In our next study we investigated the relevance of the validation principles on the Quantitative Structure Activity Relationship models issued by Organization for Economic and Co-operation and Development. We checked the goodness-of-fit, robustness and predictivity categories in linear and nonlinear models using benchmark datasets. Most of our conclusions are drawn using the sample size dependence of the different validation parameters. We found that the goodness-of-fit parameters misleadingly overestimate the models on small samples. In the case of neural network and support vector models, the feasibility of the goodness-of-fit parameters often might be questioned. We propose to use the simplest y-scrambling method to estimate chance correlation. We found that the leave-one-out and leave-many-out cross-validation parameters can be rescaled to each other in all models and the computationally feasible method should be chosen depending on the model type. We assessed the interdependence of the validation parameters by calculating their rank correlations. Goodness of fit and robustness correlate quite well over a sample size for linear models and one of the approaches might be redundant. In the rank correlation between internal and external validation parameters, we found that the assignment of good and bad modellable data to the training or the test causes negative correlations. We published these results in Molecular Informatics in 2021.

Next, we developed a new seriation merit function for enhancing the visual information of data matrices. A local similarity matrix is calculated, where the average similarity of neighboring objects is calculated in a limited variable space and a global function is constructed to maximize the local similarities and cluster them into patches by simple row and column ordering. The method identifies data clusters in a powerful way, if the similarity of objects is caused by some variables and these variables differ for the distinct clusters. The method can be used in the presence of missing data and also on more than two-dimensional data arrays. We show the feasibility of the method on different data sets: on QSAR, chemical, material science, food science, cheminformatics and environmental data in two- and three-dimensional cases. The method can be used during the development and the interpretation of artificial neural network models by seriating different features of the models. It helps to identify interpretable models by elucidating clusters of objects, variables and hidden layer neurons. We published these results in the Journal of Cheminformatics, a D1 category journal in 2023.

The last of our efforts in the field of chemometry resulted in one more publication in 2023. The validation principles on Quantitative Structure Activity Relationship issued by Organization for Economic and Co-operation and Development describe three criteria of model assessment: goodness of fit, robustness and prediction. In the case of robustness, two ways are possible as internal validation: bootstrap and cross-validation. We compared these validation metrics by checking their sample size dependence, rank correlations to other metrics and uncertainty. We used modelling methods from multivariate linear regression to artificial neural network on 14 open access datasets. We found that the metrics provide similar sample size dependence and correlation to other validation parameters. The individual uncertainty originating from the calculation recipes of the metrics is much smaller for both ways than the part caused by the selection of the training set or the training/test split. We concluded that the metrics of the two techniques are interchangeable, but the interpretation of cross-validation parameters is easier according to their similar range to goodness-of-fit and prediction metrics. Furthermore, the variance originating from the random elements of the calculation of cross-validation metrics is slightly smaller than those of bootstrap ones, if equal calculation load is applied. We published these results in the Journal of Chemometry in 2023.

Differences Relative to the Original Workplan

We experienced several differences relative to the original workplan. For these deviations there are two major reasons. 1) It is very difficult to predict the change in research interest and tendencies in advance for years at the time of the preparation of the proposal. 2) Unexpected events can occur with the participants during the execution of the proposal that can significantly modify the outcome of the project. Both factors influenced the execution of the present project, but while the first factor is natural, the second one needs more explanation. This comes next:

Of the classical simulations, the development of alkali halide potentials and their application in liquid simulations were more-or-less in accord with the original plans.

One minor area that we completely left out was the examination of water evaporation. By the end of the first year of the project it turned out that the responsible participant, Prof. G. Tóth, already lost interest in the research area, mainly because of the latest developments on the field. Nevertheless, discussing the issue, he offered several chemometric topics that can be related to model development and assessment, and may have relevance to the original workplan. We then decided to pursue this direction, which turned out to be a successful part of the project, resulting several papers, among them one D1 publication. All in all, we think, this was a fortunate and useful change, and we hope that the reviewers of the final report will agree and endorse this direction.

Of the quantum molecular dynamics field the greatest hiatus is the development of interaction models between quantum mechanically described solutes in an environment modeled by classical density functional theory. Although we had several attempts to start this part of the project, we, at the end, decided not pursue it for several reasons. First of all, Prof. Borgis, with whom we devised this part of the project, retired and our research connections got loosened. Secondly, we had very many other pressing issues in other fields which required more attention from the part of the PI. Nevertheless, to correct this issue, we started a new project, which was not explicitly included in the original plan, examination of photosynthetic systems. The photosynthetic system is a truly biochemical system, where the key part of the examination is the choice of the computational methods. Here, separation of the quantum mechanical part and the environment is necessary, similarly to our original plans, but here the environment was treated at the classical molecular mechanics level. All in all, in the last two years of the project, we launched investigations into biochemically relevant directions, but instead of doing it using quantum mechanics combined with classical density functional theory, we approached the problem at QM/MM level.

Although we invested huge efforts in the quantum molecular dynamics description of the solvated electron systems, we have not completed several important studies. Such are the development of an electron-water molecule pseudopotential, the free energy curve of an electron transfer from the surface of water cluster anions to the interior of the cluster, and bulk ammoniated electron simulations. These all turned out to be very difficult problems that needed serious reconsiderations. Based on these re-planning we decided to approach the solvated electron problems differently, using neural network potentials, which is turn again requires significant investment of time. We are presently working on the solution of these problems, and the first results are promising. We also mention that we have not given up the development of a one-electron pseudopotential, but now we plan to approach the problem from the direction of neural networks.

In addition, we started investigations in the area of proton transfer processes using path integral molecular dynamics simulations. The results of one of these projects were published, those of the other one is near completion.

Changes in the Personnel of the Project and Changes in FTEs

The participants significantly changed during the grant period. The associated FTEs have also significantly changed. Here I will list all the changes in the participating personnel, and, in a separate electronic letter too, I will describe in detail the changes in the FTEs.

Three colleagues participated in the project who were not listed initially in the funding contract. They are Bence Baranyi, Attila László Tajti and Zahra Tohidi Nafe. For all of them I asked and received a permission from NKFIH to connect them to the project.

The international collaboration with Professor Daniel Borgis, the collaboration we planned for the development of a combined theory of classical and quantum mechanical density functional theory, proved to be inefficient mainly due to the retirement of Professor Borgis.

For Professors Imre Bakó and Professor Daniel Hector Laria, the FTEs changed by a lot during the project which I also intend to fix in the present final report. Professor Bakó participated in the project only in the first year (2018/2019), with an FTE of 0.25, but afterwards his FTE contribution became negligible, practically 0.0. Professor Laria participated in the project in the first two years (2018/2019, 2019/2020) with FTEs of 0.8, but for the next two years (2020/2021, 2021/2022), during the pandemic era, his FTE contribution became 0.0, but in the last year (2022/2023) it jumped up back to 0.8 again. All in all, it means that the sum of the FTEs should be reduced for Prof. Bakó from the sum of 1.31 to 0.25, and for Prof. Laria from 3.80 to 2.20. Thus, the sum of FTEs should be reduced from the original of 15.36 to 12.70. We were informed that technically it is not possible to correct the FTE values after the completion of the project in the NKFIH EPR system. The PI should have requested the changes right after the affected periods, but unfortunately the PI unwillingly failed to do so. Nonetheless, we decided to state the correct numbers here for the record.

Summary of the Research Project

All in all, in the four years project period and in the one extra extension year, we published fourteen publications. The publication output is not great, but, in our opinion, satisfactory and (despite the pandemic situation) still consistent with our original plan and expectation of 12-16 quality papers for the full length of the proposal. We also published several other types of publications, abstracts, posters and conference lectures. Despite the difficulties at personal level, at pandemic level and at professional level, we are now certain that we finish the project relatively successfully. In addition, we will definitely publish at least three more publications on the topics of the proposal after the end of the project. We would like to have the opportunity, actually we already requested it, to attach these publications to the results of the present proposal that come out within one year from the end of the proposal.