Development of Quantum Mechanics/Molecular Mechanics Method combined with Resolution-Adapted and Neural Network Models

Lin SHEN

Key Laboratory of Theoretical and Computational Photochemistry, Ministry of Education,

College of Chemistry, Beijing Normal University, Beijing 100875, P. R. China

Email: lshen@bnu.edu.cn

Abstract:
Because of the significant change in electronic structures of complex systems with a large number of degrees of freedom, the combined quantum mechanical and molecular mechanical (QM/MM) method is an accurate and computationally efficient tool toward QM descriptions on realistic chemical reactions. Based on the potential energy calculations, direct molecular dynamics (MD) simulation using QM/MM model is very powerful for studying the mechanism of reactions in a complex environment but also very time-consuming. The research in the field of QM/MM MD by now still faces many challenges, such as the slow sampling for the MM subsystem and the demanding cost on the QM subsystem. To address the first issue, we developed a resolution-adapted method that spans three levels of resolution as quantum mechanical, all-atomic (AA) and coarse-grained (CG) models [1,2]. The resolution-adapted AA+CG force field for water, in which the interactions between two water molecules are adjusted automatically according to their distance while an all-atom structural description of the entire system is maintained during MD sampling, is applied to QM/MM approach to calculate redox potentials of aqueous metal complexes. The improvements on accuracy and efficiency highlight the importance of a sophisticated MM model. To address the second issue, we developed a neural network (NN) method for ab initio QM/MM MD simulations [3,4]. Using machine learning techniques, the QM/MM potential energy of any configuration for a given reaction system in a complex environment is predicted at the ab initio level based on semiempirical QM/MM MD sampling, and the saving in computational cost is about two orders of magnitude. Combined with an adaptive procedure for NN models, direct MD simulation on the NN-predicted potential energy surface is implemented to approximate ab initio QM/MM MD. The free energy profiles can be reproduced at the ab initio QM/MM accuracy yet at the computational cost as small as the semiempirical QM/MM models. We also discuss the possibility to extend our new methods to excited state QM/MM calculation and nonadiabatic MD simulation in order to study a broad range of problems in photochemistry.

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