Electron nuclear dynamics simulations of ion cancer therapy reactions

Juan C. Dominguez, Jorge A. Morales

Department of Chemistry and Biochemistry, Texas Tech University, Lubbock, Texas, 79409, USA

Ion cancer therapy (ICT) is an approved medical treatment that obliterates cancerous tumors with beams of high-energy ions (usually, H^+ and C^{6+}ions) [1]. Despite its established clinical use, the reaction mechanisms that underlie ICT are not known in full detail [1]. This limited understanding results from the difficulty to conduct clinical experiments without harming human subjects. To fill this gap in the ICT characterization, we are conducting computer simulations of several ICT reactions with the electron nuclear dynamics (END) method [2]. END is a time-dependent, variational, direct, and non-adiabatic approach to simulate various types of chemical reactions [1,2]. To make ICT simulations computationally feasible, we employ the simplest level (SL) version of END (SLEND) that describes the nuclei in terms of classical mechanics and the electrons with a single-determinantal wavefunction in the Thouless representation [2]. SLEND is implemented in our high-performance package PACE [2] that incorporates advanced computer science techniques (e.g., mixed programming language: C++/Fortran for numerical calculations and Python for logic flow). Here, we present various SLEND simulations of ion-molecule reactions that are computationally feasible prototypes for water radiolysis and DNA damage in ICT. These simulations involve both H^+ and C^{6+} ions and several target molecules: C_2H_4 [3], H_2O [4], C_2H_2, uracil, and cytidine. Our SLEND simulations predict various reactive process (e.g., projectile scattering, atom substitutions, target fragmentations, and target-to-projectile electron transfers) and dynamical properties (e.g., integral and differential cross sections) in good agreement with experimental data. In these studies, we also utilize a novel computational procedure to induce time-dependent symmetry breaking during simulations [3,4]. Essentially, we introduce a small symmetry breaking into the initial Hartree-Fock state of the reactants; this initial perturbation transforms into a full-blown symmetry breaking by the time of the reactants' collision. Electron-transfer properties from symmetry-breaking simulations compare better with available experimental data [3,4].

References

[1] E. Teixeira, K. Uppulury, A. Privett, C. Stopera, P. McLaurin and J. Morales, "Electron Nuclear Dynamics Simulations of Proton Caner Therapy Reactions: Water Radiolysis and Proton-and Electron-Induced DNA Damaga in Computational Prototypes," *Cancers,* vol. 10, no. 136, 2018.

[2] C. Stopera, T. V. Grimes, P. M. McLaurin, A. Privett and J. A. Morales, "Some Recent Developments in the Simplest-Level Electron Nuclear Dynamics Method: Theory, Code Implementation and Applications to Chemical Dynamics," in *Advances in Quantum Chemistry*, vol. 66, 2013, pp. 113-194.

[3] P. McLaurin, J. C. Dominguez, R. Merritt, E. Teixeira and J. A. Morales, "Symmetry-Breaking Effects on Time-Dependent Dynamics: Correct Differential Cross Section and Other Properties in H+ + C2H4 at ELab = 30 eV," *Physical Chemistry Chemical Physics,* no. 21:5006, pp. 5006-5021, 2019.

[4] J. C. Dominguez, H. Kim, E. D. Silva, D. Pimbi and J. A. Morales, Electron nuclear dynamics of time- dependent symmetry breaking in H+ + H2O at ELab = 28.5-200.0 eV: a prototype for ion cancer therapy reactions,
Accepted for publication in Physical Chemistry Chemical Physics, 2022.