

Title

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Abstract

1 Introduction

First synthesized in 2004¹¹, graphene has since experienced an explosive growth in interest¹⁴. For pristine graphene, its interactions with other particles are mainly due to Van der Waals forces and $\pi - \pi$ stacking.²² As pristine graphene is chemically inert⁶ a classical description of it is expected to suffice in simulations. Multiple molecular dynamics studies on the interactions between proteins and carbon based nanoparticles (CBNs)—such as graphene—have been published^{1,4,5,7,8,10,13,19,21,22}

2 Methods

2.1 Free Energy Methods

The Helmholtz free energy of adsorption of an amino acid onto a graphene layer (ΔA_{ads}) can be obtained from the difference in free energy of the Adsorbed and Free states:

$$\Delta A^{ads} = A^{near} - A^{free} \quad (1)$$

Where the near and free states are defined based on the distance between the graphene layer and the α -carbon of the amino acid projected onto a vector normal to the graphene layer. For a graphene layer prepared along the XY plane, this is equivalent to the distance along the Z-axis. This distance will be defined as the reaction coordinate ξ . The cut-off ranges for the near and far states will be defined based on the PMFs (potentials of mean force) along ξ of the amino acids, which can be found in the supplementary materials **TODO**.

If the potential of mean force (PMF) along ξ has been estimated for the discrete states $\{\xi_1, \xi_2, \dots, \xi_N\}$, the probability of a state ξ_j can be estimated with:

$$p(\xi_j) = \frac{e^{-\beta \text{PMF}(\xi_j)}}{\sum_{i=1}^N e^{-\beta \text{PMF}(\xi_i)}} \quad (2)$$

where β is the thermodynamic beta ($\frac{1}{k_B T}$). To estimate the probability of a state with multiple possible ξ values, the numerator is replaced with a sum over the individual values of ξ . In this way, the probabilities of the adsorbed and free states can be estimated with:

$$p(A) = \frac{\sum_{j \in A} e^{-\beta \text{PMF}(\xi_j)}}{\sum_{i=1}^N e^{-\beta \text{PMF}(\xi_i)}} \quad (3)$$

$$p(F) = \frac{\sum_{j \in F} e^{-\beta \text{PMF}(\xi_j)}}{\sum_{i=1}^N e^{-\beta \text{PMF}(\xi_i)}} \quad (4)$$

Knowing that the probability of a state

2.1.1 Umbrella Sampling

2.1.2 Well-Tempered Multiple Walker Metadynamics

2.2 Molecular Dynamics Simulation

MD simulations were performed using the GROMOS11^{16,18} and the NAMD 2.14 simulation packages¹². Details of the simulations will be presented separately for each program.

2.2.1 GROMOS

The SHAKE algorithm¹⁷ was employed to constrain all bonds to their reference values with a relative tolerance of 10^{-4} , allowing for a time-step of 2 fs using the leapfrog algorithm⁹. For water, the SPC model was used². Non-bonded interactions were computed using a triple range cut-off. Interactions within the short-range cut-off of 0.8 nm were computed every time-step, from a pair-list that was generated every 5 steps. At these time points, interactions between 0.8 and 1.4 nm were also computed which were kept constant between these updates. A reaction-field contribution was added to electrostatic interactions approximating for a homogeneous medium outside the 1.4 nm long-range cut-off, employing the relative permittivity of SPC water (61)²⁰. All interactions were calculated using the GROMOS 54a8 potential energy function, with all graphene atoms modeled as neutral sp^2 carbons¹⁵. After a steepest-descent minimization to remove bad contacts, all velocities were randomly assigned from a Maxwell-Boltzmann distribution at 298 K. All simulations were run coupled to thermostats using the weak-coupling algorithm³. The solute, graphene and solvent atoms were independently coupled to different heat baths. Additionally, the graphene layer was coupled to separate baths for regulation of its center of mass motion and its rotational and internal degrees of freedom. This totaled 4 heat baths.

2.2.2 NAMD

3 Results

3.1 Adsorption Free Energy

3.2 Adsorption Entropy

3.3 Adsorption Energy

3.4 Diffusion

4 Conclusions

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References

- [1] Mohammed N. Al-Qattan, Pran Kishore Deb, and Rakesh K. Tekade. Molecular dynamics simulation strategies for designing carbon-nanotube-based targeted drug delivery. *Drug Discovery Today*, 23(2): 235–250, Feb 2018. ISSN 1359-6446. doi: 10.1016/j.drudis.2017.10.002. URL <http://dx.doi.org/10.1016/j.drudis.2017.10.002>.
- [2] H. J. C. Berendsen, J. P. M. Postma, W. F. van Gunsteren, and J. Hermans. Interaction models for water in relation to protein hydration. *Intermolecular Forces*, page 331–342, 1981. ISSN 0924-4875. doi: 10.1007/978-94-015-7658-1_21. URL http://dx.doi.org/10.1007/978-94-015-7658-1_21.
- [3] H. J. C. Berendsen, J. P. M. Postma, W. F. van Gunsteren, A. DiNola, and J. R. Haak. Molecular dynamics with coupling to an external bath. *The Journal of Chemical Physics*, 81(8):3684–3690, Oct 1984. ISSN 1089-7690. doi: 10.1063/1.448118. URL <http://dx.doi.org/10.1063/1.448118>.
- [4] Yu Chong, Cuicui Ge, Zaixing Yang, Jose Antonio Garate, Zonglin Gu, Jeffrey K. Weber, Jiajia Liu, and Ruhong Zhou. Reduced cytotoxicity of graphene nanosheets mediated by blood-protein coating. *ACS Nano*, 9(6):5713–5724, Jun 2015. ISSN 1936-086X. doi: 10.1021/nn5066606. URL <http://dx.doi.org/10.1021/nn5066606>.
- [5] Guangxin Duan, Seung-gu Kang, Xin Tian, Jose Antonio Garate, Lin Zhao, Cuicui Ge, and Ruhong Zhou. Protein corona mitigates the cytotoxicity of graphene oxide by reducing its physical interaction with cell membrane. *Nanoscale*, 7(37):15214–15224, 2015. ISSN 2040-3372. doi: 10.1039/c5nr01839k. URL <http://dx.doi.org/10.1039/c5nr01839k>.
- [6] Ali Eftekhari and Hermenegildo Garcia. The necessity of structural irregularities for the chemical applications of graphene. *Materials Today Chemistry*, 4:1–16, Jun 2017. ISSN 2468-5194. doi: 10.1016/j.mtchem.2017.02.003. URL <http://dx.doi.org/10.1016/J.MTCHEM.2017.02.003>.
- [7] C. Ge, J. Du, L. Zhao, L. Wang, Y. Liu, D. Li, Y. Yang, R. Zhou, Y. Zhao, Z. Chai, and et al. Binding of blood proteins to carbon nanotubes reduces cytotoxicity. *Proceedings of the National Academy of Sciences*, 108(41):16968–16973, Oct 2011. ISSN 1091-6490. doi: 10.1073/pnas.1105270108. URL <http://dx.doi.org/10.1073/pnas.1105270108>.
- [8] Michael González-Durruthy, Amal Kanta Giri, Irina Moreira, Riccardo Concu, André Melo, Juan M. Ruso, and M. Natália D.S. Cordeiro. Computational modeling on mitochondrial channel nanotoxicity. *Nano Today*, 34:100913, Oct 2020. ISSN 1748-0132. doi: 10.1016/j.nantod.2020.100913. URL <http://dx.doi.org/10.1016/j.nantod.2020.100913>.
- [9] R W. Hockney. *The potential calculation and some applications*, volume 9 of *Methods in Computational Physics*, pages 136–211. Academic Press, 1977.
- [10] Baoyu Li, Yuanzhao Zhang, Xuan-Yu Meng, and Ruhong Zhou. Zipper-like unfolding of dsdna caused by graphene wrinkles. *The Journal of Physical Chemistry C*, 124(5):3332–3340, Jan 2020. ISSN 1932-7455. doi: 10.1021/acs.jpcc.9b08778. URL <http://dx.doi.org/10.1021/acs.jpcc.9b08778>.
- [11] K. S. Novoselov. Electric field effect in atomically thin carbon films. *Science*, 306(5696):666–669, Oct 2004. ISSN 1095-9203. doi: 10.1126/science.1102896. URL <http://dx.doi.org/10.1126/science.1102896>.
- [12] James C. Phillips, David J. Hardy, Julio D. C. Maia, John E. Stone, João V. Ribeiro, Rafael C. Bernardi, Ronak Buch, Giacomo Fiorin, Jérôme Hénin, Wei Jiang, and et al. Scalable molecular dynamics on cpu and gpu architectures with namd. *The Journal of Chemical Physics*, 153(4):044130, Jul 2020. ISSN 1089-7690. doi: 10.1063/5.0014475. URL <http://dx.doi.org/10.1063/5.0014475>.
- [13] Elle Puigpelat, Jordi Ignés-Mullol, Francesc Sagués, and Ramon Reigada. Interaction of graphene nanoparticles and lipid membranes displaying different liquid orderings: A molecular dynamics study. *Langmuir*,

- 35(50):16661–16668, Nov 2019. ISSN 1520-5827. doi: 10.1021/acs.langmuir.9b03008. URL <http://dx.doi.org/10.1021/acs.langmuir.9b03008>.
- [14] Edward P. Randviir, Dale A.C. Brownson, and Craig E. Banks. A decade of graphene research: production, applications and outlook. *Materials Today*, 17(9):426–432, Nov 2014. ISSN 1369-7021. doi: 10.1016/j.mattod.2014.06.001. URL <http://dx.doi.org/10.1016/j.mattod.2014.06.001>.
- [15] Maria M. Reif, Philippe H. Hünenberger, and Chris Oostenbrink. New interaction parameters for charged amino acid side chains in the gromos force field. *Journal of Chemical Theory and Computation*, 8(10):3705–3723, May 2012. ISSN 1549-9626. doi: 10.1021/ct300156h. URL <http://dx.doi.org/10.1021/ct300156h>.
- [16] Sereina Riniker, Clara D. Christ, Halvor S. Hansen, Philippe H. Hünenberger, Chris Oostenbrink, Denise Steiner, and Wilfred F. van Gunsteren. Calculation of relative free energies for ligand-protein binding, solvation, and conformational transitions using the gromos software. *The Journal of Physical Chemistry B*, 115(46):13570–13577, Nov 2011. ISSN 1520-5207. doi: 10.1021/jp204303a. URL <http://dx.doi.org/10.1021/jp204303a>.
- [17] Jean-Paul Ryckaert, Giovanni Ciccotti, and Herman J.C Berendsen. Numerical integration of the cartesian equations of motion of a system with constraints: molecular dynamics of n-alkanes. *Journal of Computational Physics*, 23(3):327–341, Mar 1977. ISSN 0021-9991. doi: 10.1016/0021-9991(77)90098-5. URL [http://dx.doi.org/10.1016/0021-9991\(77\)90098-5](http://dx.doi.org/10.1016/0021-9991(77)90098-5).
- [18] Nathan Schmid, Clara D. Christ, Markus Christen, Andreas P. Eichenberger, and Wilfred F. van Gunsteren. Architecture, implementation and parallelisation of the gromos software for biomolecular simulation. *Computer Physics Communications*, 183(4):890–903, Apr 2012. ISSN 0010-4655. doi: 10.1016/j.cpc.2011.12.014. URL <http://dx.doi.org/10.1016/j.cpc.2011.12.014>.
- [19] Sergey Shityakov, Giorgia Pastorin, Carola Foerster, and Ellaine Salvador. Blood-brain barrier transport studies, aggregation, and molecular dynamics simulation of multiwalled carbon nanotube functionalized with fluorescein isothiocyanate. *International Journal of Nanomedicine*, page 1703, Mar 2015. ISSN 1178-2013. doi: 10.2147/ijn.s68429. URL <http://dx.doi.org/10.2147/ijn.s68429>.
- [20] Ilario G. Tironi, René Sperb, Paul E. Smith, and Wilfred F. van Gunsteren. A generalized reaction field method for molecular dynamics simulations. *The Journal of Chemical Physics*, 102(13):5451–5459, Apr 1995. ISSN 1089-7690. doi: 10.1063/1.469273. URL <http://dx.doi.org/10.1063/1.469273>.
- [21] Ming Zheng, Anand Jagota, Ellen D. Semke, Bruce A. Diner, Robert S. Mclean, Steve R. Lustig, Raymond E. Richardson, and Nancy G. Tassi. Dna-assisted dispersion and separation of carbon nanotubes. *Nature Materials*, 2(5):338–342, Apr 2003. ISSN 1476-4660. doi: 10.1038/nmat877. URL <http://dx.doi.org/10.1038/nmat877>.
- [22] Guanghong Zuo, Seung-gu Kang, Peng Xiu, Yuliang Zhao, and Ruhong Zhou. Interactions between proteins and carbon-based nanoparticles: Exploring the origin of nanotoxicity at the molecular level. *Small*, 9(9-10):1546–1556, Oct 2012. ISSN 1613-6810. doi: 10.1002/smll.201201381. URL <http://dx.doi.org/10.1002/smll.201201381>.