

# Libra/cp2k workflow application: Modeling excited states in $(\text{TiO}_2)_4$

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## Abstract

The following manuscript describes the short project I conducted for the Excited States and Nonadiabatic Dynamics CyberTraining Workshop. It is mainly an application of the Libra/CP2K workflow for analysing the excited states of 4-size titania  $(\text{TiO}_2)$  nanoparticles (NPs). Libra software was thoroughly detailed during the first two days of the workshop, putting special attention to its use interfaced with CP2K for obtaining TD-DFT excitations and conducting calculations of trajectory surface hopping (TSH) nonadiabatic Molecular Dynamics (NAMD). The reason behind studying titania lies in its use as photocatalyst for water splitting procedures, as detailed in the following section. I've been working with titania systems for more than two years now (during my PhD), designing new finite systems of stoichiometric NPs and exploring their structure and ground-state properties when interacting with water. The study of excited states with NAMD represents a very appealing and promising field of study that will take my research one step further into the design of future photocatalysts for water splitting.

**Keywords** titania, nanoparticle, photocatalysis, TD-DFT, NAMD, TSH

## 1 Introduction

Among the metal oxides, titanium dioxide  $(\text{TiO}_2)$  -or titania- has gained considerable attention over the last decades in the field of photocatalysis due to its unique electronic and optical properties.[5, 13, 8] Titania is abundant, chemically stable, non-toxic, and inexpensive, making it an attractive candidate for various environmental and energy applications like air[18] and water purification[2], organic pollutant degradation[24] or production of  $\text{H}_2$  as green fuel.[15]

As a wide-bandgap semiconductor, titania can absorb ultra-violet (UV) light and generate electron-hole pairs that can be used for redox reactions on its surface. In this way, since the seminal discovery that titania can catalyse the splitting of water into hydrogen and oxygen when exposed to UV light[7], the combination of  $\text{TiO}_2$  and water has been established as a reference system for investigating the fundamental principles that underlie a wide range of photocatalytic processes. A lot of attention has gone specially into titania anatase crystal polymorph, which, even if is not the most stable one among the titania polymorphism (rutile is[11]), it is the one most used as efficient photocatalyst for water splitting, due to its high surface area, high photoactivity, and favourable energy band structure.[7]

Light activates the photocatalyst promoting the generation of electrons and holes, charged species needed to the generation of  $\text{H}_2$  and  $\text{O}_2$ , the main products resulting from the water splitting. One of the main limitations of this complex process resides in the short lifetime of such photogenerated species and somehow constitutes one of the rate-limiting steps in any photocatalyzed process. Therefore, understanding and working on charge carrier recombination dynamics is of key importance for tuning and enhancing the photocatalyst performance. To this end, nonadiabatic Molecular Dynamics (NAMD) computational implementation is commonly trusted as suited technique to investigate the properties of excited states.

In this way, I perform here a short study with  $(\text{TiO}_2)_4$  as test-study. I explore the use of either classical (force fields) or more expensive ab-initio (DFT) approaches for performing the Molecular Dynamics (MD) and getting the trajectories used to compute the system excitations. Speaking of which, I introduce here again two possibilities: using either a semilocal or a hybrid functional for describing said TD-DFT excitations. Thus, I have followed a total of four different methodologies before running nonadiabatic dynamics. I analyze the use of each of the methods in the different outputs generated through the workflow with the final goal of getting some insight into recombination dynamics of my small NP. However, since it is my first full completed workflow, some problems and strange results sprout out for some of the methods. My goal is to end up understanding all these results and be able to apply this methodology to larger titania NPs (with and without water) of different shapes and morphologies and be able to design future high-efficiency titania photocatalysts for water splitting and sustainable hydrogen production.

## 2 Computational Details and Methodology

Fig. 1 represents a general schematic view of the different steps comprising the Libra[1]/CP2K[14, 16] workflow, ending with the calculation of the decay (and recovery) times of the different excited states.

First of all, Molecular Dynamics (MD) simulations were performed to obtain a 1 ps trajectory at 300 K of our structure of bare  $(\text{TiO}_2)_4$  NP. This structure (Fig. 2) was previously globally optimized on a former work of my research group. Two codes were employed for the subsequent MD simulation: GULP4.4[9, 10] package for running classical MD im-

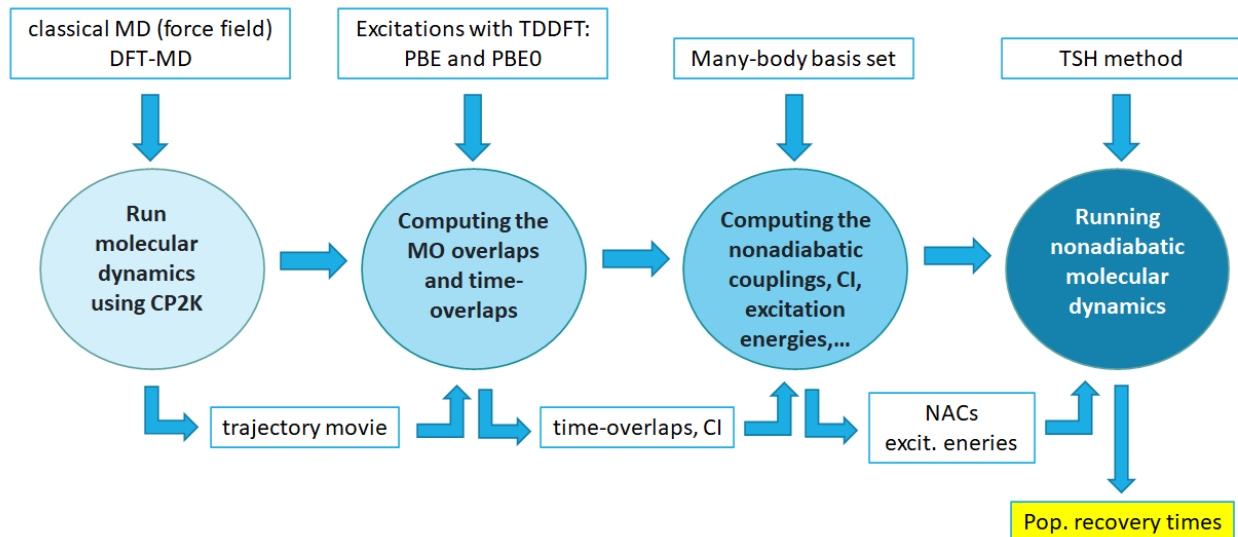


Figure 1: Schematic representation of the Libra/CP2K workflow

plementing a NanoTiO interatomic potential (IP)[17]; and CP2K for performing ab-initio MD using DFT. In the latter case, the electronic exchange and correlation is treated using the Perdew-Burke-Ernzerhof (PBE) generalized gradient approximation.[20] The valence electrons are described by the mix of the localized double-zeta-valence-polarized (DZVP) basis set[26] and the plane-wave basis selected with a charge density cutoff of 300 Ry. The core electrons for Ti and O are described using Goedecker-Teter-Hutter (GTH) pseudopotentials[12]

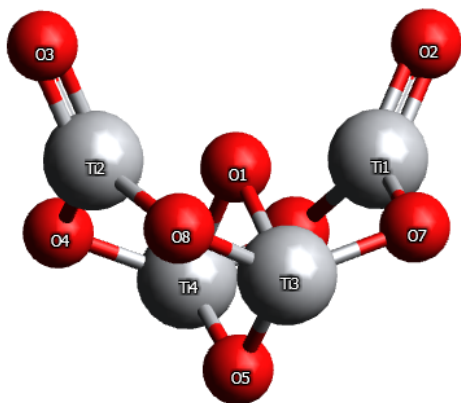


Figure 2:  $(\text{TiO}_2)_4$  globally optimized structure

The MD trajectories obtained following these two procedures are then used to compute the MO overlaps and time-overlaps in the step 2 of the workflow, relying on the “Gaussian cube-file”-based approach[6] within CP2K. Linear-response TD-DFT calculations are trusted in order to perform our excited states analysis. We use semilocal PBE and hybrid PBE0 (that includes 25% of the exact exchange energy from Hartree-Fock theory) functionals in this step, exploring 10 different excited states. I note here that we have conducted therefore

4 different methodologies leading to our excited states calculation: (i) classical IP MD + PBE TD-DFT; (ii) IP MD + PBE0 TD-DFT; (iii) ab-initio PBE MD + PBE TD-DFT; and (iv) PBE MD + PBE0 TD-DFT.

In step 3 of the workflow, we compute the nonadiabatic couplings (NACs) between different pairs of excited states. These states can be either Kohn-Sham states or single-particle or many-body excited states. We are working here at the Many-body level, as we will later justify.

Finally, in step 4 of our workflow we run nonadiabatic molecular dynamics using the computed nonadiabatic couplings (NACs) in the MB bases and the average excitation energy of the excited states over the MD trajectory. The Neglect-of-BackReaction Approximation (NBRA) is trusted[3, 4, 21] and NAD runs are propagated through 1000 fs. For each nonadiabatic simulation, 40 realizations (each one with different initial conditions) of the stochastic TSH trajectories are used. We calculate properties of interest- in our case the population recovery times- based on an average of the total number of trajectories. As for the TSH algorithms, we consider the FSSH (Tully’s fewest switches surface hopping).[25] We leave the introduction of decoherence for future research.

### 3 Results and discussion

Excited states of nanoscale systems and periodic solids are (nearly) always multiconfigurational so a single particle description -a single electron configuration- of our states would be inadequate most of the time. Therefore, excited states require a description based on a combination of different configurations, each representing a different arrangement of electrons in the MOs. These configurations contribute to the overall wavefunction of the excited state, and their combined effects give rise to the observed properties and behaviour of the system in that state. In this way, Many-body effects play an important role in quantum-confined systems, and it is key

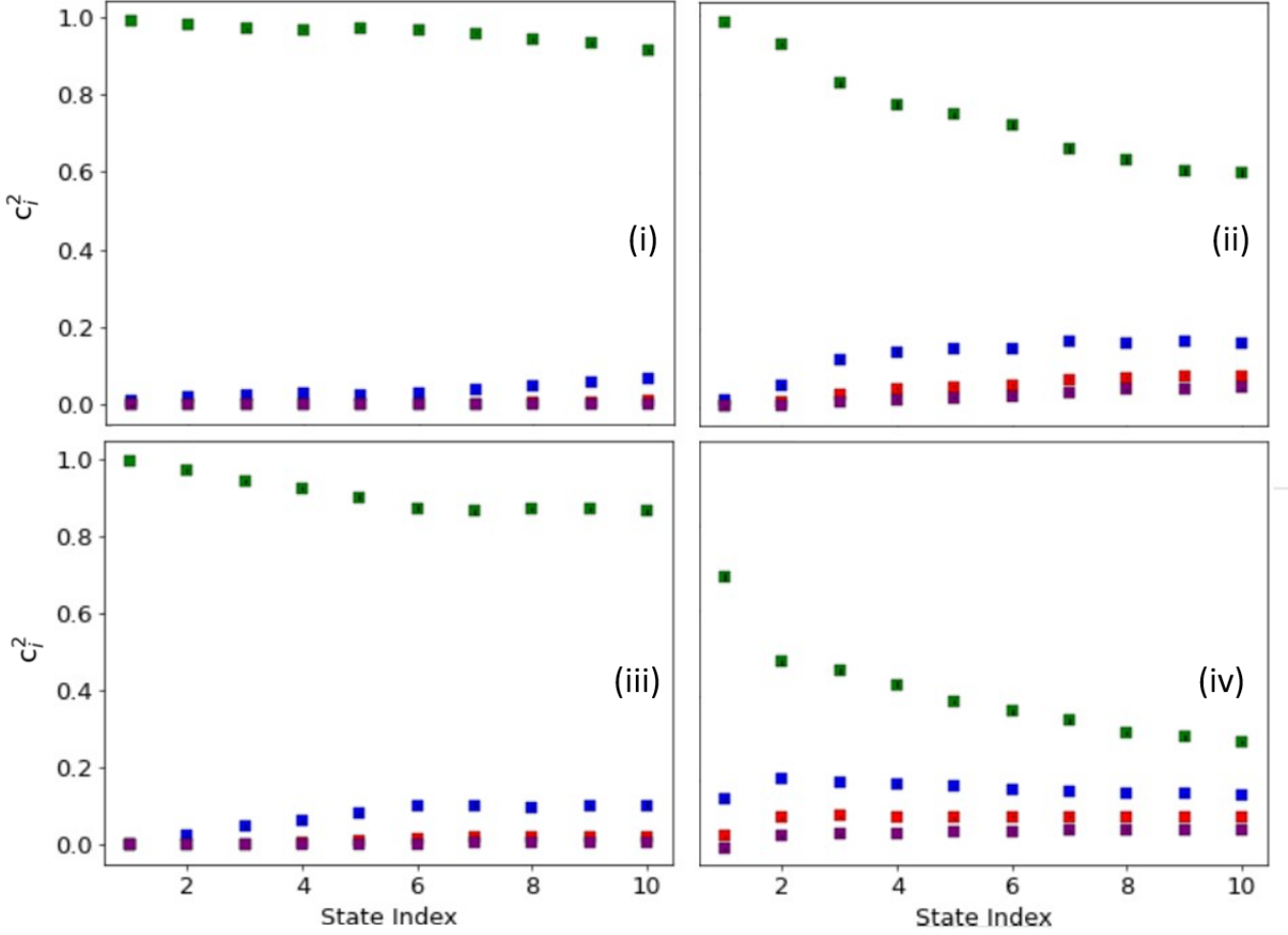


Figure 3: Squares of the four largest CI coefficients (green-blue-red-purple) for each of the considered 10 excited states and for the 4 ((i),(ii),(iii),(iv)) methodologies.

to account for these effects in nonadiabatic dynamics simulations, using thus many-body bases representation. In this MB representation, the composition of the excited states is quantified by the squares of the configuration interaction (CI) coefficients.

TD-DFT has been used as a not-too-expensive-option to account for MB effects thanks to the introduction of a time-dependent exchange-correlation functional (PBE and PBE0 in our case). Fig. 3 shows the squares of the four largest CI coefficients for each of the considered 10 excited states and for the 4 ((i)-(iv)) methodologies. In the left-hand side plots -for which TD-DFT excitations were performed using the PBE exchange-correlation functional- we see a comparable evolution of the coefficients: a single SD excitation dominance that starts to slowly break down as we consider higher excited state indexes. We don't see major differences between using classical or AIMD for generating our trajectory files -which is always a good argument towards the use of classical MD. The use of PBE0 for computing the TDDFT excitations leads to a stronger multiconfigurational character of our excited states. Even for lower excitation energies, the single particle approximation shouldn't be trusted to model the excited states dynamics in these two (right-hand side) cases. This is specially prominent in the right bottom figure (AIMD generated trajectory), for which the most prominent

single electron configuration contribution is no larger than 75%.

We can move on now to the excitation energy evolution analysis of these 10 states. Fig. 4 shows a propagation of these energies in the first 500 fs of our simulation. The use of PBE0 functional clearly leads to higher energies, an improvement on the description when compared to semilocal functional such as PBE. GGA functionals (pure functionals in general) tend to underestimate the HOMO-LUMO energy gaps[22] and the related charge-transfer excited state energies[23] -in contrast to the reported better description of the excitation energies of charge-transfer states.[19] Finally, we also note an analogous energy upshift in the two cases in which we performed our initial propagation with PBE AIMD.

Before running the different nonadiabatic dynamics, we need to compute the nonadiabatic couplings between the 10 different excited states. Sadly, we got here a not yet resolved failure in the computation of such NACs in the case (ii) (classical MD + PBE0 treatment of the excitations): a non-expected huge coupling is obtained between the ground state and first excited state. We discard this (ii) procedure and compute the rest of the NACs. Fig. 5 shows the nonadiabatic couplings map between the 10 states from methodologies (iii) and (iv). We can easily report higher couplings in case (iii)

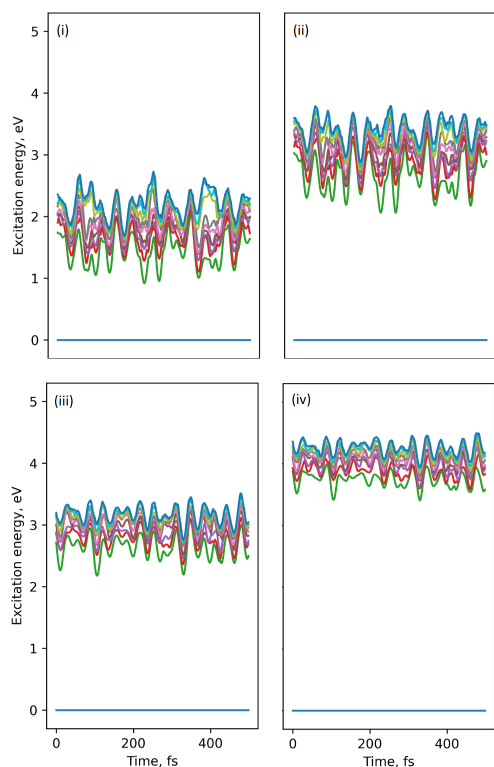


Figure 4: Calculated excitation energies evolution of the 10 considered excited states

as a result of the mentioned underestimation of the gaps by GGA-level-of-theory PBE functional. Besides, we can also note a homogeneous NACs distribution in figure (iv), which can be explained in terms of the stronger multiconfigurational nature of the excited states in this PBE0 based methodology (Fig. 3 (iv)). On the contrary, figure (iii) shows a increasing NACs tendency towards the map diagonal. Although it is not showed here (mainly for representation purposes), the AIMD trajectory with PBE excitations (methodology (i)) resembles a lot to case (iii), a fact that promotes again the use of cheaper classical molecular dynamics.

Lastly, we pick ten geometries of our MD of step 1 as starting points for the nonadiabatic dynamics runs. Each considered geometry is separated by 100 fs of nuclear evolution. For each of the nonadiabatic runs we use 40 different sets of initial conditions (starting geometry and the starting individual state) of the stochastic FSSH trajectories, so we have a total number of 400 trajectories.

The different properties of interest -like energies or population- are computed based on an average of the total number of these trajectories. Here we have focused on calculating population recovery states times, which can be easily computed. We are specially interested in the population recovery of the ground state, a quantity which could be associated to the photocatalytic performance of our titania systems of interest,

Fig. 6 shows the population recovery of ground state in our methodologies (i) and (iii). Unfortunately, calculations involving FSSH trajectories for AIMD evolution of nuclei and PBE0 as TD-DFT exchange-correlation functional (method-

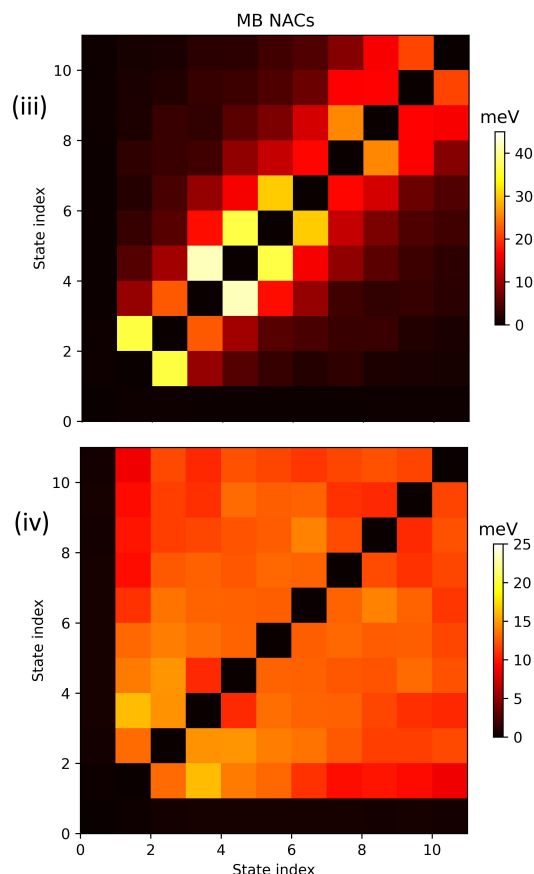


Figure 5: Computed nonadiabatic couplings (NACs) for the 10 excited states obtained in methodologies (iii) and (iv)

ology (iv)) yield non-conclusive results that need further exploration (like using a larger number of initial conditions, another TSH method...). Sticking to the two PBE-TDDFT methodologies, we see a longer recovery time in the bottom figure associated to the use of AIMD for obtaining our structure. The faster decay of ground state in figure (i) will point towards the use of classical MD in step 1.

Population recoveries are calculated for all the considered trajectories and fitted to an exponential function. Red solid line is the exponential fit for the average among all trajectories; while dashed lines represent these average  $\pm$  certain error. Each of the grey line correspond to a set of initial conditions.

## 4 Conclusions

Using  $(\text{TiO}_2)_4$  as test-system we have presented in this project a straightforward application of the Libra/CP2k workflow detailed during the Excited States and Nonadiabatic Dynamics CyberTraining Workshop.

Although this work does not represent a full conclusive innovative research, it constitutes a detailed description of the different steps one may take for computing nonadiabatic molecular dynamics to get insight into the different state populations evolutions. In the case of titania, this information is key since it is closely linked to its performance as catalyst in photoexcitation processes.

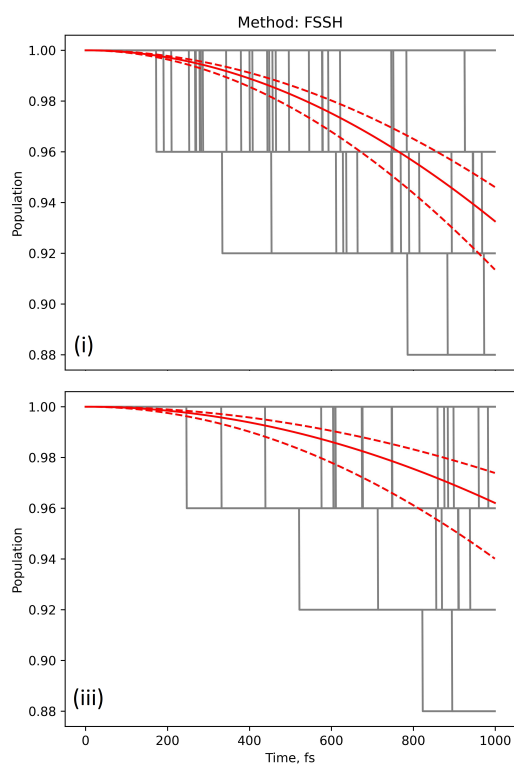


Figure 6: Ground state recovery times (1-pop(GS)) in methodologies (i) and (iii)

The output of these steps -Excitation energies, NACs- are presented, with a brief discussion of the impact of the different procedures for generating the initial trajectories (classical vs ab-initio MD) and the treatment (PBE vs PBE0) of excited states. Further research needs of course to be done, namely introducing decoherence to our TSH method, extending the simulation times and number of initial conditions or testing other hybrid functionals.

## References

- [1] Alexey V Akimov. Libra: an open-source “methodology discovery” library for quantum and classical dynamics simulations, 2016.
- [2] Sanja J Armaković, Maria M Savanović, and Stevan Armaković. Titanium dioxide as the most used photocatalyst for water purification: An overview. *Catalysts*, 13(1):26, 2022.
- [3] Colleen F Craig, Walter R Duncan, and Oleg V Prezhdo. Trajectory surface hopping in the time-dependent kohn-sham approach for electron-nuclear dynamics. *Physical review letters*, 95(16):163001, 2005.
- [4] Walter R Duncan, Colleen F Craig, and Oleg V Prezhdo. Time-domain ab initio study of charge relaxation and recombination in dye-sensitized tio2. *Journal of the American Chemical Society*, 129(27):8528–8543, 2007.
- [5] Marye Anne Fox and Maria T Dulay. Heterogeneous photocatalysis. *Chemical reviews*, 93(1):341–357, 1993.
- [6] MJ ea Frisch, GW Trucks, HB Schlegel, GE Scuseria, MA Robb, JR Cheeseman, G Scalmani, VPGA Barone, GA Petersson, HJRA Nakatsuji, et al. Gaussian 16, revision c. 01, 2016.
- [7] Akira Fujishima and Kenichi Honda. Electrochemical photolysis of water at a semiconductor electrode. *nature*, 238(5358):37–38, 1972.
- [8] Akira Fujishima, Xintong Zhang, and Donald A Tryk. Tio2 photocatalysis and related surface phenomena. *Surface science reports*, 63(12):515–582, 2008.
- [9] Julian D Gale. Gulp: A computer program for the symmetry-adapted simulation of solids. *Journal of the Chemical Society, Faraday Transactions*, 93(4):629–637, 1997.
- [10] Julian D Gale and Andrew L Rohl. The general utility lattice program (gulp). *Molecular Simulation*, 29(5):291–341, 2003.
- [11] Dorian AH Hanaor, Mohammed HN Assadi, Sean Li, Aibing Yu, and Charles C Sorrell. Ab initio study of phase stability in doped tio 2. *Computational Mechanics*, 50:185–194, 2012.
- [12] Christian Hartwigsen, Sephen Goedecker, and Jürg Hutter. Relativistic separable dual-space gaussian pseudopotentials from h to rn. *Physical Review B*, 58(7):3641, 1998.
- [13] Kazuhito Hashimoto, Hiroshi Irie, and Akira Fujishima. Tio2 photocatalysis: a historical overview and future prospects. *Japanese journal of applied physics*, 44(12R):8269, 2005.
- [14] Jürg Hutter, Marcella Iannuzzi, Florian Schiffmann, and Joost VandeVondele. cp2k: atomistic simulations of condensed matter systems. *Wiley Interdisciplinary Reviews: Computational Molecular Science*, 4(1):15–25, 2014.
- [15] Hicham Idriss. Hydrogen production from water: past and present. *Current Opinion in Chemical Engineering*, 29:74–82, 2020.
- [16] Thomas D Kühne, Marcella Iannuzzi, Mauro Del Ben, Vladimir V Rybkin, Patrick Seewald, Frederick Stein, Teodoro Laino, Rustam Z Khaliullin, Ole Schütt, Florian Schiffmann, et al. Cp2k: An electronic structure and molecular dynamics software package-quickstep: Efficient and accurate electronic structure calculations. *The Journal of Chemical Physics*, 152(19), 2020.
- [17] Oriol Lamiel-Garcia, Andi Cuko, Monica Calatayud, Francesc Illas, and Stefan T Bromley. Predicting size-dependent emergence of crystallinity in nanomaterials: titania nanoclusters versus nanocrystals. *Nanoscale*, 9(3):1049–1058, 2017.
- [18] Alireza Haghighat Mamaghani, Fariborz Haghighat, and Chang-Seo Lee. Role of titanium dioxide (tio2) structural design/morphology in photocatalytic air purification. *Applied Catalysis B: Environmental*, 269:118735, 2020.
- [19] Martín A Mosquera, Carlos H Borca, Mark A Ratner, and George C Schatz. Connection between hybrid functionals and importance of the local density approximation. *The Journal of Physical Chemistry A*, 120(9):1605–1612, 2016.
- [20] John P Perdew, Kieron Burke, and Matthias Ernzerhof. Generalized gradient approximation made simple. *Physical review letters*, 77(18):3865, 1996.
- [21] Oleg V Prezhdo, Walter R Duncan, and Victor V Prezhdo. Photoinduced electron dynamics at the chromophore–semiconductor interface: A time-domain ab initio perspective. *Progress in surface science*, 84(1-2):30–68, 2009.
- [22] Sivan Refaely-Abramson, Roi Baer, and Leeor Kronik. Fundamental and excitation gaps in molecules of relevance for organic photovoltaics from an optimally tuned range-separated hybrid functional. *Physical Review B*, 84(7):075144, 2011.
- [23] Sahar Sharifzadeh, Pierre Darancet, Leeor Kronik, and Jeffrey B Neaton. Low-energy charge-transfer excitons in organic solids from first-principles: The case of pentacene. *The Journal of Physical Chemistry Letters*, 4(13):2197–2201, 2013.

- [24] Meisam Soleimani, Jahan B Ghasemi, Ghodsi Mohammadi Ziarani, Hassan Karimi-Maleh, and Alireza Badii. Photocatalytic degradation of organic pollutants, viral and bacterial pathogens using titania nanoparticles. *Inorganic Chemistry Communications*, 130:108688, 2021.
- [25] John C Tully. Molecular dynamics with electronic transitions. *The Journal of Chemical Physics*, 93(2):1061–1071, 1990.
- [26] Joost VandeVondele and Jürg Hutter. Gaussian basis sets for accurate calculations on molecular systems in gas and condensed phases. *The Journal of chemical physics*, 127(11), 2007.