

# Summary

At present, a plethora of techniques is available to study molecular systems and chemical reactions. In this light, *ab initio* many body techniques enable us, without any experimental input, to compute molecular energetics and a whole range of chemical properties. A twofold classification can be made, separating wave function based methods (such as Hartree-Fock) from density functional theory (DFT). In this thesis, the focus mainly lies on the density functional method, both from a conceptual as computational viewpoint - for the latter, one of the reasons being its excellent cost-to-performance ratio. The formulation of the Hohenberg-Kohn theorems in 1964 provided the starting point for the fast development of fundamental DFT, yielding all basic ingredients for a complete many-body theory. In a next step, Kohn and Sham introduced orbitals within the formalism, paving the way to a breakthrough of DFT as an important computational tool within modern chemistry. In addition to these developments, much attention has been paid to the insights DFT can give into chemical reactivity. In particular, the density functional methodology provides an excellent framework to define a variety of well-known chemical concepts.

In this thesis, the applicability of several fundamental DFT-based reactivity indicators has been tested for a variety of reactions occurring in diverse domains of chemistry. The chemical potential, global hardness and global softness are used to discuss the reactive behavior of one single molecule or a set of related molecules, providing reactivity sequences for the latter. The Fukui function is used as an intra-molecular descriptor, whereas the local softness can provide inter-molecular reactivity information about regio selectivity. In order to test the usefulness of the aforementioned properties, they are usually used in conjunction with well-known chemical principles such as the electronegativity equalization, the principle of maximum hardness and the hard and soft acids and bases (HSAB) principle. A validation of the results is obtained through comparison with *ab initio* thermodynamic and kinetic data. In general, DFT-based concepts have proven to be of great use in the interpretation of a variety of experimental and theoretical results. It remains nevertheless challenging to make predictions about their success or failure for specific types of interactions. In order to rely on the indicators as independent and/or predictive tools for the description of chemical reactivity, there is need for practical guidelines describing which indicators are suitable for a certain problem. The descriptors probe electronic interactions, however it is clear that they do not monitor other effects, such as steric contributions. Whenever the indicators are tested, their limitations must *a priori* be kept in mind. For instance, some of the reactions studied in this work exhibit high reaction barriers due to large steric hindrance effects between the two reactants and thus, the indicators are not expected to

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be successful.

The largest group of applications concerns radical reactions. The majority of them occur during the formation of coke, which is a side process of thermal cracking of hydrocarbons. Radical systems are particularly interesting and challenging. However so far only a handful of papers examined and discussed their behavior using reactivity descriptors. In the specific case of hydrogen abstraction reactions at polyaromatic species by a methyl radical, accurate, reliable and yet affordable thermodynamic and kinetic data have been obtained. Other studied bimolecular radical reactions are addition reactions of radicals to small olefins and the initiation and first propagation steps within the polymerization process of polyethylene and poly(vinylchloride). Overall, it can be concluded that the radical Fukui function is capable of indicating the preferred site of reaction. This clearly indicates the importance of frontier orbital effects for this specific type of interaction. The local HSAB principle was also successfully applied, leading to correct reactivity sequences when related molecules were compared with each other. Hence the local softness is a suitable indicator for studying bimolecular radical reactions. This is in accordance with earlier suggestions and with the categorization of Klopman, as the larger radicals are characterized by high global softness values. Whereas the local viewpoint leads to satisfactory results, the global HSAB principle fails for some specific bimolecular radical reactions and is therefore not recommended. In addition to these bimolecular reactions, two examples of unimolecular radical cyclization reactions have also been studied. For these reactions, the Fukui function is used to describe the intra-molecular regio selectivity. However, the correct site of cyclization could not be indicated. Since these reactions correspond to a constrained charge transfer – the spin number remains constant, whereas the total number of electrons changes at a local level – the spin-polarized reactivity descriptors, and in particular the spin-polarized Fukui function has been tested and indeed, its usefulness is demonstrated.

A second group of studied bimolecular reactions correspond to typical reactions occurring within zeolite catalysis. The small probe molecules are characterized as hard systems, and both polar and apolar representatives were chosen. The zeolite catalyst was modelled by a small 5-tetrahedral cluster, and in addition to the traditional oxygen-bridged cluster the influence of amine substitution was tested. These reactions were difficult to describe using DFT-based reactivity descriptors. The global HSAB principle fails for the interactions with the polar molecules, as in these cases polarization effects – which are not included in the purely electron transfer process – are dominant. In contrast, the reactions between the zeolite clusters and the apolar molecules do follow the HSAB rule. From a local point of view, the complex mechanism of these concerted reactions, occurring simultaneously at the acid and basic site of the zeolite framework, could not be specified based on local descriptors. Multiple-site interactions in general remain a domain for further research. In addition, the local hardness might be more suitable to describe interactions with hard

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molecules, although at present the calculations remain troublesome and no practical scheme is presented yet.

A final application concerns a unimolecular ionic cyclization reaction leading to the formation of a four-membered  $\beta$ -lactam ring. This is an example in which competing pathways can take place because the formation of the more stable six-membered ring, instead of the strained four-membered ring, is initially expected. The anion reactant is a very soft species and the traditional local indicator, i. e. the Fukui function, succeeds in correctly predicting the preferred reaction path. Therefore the indicator adds to the unravelling of the origin of the experimentally observed cyclization preference. Moreover, extension to bimolecular reactions using this anion reactant also revealed the successful applicability of the local softness, as also these results were in correspondence with reaction barriers obtained at 0 Kelvin.

In this thesis, one of the main advantages of using reactivity descriptors was accentuated, in particular their low computational cost. Not only do they solely require information from the reactants, but it was furthermore demonstrated that reactivity sequences are mainly independent of the level of theory used for geometry optimizations as well as for single-point energy calculations. An extended set of theoretical procedures, ranging from simple ab initio methods such as Hartree-Fock, over a very popular and successful functional, to the latest class of highly promising methods. The observation of level-of-theory independency for the calculation of the global descriptors is highly reassuring and adds to the reliability of DFT-based reactivity indicators. It must however be emphasized that overall the perturbative approach should be used complementary to information obtained from thermodynamics and kinetics.