



D8.1 - SURF Transnational access success story

Deliverable No.:	D8.1
Deliverable Name:	SURF Transnational access success story
Contractual Submission Date:	30/04/2022
Actual Submission Date:	19/05/2022
Version:	1.1



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730897.

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Project Acronym:	HPC-Europa3
Project Full Name:	Transnational Access Programme for a Pan-European Network of HPC Research Infrastructures and Laboratories for scientific computing
Deliverable No.:	D8.1
Document name:	SURF Transnational access success story
Nature (R, P, D, O):	D
Dissemination Level (PU, PP, RE, CO):	PU
Version:	1.1
Actual Submission Date:	19/05/2022
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ABSTRACT:

Different visitors in the Quantum Chemistry group at the Rijksuniversiteit Groningen have made a really important contribution to research, thanks to the collaboration with the head of the group (Prof. Remco Havenith) and also the help of the origin groups of some of the students. This story shows how collaborations can actually span over 4 different countries and keep connected via the Dutch national supercomputing systems and the group of Prof. Havenith.

KEYWORD LIST:

Computational chemistry,

MODIFICATION CONTROL			
Version	Date	Status	Author
1.0	01/05/2022	Draft	Carlos Teijeiro Barjas (SURF)
1.1	19/05/2022	Final	Carlos Teijeiro Barjas (SURF)

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Executive summary

Different visitors in the Quantum Chemistry group at the Rijksuniversiteit Groningen have made a really important contribution to research, thanks to the collaboration with the head of the group (Prof. Remco Havenith) and also the help of the origin groups of some of the students. This story shows how collaborations can actually span over 4 different countries and keep connected via the Dutch national supercomputing systems and the group of Prof. Havenith.

The Quantum Chemistry group from the Rijksuniversit Groningen [1] represents one of the most active groups in the use of the Dutch national compute facilities at SURF. Their work is essentially related to method development in computational chemistry, and its developments have been directly applicable to simulation of photovoltaic technology, particularly in the focus group “Next Generation Organic Photovoltaics” funded by the National Research Funding Organization in the Netherlands (NWO). The head of the group, Prof. Remco Havenith, has contributed to more than 150 publications in the field of computational chemistry and has advised 11 PhD thesis in the last years.

Relevant questions for a directed design of new photovoltaic materials are concerned with the relation between structure and photo-excitation, exciton mobility in polymers, electron/hole transfer in interfaces, and stability and durability. In order to answer these questions, state-of-the-art Density Functional Theory (DFT) and ab initio calculations is performed. For the interpretation of the results in terms of chemical concepts, Valence Bond theory is used.

With support of the HPC-Europa3 program, the group of Prof. Havenith could establish new research directions and collaborations. Within the HPC-Europa3 program, they worked on different projects, ranging from fundamental chemistry, via biochemistry to materials science. Many of these projects were performed not only in collaboration with the university of the guest, but also with the University of Antwerp (Prof. A. da Cunha).

Together with the University of Porto (with visitor A. Pinto), the group worked on the hGIIA PLA2 enzym. The secreted hGIIA PLA2 has been shown to be involved in the inflammatory response of pathologies such as rheumatoid arthritis. The information provided by the minimum free energy path of the reaction mechanism, which includes the structural and energetic characterization of the reagent, transition state and product, is crucial for the rational design of new inhibitors. Several hypotheses based on experimental studies have been put forward, however, there is no consensus on the reaction mechanism that is more likely to occur.

The research work helped to find that the single water molecule hypothesis is more probable, since the related conformations have higher statistical significance in the molecular dynamics simulations performed. Additionally, we found an activation energy of 19.90 kcal/mol (Figure 1), which is close (*i.e.*, within the error associated with the method) to the estimated value from a similar enzyme ($\Delta G^\ddagger = 15.50$ kcal/mol, estimated from the k_{cat} of the pancreatic GIIA PLA2 belonging to *Bos Taurus*).

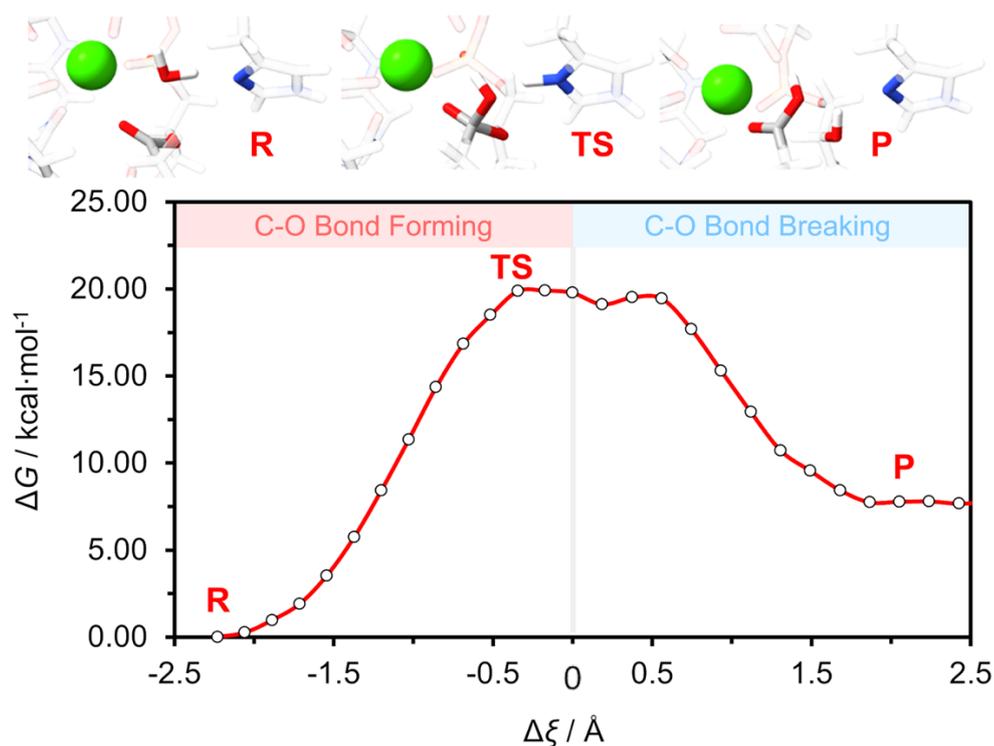


Figure 1. Free energy profile of the reaction, and structures of the reactants (R), transition state (TS), and products (P).

With the University of Porto (visitor P. Teixeira Ferreira) the group also worked on revealing the catalytic mechanism of DszA. The main proposal in the literature point to an initial deprotonation of the N1 atom of FMN followed by the binding of dioxygen to the C4 atom of FMN forming a C4aOOH intermediate. Then, an enzymatic catalytic base would assist on the formation of a peroxyhemiacetal intermediate between the C4aOOH and DBTO₂. The proximal oxygen is then protonated by the proton of the N5 atom of FMN and subsequently attacks the N5 atom forming an N5-oxide flavin. The final step is the conversion of DBTO₂ to 2'-hydroxybiphenyl 2-sulfinic acid (HBPS). Quantum Mechanics/Molecular Mechanics MD (QM/MM MD) simulations were used to test the plausibility of this mechanism (Figure 2).

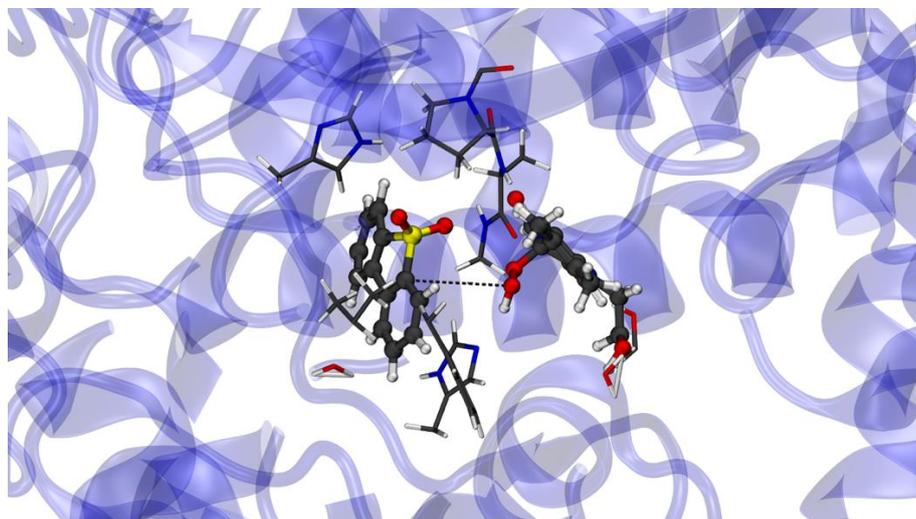


Figure 2. Representation of the QM/MM model. QM layer is represented in licorice with the cofactor and substrate in CPK. The protein is represented in blue in cartoon.

From this work a free energy profile for the reaction (Figure 3) was obtained, and it was observed that instead of the formation of a peroxyhemiacetal intermediate a simple OH transfer to the DBTO₂ occurred via the transition state depicted in Figure 4, with no residue acting as catalytic base. We found our product HBPS even though not in the final conformation and C^{4a} oxide. Another model with C4aOO⁻ instead of C4aOOH was also tested but that was found to be unstable; the C4aOO⁻ cofactor is spontaneously re-protonated to C4aOOH, thus we did not follow this hypothesis further. A last model that was tested was a model in which N5OOH is formed instead of C4aOOH from the reduced FMN cofactor. This was recently proposed for the RutA flavoenzyme. This model however was highly unstable; the bond between the two oxygens breaks spontaneously leaving N5O and an OH group that is spontaneously protonated in the enzymatic media.

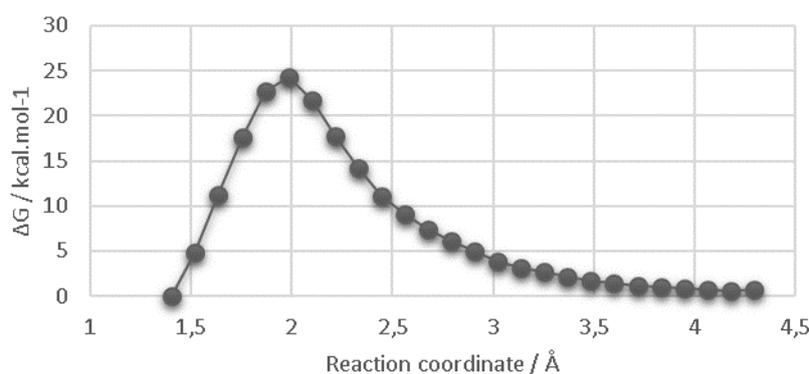


Figure 3. Free energy profile obtained for the transfer of the OH group to DBTO₂. The reaction coordinate was defined as the distance between the oxygen of the OH group and the C1 of DBTO₂. Each circle in the chart corresponds to one window of the Umbrella Sampling. Each window was run for 5 ps at the PBE/DZVP-MOLOPT-GTH-PBE:FF14SB level of theory.

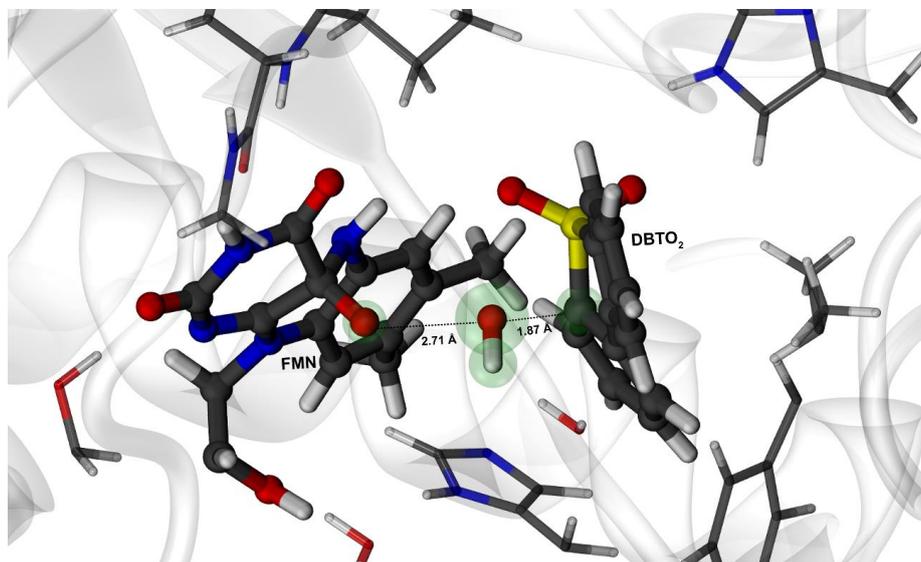


Figure 4. Representation of the structure of the transition state obtained by retrieving the most representative conformation of the umbrella sampling window with the highest free energy.

Together with University of Brussels (visitor E. Desmedt), the group focused on the aromaticity expanded porphyrins. Introducing structural changes such as core-modifications and *meso*-substitutions into expanded porphyrins can alter the (anti)aromatic character of the macrocycle. By studying the ring current maps of these expanded porphyrins, it is possible to visualize the influence of this modification on ring current and measure their current strengths at points close to the modification. For [26]-hexaphyrin, a diatropic ring current is visible (Figure 5). The ring currents of the expanded porphyrins are still being visualized and both diatropic and paratropic ring currents for our aromatic and antiaromatic systems have been observed. It is expected that for some modified expanded porphyrins no clear diatropic or paratropic ring current will be discernible, coinciding with a nonaromatic system.

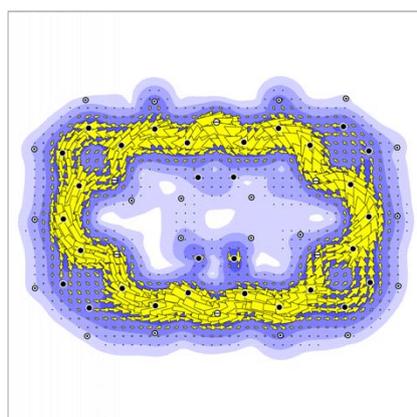
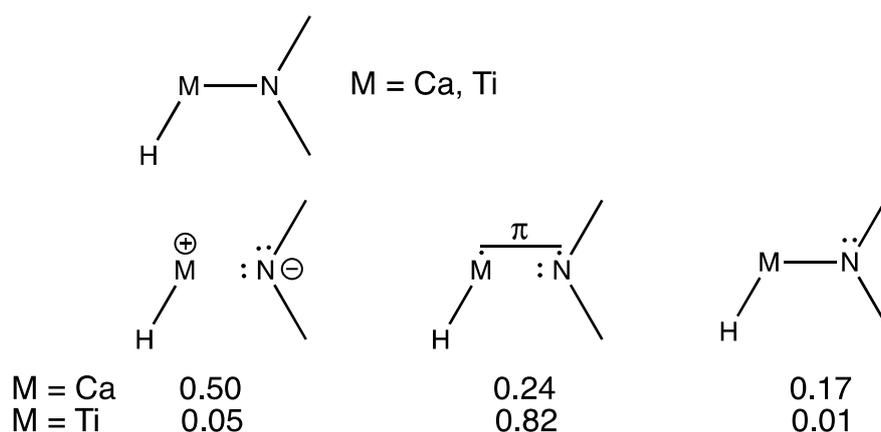


Figure 5. Plot of the induced π current density, plotted in a plane $1 a_0$ above the molecular plane. Diatropic current is plotted anti-clockwise.

With the University of Brussels (with visitor B. De Tobel), the work focused on the study of chemical bonding using valence bond theory. The main research goal of this project was the evaluation of the bonding behaviour of alkaline-earth metal hydride complexes ($\text{H-M-N}(\text{Me})_2$) that are used to catalyse hydrogenation reactions of imines and alkenes at mild reaction conditions. These simple alkaline-earth metal complexes are investigated in the context of the search for alternatives to conventional hydrogenation catalysts driven by lowering catalyst cost and environmental concerns. This bonding behaviour will then be compared between the group II metals themselves, as well as with analogous alkali- and transition metal complexes. Using Valence Bond (VB) theory an explanation for the observed non-VSEPR structures for the heavier group II metal complexes may be found. It is suggested that the heavier group II metals (Ca, Sr, Ba) are able to use their inner (n-1)d orbitals, which might explain the bend in the bite angle of the metal hydride complex.

Two structures were studied initially: the **Ca complex** was chosen for the group II metals while the other complex was the **Ti complex** (Scheme 1) since we want to investigate whether the bonding behavior (d-type bonding) of the heavier group II metals is comparable to that of transition metal complexes.



Scheme 1. The structure of the studied molecules, together with the most important VB structures. Indicated are the weights of each structure.

The valence bond theory calculations on the Ca and Ti analogue of the $\text{H-M-N}(\text{Me})_2$ complex have been performed using TURTLE, the valence bond module in GAMESS-UK, using the Def2-SVP basis set. The structures that have been considered in creating the VB wavefunctions of these complexes consist of all spin-coupling patterns that comprise all combinations of possible ionic and covalent bonding types for the H-M and M-N bond in the $\text{H-M-N}(\text{Me})_2$ system. For the M-N bond, both σ and π -bonding patterns have been considered.

For the Ca system, the VB structure with the largest weight in the VB wavefunction is the $\text{N}^- \text{Ca}^+ \text{H}$ structure, followed by the covalent N-Ca-H structures, where the σ - and π -spin coupled combination have similar weights (Scheme 1), suggesting that a small amount of π -backbonding between Ca and the ligand can occur. Mulliken analysis of the VB orbitals (Figure 6) indicate that the bonding orbitals of Ca indeed have some d-character. This is most prominent in the π -backbonding orbital (64%), but is definitely not negligible in the σ -bonding combinations for both the Ca-N (27%) and Ca-H (15%) bond.

The Ti system has only one dominant structure in the VB wavefunction, which is the N-Ti-H structure with the π -spin coupling in the N-Ti bond, indicating a large amount of π -backbonding. Mulliken analysis of the bonding orbitals on Ti reveal the very prominent d-character of these orbitals, where only a small amount of s-character (10%) can be found for the orbital of the Ti-H bond (Figure 6). This is completely in line with what one would expect from transition metals.

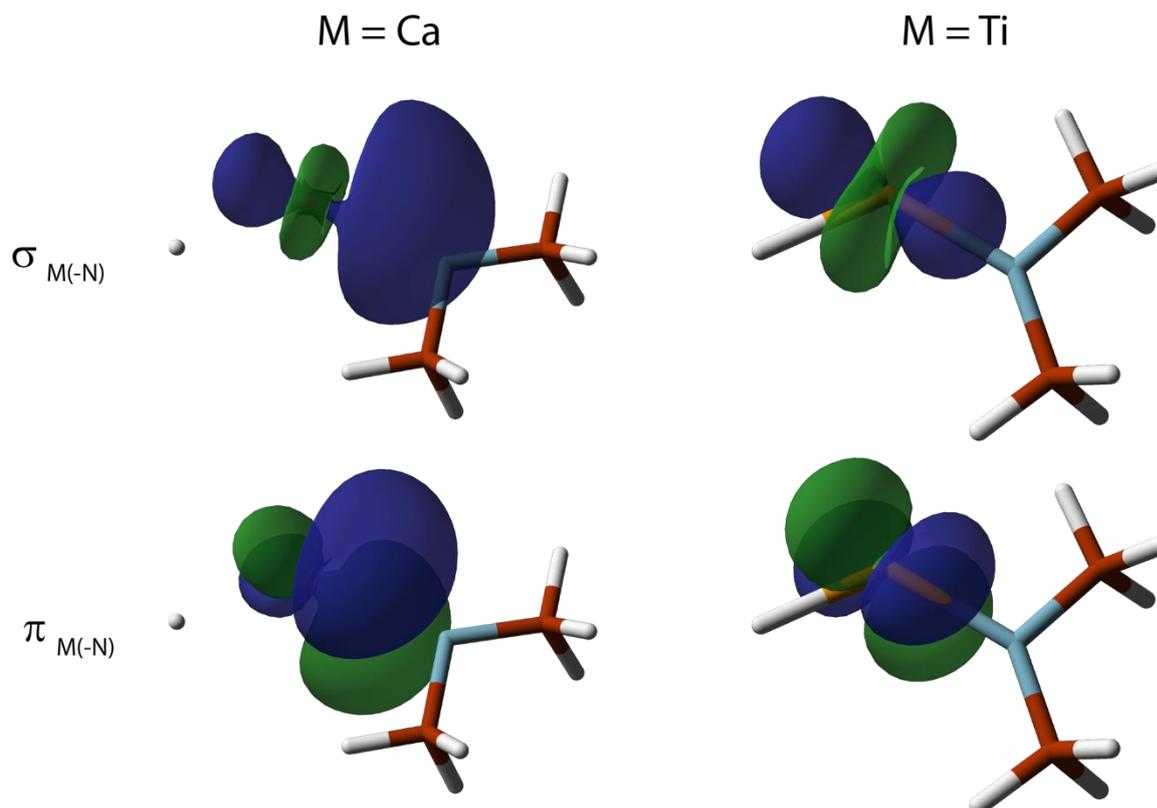


Figure 6. The metal orbitals involved in the bonding to the $\text{N}(\text{CH}_3)_2$ fragment.

Currently, the Mg complex is being investigated. At first sight, no d-character is expected to arise in the bonding orbitals from Mg. This validates the abovementioned hypothesis that the heavier group II metals are able to use their inner $(n-1)d$ orbitals, explaining the bend in the bite angle for the $\text{H-M-N}(\text{Me})_2$ metal hydride complexes.

The last project with the University of Bayreuth (with visitor F. Eller) was concerned with the behaviour of polymers in solution. In experiments there were two identified methods of charging polymers to significantly enhance and control the aggregation behaviour of the prototypical material P3HT (Poly(3-hexylthiophene-2,5-diyl)) in the solvent chloroform. The aim was to achieve a better understanding of the processes on a molecular scale. Furthermore, these findings should be used in combination with simulations of other materials to apply the mechanism also to other materials (polymers, solvents and solvent additives) and find out which structural properties of involved materials are required for a successful aggregation control.

D8.1 – SURF Transnational access success story

It was possible to achieve a better understanding of the processes occurring on a molecular scale already with quite simple geometry optimizations. They provided the missing link between what was already known from literature and our experimental results. Moreover, energy scans gave us a conclusive picture of the stiffness of different oligomers with different experimental treatments. Furthermore, a molecular dynamics routine could be implemented and test it using simulations of some test systems. In Figure 7, one of the snapshots of a polymer in solution is shown. These simulations already give plausible results and can now be applied for large material screenings.

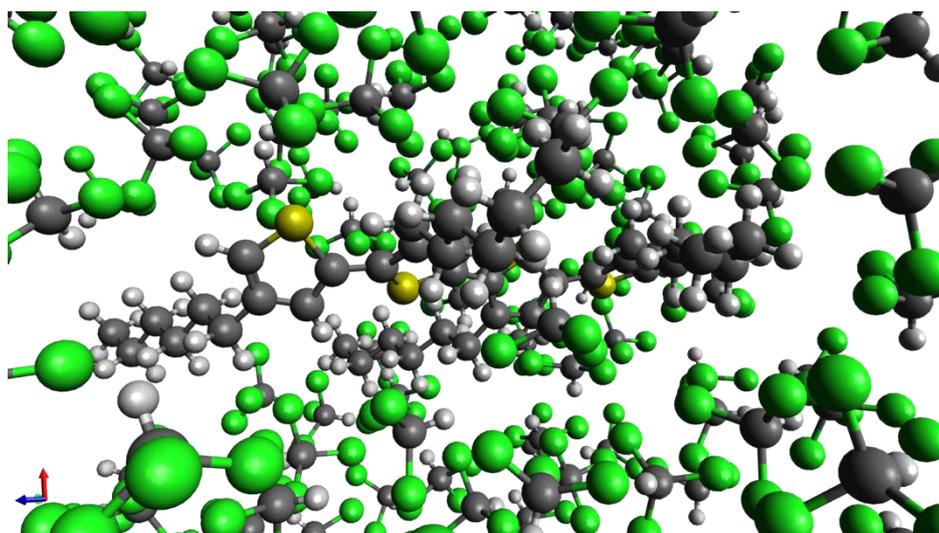


Figure 7. One of the configurations of the MD simulation of a polymer in solution.

Overall, all the projects have been providing large contributions to the research from the Quantum Chemistry group and also the possibility of establishing new international collaborations. As a result, Prof. Havenith stresses the high importance of the HPC-Europa3 program to make this contact possible in terms of on-site scientific interaction and access to compute time.

[1] <https://www.rug.nl/research/quantum-chemistry/havenith-group/>