Encapsulating functional organic molecules in porous solids

Adsorption of pharmaceuticals and personal care products in zeolites studied with density functional theory calculations

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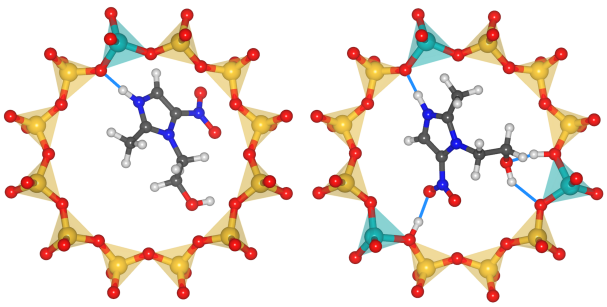
In Short

- Electronic structure calculations can provide atomic-level insights into the adsorption of pharmaceuticals, personal care products, and other functional organic molecules in the pores of zeolites.
- The role of "multi-site" interactions in stabilising adsorbed molecules was studied for a group of organic compounds of environmental relevance.
- The interaction of 5-fluorouracil, an anti-cancer drug, with different types of acid sites was investigated systematically.
- Ongoing work looks at cation-exchanged zeolites for drug delivery applications and at the adsorption of pharmaceuticals at the external surfaces of clinoptilolite, a natural zeolite mineral.

Pharmaceuticals, personal care products (for example, disinfectants, fragrances, or UV filters) and other functional organic molecules (such as herbicides and pesticides) are ubiquitously used in our modern society. Their release into the environment, *e.g.*, via municipal or hospital wastewaters, has become a matter of significant concern due to possible adverse effects on the ecosystem and, potentially, also on human health.1 Since conventional wastewater treatment plants are not designed for the removal of these *emerging organic contaminants*, a variety of advanced treatment technologies are under investigation. In this context, zeolites, crystalline porous materials having a tetrahedral framework structure, are receiving continued attention as they could be used in the adsorption-based removal of organic contaminants from water.2 Besides, zeolites could also play a role as host materials for the storage and controlled release of drug molecules.

Although a number of experimental studies have addressed the adsorption of functional organic molecules in zeolites, even advanced experimental techniques can only provide limited insights into the structure of the adsorption complexes and the dominant interactions. Rather surprisingly, computational chemistry methods have scarcely been used in this area, despite their widespread application in other fields of zeolite science.3 In this project, electronic structure calculations in the framework of dispersion-corrected density functional theory (DFT) are employed to investigate the adsorption of functional organic molecules in different types of zeolites, anticipating that an in-depth understanding of the adsorption processes at the atomic level will be crucial for the further development of new applications, for example in wastewater treatment or drug delivery.

Recent work associated with this project studied the adsorption of five organic contaminants in aluminosilicate zeolites containing different amounts of aluminium atoms and charge-balancing framework protons. It was a key aim of this study to investigate to what extent "multi-site" interactions, localised interactions of one guest molecule with more than one region of the framework, contribute to the stabilisation of the adsorption complexes. For illustrative purposes, Figure 1 shows adsorption complexes of metronidazole (MNZ), an antibiotic, in faujasite-type (FAU) zeolites containing one or three aluminium atoms within one twelve-membered ring of tetrahedra. In the H-FAU_3H system, simultaneous interactions with different protons and additional hydrogen bonds result in a significant stabilisation, with the adsorption energy E_{ads} being 44% more negative than for the H-FAU_1H case. Qualitatively similar observations were made for caffeine, whereas the bulky antibiotic trimethoprim and bisphenol A, widely used in the production of plastics, were found to benefit much less from multi-site interactions.



MNZ@H-FAU_1H E_{ads} = −186 kJ/mol

MNZ@H-FAU_3H E_{ads} = −267 kJ/mol

***Figure 1:** Representative adsorption complexes of metronidazole in FAU-type zeolites containing different numbers of aluminium atoms (green) and framework protons. For clarity, only the local environment of the adsorbed molecules is shown.*

The interaction with multiple framework protons was also one of the key research questions in a systematic study addressing the adsorption of

5-fluorouracil (5-FU), an anti-cancer drug, in FAU-type zeolites.4 Despite a relatively strong interaction with the framework, DFT-based molecular dynamics simulations including co-adsorbed water molecules showed that water quickly displaces 5-FU from the framework protons. While the competitive adsorption of water would thus have a detrimental effect on the ability of zeolites to remove 5-FU from aqueous solution, 5-FU release triggered by exposure to humidity could be interesting in a drug delivery context. Further calculations have investigated the interaction of 5-FU with extra-framework aluminium (EFAL) sites. A representative local environment, based on a previously proposed model of a framework-associated EFAL site,5 is shown in Figure 2. According to the simulations, such 5-FU@EFAL complexes are stable in the presence of water, explaining the experimental observation that 5-FU is not released from EFAL-rich FAU samples.6

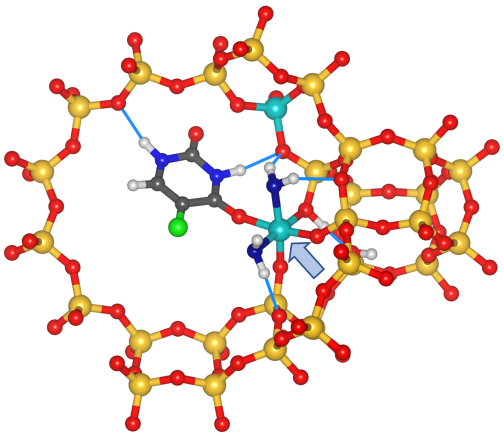


Figure 2: *Low-energy configuration of 5-FU interacting with a framework-coordinated, octahedral EFAL site in a FAU-type zeolite. The EFAL site is highlighted with an arrow.*

In aluminosilicate zeolites, the affinity towards water increases with decreasing Si/Al ratio. For that reason, relatively Al-rich zeolites are usually less suitable for the selective removal of organic contaminants from water than their Si-rich counterparts. However, they are receiving considerable attention in the field of drug delivery, where the storage and release properties can be tuned through an exchange of the charge-balancing extra-framework cations. Experimental work performed by collaboration partners showed that the adsorption of ciprofloxacin, an antibiotic, in FAU-type zeolites exchanged with different cations (Mg^{2+}, Ca^{2+}, Sr^{2+}, Zn^{2+}) is strongly affected by the cation type. Moreover, incomplete release was observed for the Zn^{2+}-exchanged zeolite. The observed trends could be explained on the basis of DFT calculations.7 Ongoing work extends this approach to bisphosphonate drugs, which are used to treat osteoporosis.

Another current, purely computational investigation looks at the adsorption of pharmaceuticals at the external surfaces of clinoptilolite, a natural zeolite that could be particularly attractive for environmental applications due to its good availability and low cost. As for the FAU-type zeolites mentioned above, particular emphasis is placed on the effect of cation exchange on the adsorption properties.

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More Information

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