Differential Adsorption of L- and D-Lysine on Achiral MFI Zeolites as Determined by Synchrotron X-Ray Powder Diffraction and Thermogravimetric Analysis

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Abstract: Reported here is the first crystallographic observation of stereospecific bindings of L- and D-lysine (Lys) in achiral MFI zeolites. The MFI structure offers inherent geometric and internal confinement effects for the enantiomeric difference in L- and D-Lys adsorption. Notable differences have been observed by circular dichroism (CD) spectroscopy and thermogravimetric analysis (TGA). Distinct L- and D-Lys adsorption behaviours on the H-ZSM-5 framework have been revealed by the Rietveld refinement of high-resolution synchrotron X-ray powder diffraction (SXRD) data and the density-functional theory (DFT) calculations. Despite demonstrating the approach for L- and D-Lys over MFI zeolites at an atomistic resolution, the differential adsorption study sheds light on the rational engineering of molecular interaction(s) with achiral microporous materials for chiral separation purposes.

Living organisms predominantly rely on the L-form enantiomer of amino acids,[1,2] such as L-lysine (Lys) and L-arginine. The L- and d-enantiomers are only different in the optical property because of the presence of a chiral carbon centre(s).[3] There are, however, limited tools to characterise the stereochemistry of the biochemical and chemical species. To the best of our knowledge, to probe the chirality of amino acids, the only available technique is circular dichroism (CD) spectroscopy.[4] There is no other existing thermal, structural, spectroscopic, or microscopic technique that can offer similar stereospecific investigation. CD relies on the observation of left-handed or right-handed circularly polarised light when the circular light interacts with a chiral centre.

As the production of non-100% enantiomeric excess (ee) is common in many chemical and pharmaceutical synthesis processes, reliable chiral separation materials are urgently required. Microporous materials, such as zeolites and metal–organic frameworks (MOFs), are one of the emerging sorbent materials for chiral separation by selective adsorption. It is because of their high internal surface area, high porosity, well-defined pore size, and tuneable binding sites.[5] For example, chiral HMOF-1 was reported for Lys separation and achiral MIL-47 and MIL-53 for ibuprofen separation.[6,4] Based on the molecular simulation, the steric confinement effect exerted by the narrow porous structure of achiral MIL-47 and MIL-53 on the bulky ibuprofen molecules leads to the stereospecific interactions.

However, the synthesis of chiral microporous materials is challenging, and hinders their potential in broader commercial applications in chiral separation. Given the low-cost and high abundance of achiral zeolites and MOFs, it is critical to study how they can separate chiral molecules. Based on DFT calculations, van Erp et al. have proposed the presence of “chiral cells” in Al-rich MFI zeolites doped with Ca2+. Also, specific metal complexes with various amino acids and organic ligands have been heterogenised into host-zeolite matrices for catalysis applications. Notable examples include zeolite-encapsulated metal-salen complexes[6] and zeolite-encapsulated amino-acid/transition-metal complexes.[7]

Our group has proven expertise in elucidating the surface interactions between gaseous adsorbate molecules and microporous materials by combining crystallographic and theoretical evidence. The slight-but-significant alteration of the scattering factors in diffraction data from state-of-the-art synchrotron X-ray facilities has enabled us to determine the atomic parameters of the adsorbate molecules about the framework. By further combining it with periodic density-functional theory (DFT) calculations, comprehensive kinetic and mechanistic information have been revealed.[10,11] The terytiary structures of the adsorbate-framework adducts demonstrate unique spatial and chemical properties, akin to the bioenzymatic systems.[12,13]

In this work, by taking advantage of the structural specificity of the zeolite MFI framework type and the molecular and stereospecificities of L- and D-Lys, the sorption interactions between Lys and the zeolitic Bronsted-acid sites (BASs) are revealed. By combining high-resolution synchrotron X-ray powder diffraction (SXRD) and DFT calculations, noticeably different adsorbate structures for L- and D-Lys on H-ZSM-5 are revealed. Through in situ SXRD and thermogravimetric analysis, the differential adsorption study sheds light on the rational engineering of molecular interaction(s) with achiral microporous materials for chiral separation purposes.

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The sorption quantity and kinetics in Figures S2 and S3, H-ZSM-5 (SiO₂:Al₂O₃ as 81 mg/g H-ZSM-5) adsorbs L- and d-Lys differently. The difference is significant and far beyond standard experimental error. It suggests both the zeolitic structure and the framework-Al concentration can play pivotal roles in the differential adsorption of L- and d-Lys, and agrees with previous computational findings.²,³ Besides the noticeable enantioselectivity as observed in high-Al H-ZSM-5(46), we also observed minor inconsistencies in the peak desorption temperatures in peak 2 in the low-Al H-ZSM-5(81, 300). As shown in the TGA of L- and d-Lys, most of the weight loss is observed at low temperature from the removal of physisorbed species. However, because of the minor and insignificant change in the TGA curves, it is hard to evaluate the difference with high certainty. From the experimental data, no clear pattern between the Al concentration (in H-ZSM-5) and the difference in TGA findings can be drawn. It is known that the Al position in zeolites is critically dependent on nature of the zeolite, precursors and synthesis conditions. Therefore, it infers that the differential adsorption property of Lys can be related to the crystallographic sitting of the Al in the H-ZSM-5 framework, which has also been demonstrated in a related computational study.³

Similarly, the sorption properties at the adsorption pH of 1.0 have also been analysed (see Figure S4), and the peak desorption temperatures are summarised in Table S1. To probe the effect of the zeolite framework type and acidity, H-MOR (MOR) and H-ZSM-5 (MFI) of different SiO₂:Al₂O₃ ratios were further studied (Figures 1c and d; see Figure S5 and Table S2). The major pore system in H-ZSM-5 (MFI framework type) possesses interconnecting straight and sinusoidal channels, whereas H-MOR only possesses straight channels (MOR framework type; see Figure S6). The main peak desorption temperatures in the H-ZSM-5 samples were measured as approximately 150–170°C, suggesting comparable BAS strength of the samples. The apparent activation energies for L- and d-Lys desorption from H-ZSM-5(46) have been approximated by the modified Arrhenius equation to be 16.69(2) and 18.96(2) kJmol⁻¹ respectively (see Figure S7 and Table S3), which fall in the diffusion control regime.⁷ It suggests that the H-ZSM-5 structure may affect the desorption route of L- and d-Lys differently.

Lys and Phe have different chemical and structural properties. The difference in the side-chain R group is: Lys has a lysyl side chain (straight chain), whereas Phe has a phenyl side chain (bulky). Whilst H-MOR does not differentially adsorb L- and d-Lys, H-MOR illustrates notable enantioselectivity in the adsorption of L- and d-Phe (as shown in the CD and TGA measurements in Figure S3 and Table S2). In contrast to the proximate peak desorption temperatures of L- and d-Lys from H-MOR (cf. 206.8°C and 207.7°C), those of L- and d-Phe from H-MOR are noticeably different (cf. 206.8°C and 201.7°C). We postulate it can be caused by the confinement effect because of the bulky Phe molecules. A more detailed discussion is described in the TGA section in the Supporting Information. Also, by comparing the peak desorption temperatures, the BAS strength (the ability to protonate incoming molecules) in H-ZSM-5 was found to be weaker than that of H-MOR. Previous computation findings have proposed that the BAS
strength is highly dependent on the zeolite structure, and is governed by the SiO$_2$:Al$_2$O$_3$ ratio: the more acute is the angle of Si-O-Al, the stronger are of the BASs.[18]

The Rietveld refinement of the SXRD data enables the direct visualisation of the adsorbate structures about the zeolitic framework. The synchrotron data were collected on Beamline I11 at Diamond Light Source (UK) and Beamline BL02B2 at SPring-8 (Japan). The X-ray energy of the incident beam was tuned to 15 keV with the calibrated $\lambda = 0.824527$ (2) Å (Beamline I11) and 18 keV with the calibrated $\lambda = 0.689556(2)$ Å (BL02B2). The tuned energy for each beamline emits the optimum X-ray flux to achieve high contrast (signal-to-noise ratio) and high angular resolution.

Herein, we will only focus on the adsorbate structures of L- and D-Lys on H-ZSM-5(46) as these two samples have the largest differences in TGA and CD measurements.

The SXRD patterns and the structural profiles are presented in Figure 2. The difference in the Bragg’s peak intensities of the SXRD patterns of L- and D-Lys pre-adsorbed onto H-ZSM-5 at pH 1.0 and 2.2 is subtle, but significant. It suggests that the adsorption behaviours of L- and D-Lys on H-ZSM-5 may affect the structural and atomic parameters. Supported by the good refinement fit (the small discrepancies in the grey difference profiles), and indicated by low-reliability factors ($R_{wp}$, $R_{exp}$ and $\chi^2$), the detailed structural parameters are presented in Table S4. At the adsorption pH of 1.0, the lattice volume is expanded by 0.33% upon L-Lys adsorption and by 0.28% upon D-Lys adsorption. Whereas, at the adsorption pH of 2.2, the lattice volume is expanded by 0.38% upon L-Lys adsorption and by 0.49% upon D-Lys adsorption. This data agrees with the previous structural findings, where the adsorption of water by H-SAPO-34 increased the cell volume by about 0.5%.[19] From the in situ SXRD measurements studying the temperature-programmed desorption behaviour, apparent differences in the desorption behaviours can be seen from the shape for the in situ SXRD profiles in Figure 2.

The Rietveld refinements of the SXRD data collected on L- and D-Lys pre-adsorbed onto H-ZSM-5 at pH 1.0 and 2.2 at 25°C revealed two independent binding sites, I and II (Wyckoff letter of 4c and 4c), which are presented in Figure 3. It agrees with our previous adsorbate-framework studies of larger organic molecules. At the adsorption pH of 1.0, the total site occupancy factor (SOF; the sum of Sites I and II) of L-Lys in H-ZSM-5 was measured as 0.90(1) (94 mg g$^{-1}$H-ZSM-5) and of D-Lys as 0.88(1) (92 mg g$^{-1}$H-ZSM-5). Whereas, at the adsorption pH of 2.2, the total SOF of L-Lys in H-ZSM-5 was measured as 0.86(1) (90 mg g$^{-1}$H-ZSM-5) and of D-Lys as 0.91(1) (95 mg g$^{-1}$H-ZSM-5). Both agree with the TGA findings.

Site I is in the sinusoidal-straight cross-channel region and Site II is in the straight channel region. From the Rietveld refined structures, both L- and D-Lys exhibit an end-on interaction to the protonic BAS (δ+). However, the chirality of Lys plays a significant role in the adsorbate geometries on the H-ZSM-5 framework, as seen in the refined structures. Taking Site I as an example, the ω-amino group in L-Lys is found to be located close to the opposite side of the ω-carboxylate group of the 10-membered ring, whereas, for D-Lys, the ω-amino and ω-carboxylate groups interact with the same side of the 10-membered ring on H-ZSM-5. The side-chain also exhibits different geometries, for example, for D-Lys on H-ZSM-5, the tail of the side-chain points downward, with the whole Lys...
The molecule appears to be coiled up. This observation infers that Site I of \textit{d}-Lys may have higher potential energy with respect to the framework, whilst Site I of \textit{l}-Lys is less strained and expresses a more stable conformation. Similar crystallographic observations can also be seen in Site II where the tail of the Lysyl R group of \textit{l}-Lys is directed to the centre of the sinusoidal channel exit, whereas that of \textit{d}-Lys is located closer to the framework wall of the sinusoidal channel. From a molecular perspective, the non-Al adjacent O framework atoms are typically believed to be quite inert in forming interactions with incoming adsorbate species.

To study the Lys–framework interactions at the atomistic resolution, the closest interatomic distance between the \textit{a}-carboxylate and \textit{a}-amino groups with the framework O atoms were analysed. Note that as H atoms cannot be directly located by this technique, the rigid framework O atoms are chosen as the crystallographic pointers in measuring the interatomic distances to represent the actual chemical acid-base information, that is, $O_{\text{framework}} - C_{\text{0}}$. The interatomic distances are comparable to those in our previous reports on the study other adsorbate molecules (namely, methanol, ammonia, pyridine, and furans) on H-ZSM-5 and H-USY zeolites. It suggests the formation of acid-base adducts between Lys and BASs. As seen in Figure 3, when \textit{l}- and \textit{d}-Lys are pre-adsorbed on H-ZSM-5(46) at pH 2.2, the closest interatomic distances observed at Site I are, for \textit{l}-Lys: $O_{9\text{LysI}} - O_{18\text{framework}} = 2.47(3)$ Å and $N_{10\text{LysI}} - O_{21\text{framework}} = 3.03(3)$ Å, and for \textit{d}-Lys: $O_{9\text{LysI}} - O_{18\text{framework}} = 3.02(3)$ Å and $N_{10\text{LysI}} - O_{21\text{framework}} = 2.74(3)$ Å. The crystallographic O21 framework site is located on the opposite side of the 10-membered ring with respect to O15 framework. Whereas, for Site II, the closest interatomic distances observed are for \textit{l}-Lys: $O_{8\text{LysII}} - O_{7\text{framework}} = 2.42(3)$ Å and $N_{10\text{LysII}} - O_{1\text{framework}} = 3.69(3)$ Å and for \textit{d}-Lys: $O_{8\text{LysII}} - O_{7\text{framework}} = 2.40(3)$ Å and $N_{10\text{LysII}} - O_{5\text{framework}} = 3.37(3)$ Å. The closest interatomic distances for \textit{l}- and \textit{d}-Lys pre-adsorbed on H-ZSM-5 at pH 1.0 are comparable to those pre-adsorbed at pH 2.2. The refined adsorbate structures are verified with our DFT calculations (Figure 4). Indeed, the adsorption mode and interatomic distances between \textit{l}- and \textit{d}-Lys and the H-ZSM-5 framework are comparable to each other.

As reported in our previous works, Site I of the H-ZSM-5 sample was determined to be the strongest adsorption site by in situ SXRD measurements.\cite{12,13} We have therefore employed DFT calculations to study the adsorbate binding structures and binding strengths at Site I. Our theoretical results derived from the DFT calculations within the CASTEP of the \textit{l}- and \textit{d}-Lys in H-ZSM-5 zeolite support the above experimental observation packages (see computational details in the Supporting Information).\cite{23–25} The DFT calculations investigated the binding behaviours of both \textit{l}- and \textit{d}-Lys in H-ZSM-5 (Al at T6 crystallographic site\cite{12,13}). The relaxed structure of the binding behaviours are shown in Figures 4a and b, and they are consistent with the Rietveld refinements.
refined crystal structures in Figure 3. The O–O and N–O interatomic distances are in the range between 2.5–3.1 Å, supporting the refinement results.

The corresponding electron density plots show a slight difference (Figures 4c and d). The binding energy of l-Lys on H-ZSM-5 is substantially reduced to 0.17 eV at 0 K, whereas d-Lys has a much higher barrier of 4.71 eV at 0 K to achieve stable binding (Figure 4e). The binding preference is also reflected by the projected partial density of states (PDOS). The overall electronic distribution of the local region of H-ZSM-5 has been modified by the binding of l-Lys, and noticeably shifted the valence bands. By further comparing the PDOS (see Figure 4(f)), the H-ZSM-5 framework can better stabilise l-Lys on the internal surface. From the DFT calculated difference in adsorption binding energies, the differential adsorption of Lys as observed can be accordingly explained. Consistent with the TGA and CD findings, d-Lys is more preferentially adsorbed by the H-ZSM-5 samples. The BAS and the MFI framework make the channel exit at the intersection physically different from each other and renders an active chiral environment to offer enantiospecific localization adsorption geometries for l- and d-Lys.

In summary, the interactions between chiral l- and d-Lys molecules and the achiral microporous surface of H-ZSM-5 have been elucidated at an atomistic resolution. MFI and MOR, with specific framework Al distributions, show notably different enantioselective properties on straight-chain Lys and bulkier Phe. In agreement with previous computational reports, achiral zeolite frameworks can provide unique local adsorption geometries which may consequently offer enantioselectivity. This combined structural-computational analysis can be transferable to investigation of the stereoselectivity in related microporous materials, and can also offer practical insights into the rational design of achiral solid-state materials for chiral separation.

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Conflict of interest

The authors declare no conflict of interest.

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Chiralität

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