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CONSEQUENCES OF CONFINEMENT FOR CATALYSIS WITHIN VOIDS OF MOLECULAR DIMENSIONS

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Present state of research on confinement effects and transition state selectivity in catalysis by microporous solids

Shape selectivity concepts have sought to capture the ability of voids of sub-nanometer size to control molecular traffic via diffusional constraints and to stabilize transition states via specific contacts between organic guest moieties and the inorganic confining voids with the intent to control reactivity and selectivity in chemical transformations on microporous solids. H-forms of zeotypes, most prominently of aluminosilicate composition, act as Brønsted acids with conjugate anions of stability that are essentially independent of the framework type; van der Waals stabilization of bound species, intermediates, and transition states combine in practice to bring remarkable catalytic diversity to zeotype frameworks that differ in structure, but are similar otherwise in composition and acid strength. Each framework type, in turn, contains distinct crystallographic sites, in which the presence of Al and charge-balancing cations lead, in turn, to different confining environments. Differences in size and shape among transition states, bound precursors, and the confining voids, taken together with the ∼200 known zeotypes continue to provide the design flexibility that underpins the spectacular success of zeotypes in the practice of catalysis.

Recent experimental and theoretical developments that address the mechanism of chemical transformations and the structure and binding properties of inorganic solids have led to a shift from heuristic geometric constructs towards firmer conceptual grounds; in doing so, they have created unexpected practical successes. This account describes some examples of how the preferential stabilization of a transition state brings forth specific enhancements in reactivity or selectivity, mediated by entropic or enthalpic effects that lower the activation free energies of elementary steps. In doing so, the examples chosen illustrate how the placement and detection of binding sites at specific locations, the mechanistic expression of reactivity in terms of elementary steps, and the interpretative and design prowess of modern theoretical treatments that describe dispersion forces and entropic effects combine to provide predictive guidance and, quite often, unprecedented quantitative assessments. As a result, reactivity descriptions based on geometry or acid strength are

replaced by their more relevant energetic descriptors — van der Waals confinement energies, proton affinities of organic molecules, and deprotonation energies — to account for reactivity, here for different reactants on diverse solid acids, but in general for catalysis within confined spaces. The focus here on confinement effects, to the exclusion of other features also relevant for reactivity, merely reflects the focus of the session and the limitations of space.

Recent research contributions to catalysis by microporous materials

Enthalpic stabilization of transition states within siliceous voids of molecular dimensions without specific binding sites [1, 2]

The concept of "physical catalysis" denotes the ability of a confining pocket of molecular dimensions to enhance the rate of homogeneous reactions without effecting specific interactions of transition states or intermediates with any type of binding site. Mesoporous silicas and purely siliceous zeolites (SIL, CHA, BEA) catalyze reactions between NO and O_2 at near ambient temperatures with kinetic trends identical to those in homogeneous routes [1]. NO oxidation rates are 10^2–10^4 times higher within the intracrystalline void space than in the extracrystalline gas phase; such rates are similar on SIL materials with and without silanol defects. Such remarkable rate enhancements reflect the stabilization of termolecular transition states (TS) by confinement, mediated by van der Waals forces and without the involvement of specific binding sites. Voids enthalpically stabilize TS structures similar to those prevalent in homogeneous routes, leading to negative apparent activation energies and to unprecedented reactivity at the near ambient temperatures that favor NO_2 formation thermodynamics. The concomitant entropy losses upon confinement become inconsequential because of the preeminent role of enthalpy for Gibbs free energies at these low temperatures. These data and their mechanistic interpretation provide clear evidence for the mediation of molecular transformations by mere confinement of TS structures, without the specific chemical binding of any reactants or transition states at active sites. These interpretations and the non-chemical nature of the stabilizing interactions are consistent with density functional theory treatments that accurately describe measured rate enhancements when using density functionals accounting for dispersion forces, but which predict no detectable rate enhancements with functionals that exclude these interactions [2]. This example of catalysis without specific binding finds practical outlets in the management of NO_x emissions via lean deNO$_x$ traps, during fast selective catalytic reduction strategies mediated by NO_2, and in the synthesis of nitrates and nitric acid. The underpinning phenomena, however, are likely to prevail and to impact other low-temperature associative or radical-mediated chemical transformations that proceed, albeit slowly, as homogeneous reactions at low temperatures, such as acetylene trimerization, triene cyclizations, and Diels–Alder reactions in general.

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Remarkable specificity of active sites within eight-member ring (8-MR) structures for the carbonylation of methyls to acetyls [3–5]

The most useful (and only known) selective route for the formation of a single C–C bond between C_1 molecules is the carbonylation of methanol to acetic acid, a reaction currently practiced in large scale using organometallic complexes of precious metals and CH_3I intermediates. Persistent efforts to react CO with CH_3OH on acid-forms of zeotypes led to very low rates and fast deactivation, symptomatic, as shown later [3], of the competing hydrolysis of bound methyls with H_2O molecules formed via fast CH_3OH homologation and dehydration reactions, of the weak nucleophilic nature of CO, and of voids that did not preferentially stabilize the carbonylation TS in the chosen zeotypes. These hurdles were surmounted by using DME instead of CH_3OH, thus ensuring anhydrous conditions during catalysis, and by the discovery that 8-MR structures provide voids that are uniquely capable of enforcing effective van Waals contacts with the carbonylation transition state [3, 4]. In doing so, the paradigm of a given framework type as a unique descriptor of its catalytic properties was revisited, making the placement of heteroatoms, Al in the case of aluminosilicate acids, at crystallographic sites with diverse local environments for a given silicate framework a design criterion for reactivity and selectivity. Such findings led the field to seek synthesis protocols that purposely place heteroatoms at specific locations, as well as chemical or spectroscopic means to assess the success of these protocols.

Carbonylation occurs on acid forms of zeotypes via a kinetically-relevant step consisting of backside attack by CO on DME-derived bound methyls at Al sites, as shown by kinetic and isotopic data, infrared spectra, and transient placement and scavenging of bound CH_3 groups within different crystalline aluminosilicates [3, 4]. The relevant transition state structures are preferentially stabilized (relative to their bound CH_3 precursors) at 8-MR motifs that prevail in MOR and FER frameworks, leading to the formation of methyl acetate with > 99% selectivity at 450–500 K. Al sites within larger voids (10-MR, 12-MR motifs) lead to much lower rates and to unselective homologation reactions.

Such inferences about mechanisms and structural motifs required the emergence of methods to assess the number, type, and location of active sites within environments that differed markedly in accessibility and confining properties. The use of organic titrants of different size and the deconvolution of location-dependent O–H infrared bands led to the accurate assignment of reactivity at each specific location, while exchanged cations and controlled dealumination created novel materials with diverse distributions of Al and protons among void environments. The correlation between 8-MR Al sites and carbonylation turnover rates led, in turn, to a conceptual framework for seeking even more reactive void structures. Such specificity of methyl reactivity through confinement within small channels was not anticipated; it was considered unprecedented at the time for microporous inorganic solids, which typically influence reactivity by mere size exclusion of bulkier transition states or

by controlling molecular access to active sites. These confinement effects depend on an appropriate "fit" that causes van der Waals forces to preferentially stabilize the TS relative to its relevant precursors. The preeminent role of dispersive forces is evident in DFT-derived carbonylation TS enthalpies that are not influenced by location when using functionals that neglect such forces, but become favored at 8-MR locations when using either higher levels of theory or functionals that describe non-specific induced dipole interactions. As in NO oxidation, the enthalpic benefits of confinements in carbonylation prevail over the concomitant entropic penalties at low temperatures, for which the right fit becomes a tighter fit for TS structures than for their bound precursors.

Transition state entropies and the benefits of looser fits and of partial confinement at higher reaction temperatures [5–8]

As the previous two examples show, confinement imposes enthalpy-entropy compromises that determine the free energies of TS and precursor structures and thus turnover rates. The key-lock visual constructs of enzymatic and host-guest chemistries rely on "shape matching" formalisms that enhance enthalpic stabilization through effective contacts between organic moieties and confining voids. Inorganic voids, with their remarkable structural integrity, significantly extend the useful temperature range, thus becoming practical in catalysis of endothermic reactions that are thermodynamically infeasible at lower temperatures. At higher temperatures, looser fits and the concomitant higher entropies of transition states can offset the enthalpic benefits of confinement and lead to lower activation free energies. These preeminent effects of entropy at high temperatures became evident in alkane dehydrogenation and cracking on microporous solid acids [5], for which the marked effects of alkane size on reactivity were shown to reflect the higher entropy of late transition states, at which alkane or H_2 leaving groups acquire significant mobility at ion-pair transition states. Yet, their turnover rates are higher in 8-MR pockets than in larger 12-MR channels in MOR, in spite of seemingly tighter environments. In fact, the relevant transition states are confined only in part within the shallow 8-MR pockets; as a result, they retain higher entropies than fully-confined structures, but also the ability to interact with the locally confined conjugate anion formed upon proton transfer to form the transition state. Partial confinement and the concomitant entropic benefits cause the preferential stabilization of the looser ion-pair TS structures that prevail for transition states with higher enthalpies. Such TS structures tend to occur later along the reaction coordinate, causing partial confinement to favor the more enthalpically demanding reactions among competing paths; for instance, dehydrogenation of linear alkanes (versus cracking) and cracking of isoalkanes (versus dehydrogenation) are favored at protons in 8-MR pockets over those in larger 12-MR channels in MOR frameworks. Partial confinement accounts for ubiquitous phenomena often described as "pore mouth catalysis"; it also provides predictive guidance for altering selectivities by placing protons at specific

locations within crystalline aluminosilicate frameworks otherwise indistinct in acid strength [9]. The examples discussed so far underscore the role of temperature as the arbiter of enthalpy-entropy compromises in determining activation free energies and thus rates and selectivities in acid catalysis within confining voids.

Mechanism-based descriptors of confinement effects — from geometry-matching to activation free energies and from static to dynamic constructs of host–guest interactions [10, 11]

Mechanistic interpretations of measured turnover rates enable the assignment of precise chemical origins to kinetic and thermodynamic constants in rate equations, as well as the identification of specific transition states and intermediates that determine activation free energies. In acid catalysis, the free energy differences responsible for reactivity and selectivity reflect the (relative) stabilization of transition states and their relevant precursors via electrostatic interactions that depend on acid strength, a property that is similar for protons in all aluminosilicate frameworks [9], and through van der Waals interactions imposed by confinement within voids of molecular dimensions. The two examples in this section illustrate the evolution of descriptors of confinement from those based on rigid shapes and sizes to ones involving estimates of van der Waals energies and dynamic structures in order to describe geometry-matching in a manner that reflects the rigorous kinetic and energetic contexts of confinement.

The remarkable ability of small inorganic voids to stabilize molecular guests has been assessed until recently using formalisms based on geometric similitude and on heuristic topological descriptions of the void space [12], often as visual descriptors based on the largest spheres that can be either inscribed or translated without obstructions throughout a porous solid [13]. These geometric descriptors are being replaced with experimental and theoretical physisorption energies for molecular proxies of the relevant transition states [10] and with theoretical estimates of interaction energies and specifically of their dispersive components. The latter are enabled by dispersion-corrected density functionals that detect how inorganic frameworks distort in response to molecular guests in order to enforce more effective van der Waals contacts with guest species [11].

The first-order rate constants for acid-catalyzed CH_3OH dehydration to DME reflect the free energies of bimolecular transition states relative to their smaller H-bonded CH_3OH precursors. They depend exponentially on measured adsorption energies of n-hexane probe molecules and on the ensemble-averaged dispersive components of DME adsorption enthalpies derived from DFT or Lenard-Jones potentials on FAU, SFH, BEA, MOR, MTW, MFI, and MTT zeolites [10], indicating that van der Waals forces predominantly account for the diverse reactivity of these different frameworks. In contrast, zero-order rate constants reflect the stability of the same transition state, but relative to similarly-sized CH_3OH dimers; as a result, measured (and DFT-derived) rate constants depend only weakly on the nature of

the void space, because dispersive forces stabilize guests of similar size to the same extent. These results, taken together, demonstrate the preeminent effects of confinement on zeolite reactivity and the manner by which the local voids within different intracrystalline environments give rise to the remarkable catalytic diversity of aluminosilicates. Enthalpic stabilization prevails over entropy losses upon confinement at these low temperatures (400–450 K), in a manner reminiscent of the effects of solvents and of "pockets" in catalysis by molecular complexes and enzymes.

Kinetic and infrared data and theoretical treatments that account for dispersive interactions show that alkene dimerization rate constants on aluminosilicates (TON, MFI, BEA, FAU, mesoporous MCM-41) reflect the free energy of the bimolecular C–C bond formation TS referenced to alkene-derived monomers [11]. These activation barriers decrease as voids approach the size of transition states given by theory, thus causing TS structures to be preferentially stabilized over smaller bound precursors via contacts with the confining framework. Such heuristic geometric analogies are being replaced by the dispersive components of DFT-derived energies for TS and intermediates; these descriptors account for size and shape and for the most effective "fit" for a given reaction among different frameworks. The dispersion forces recently built into density functionals allow structure optimizations of TS and bound intermediates to balance the energy costs of framework distortions with any concomitant enhancements of van der Waals contacts with guest molecules. These distortions lead to global energy minima and optimal reaction paths and cause framework O-atom displacements to vary systematically with the size and shape of TS and precursor structures. It seems plausible that such lattice distortions upon adsorption of guest molecules are larger and most consequential near the external surfaces of zeolite crystals; they may therefore shed light on phenomena, such as "skin effects" and "pore mouth catalysis", typically invoked with limited mechanistic evidence to account for some unexpected effects of external crystal surfaces on diffusion and catalysis.

Perspectives, advances and opportunities in catalysis by microporous solids

The examples and concepts described herein have relied on mechanistic details and practical advances made evident by advances in (i) the synthesis of materials with well-defined structures, high crystallinity, and isolated O–H species acting as Brønsted acids of uniform strength; (ii) methods that determine the number (and in some cases the location) of accessible protons during catalysis; (iii) measurements of rate and selectivity data in the absence of (or with known) diffusional constraints; and (iv) mechanistic interpretations underpinned by theoretical methods that account for van der Waals interactions and which allow increasingly accurate estimates of the entropy and enthalpy components of activation free energies. In all aspects of these enabling advances, the merits and the impact remain largely unexploited and the hurdles become more difficult as the easier challenges are met. Yet, the

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conceptual and practical benefits of confinement and solvation by van der Waals forces are likely to move forward undeterred, as the methods of interrogation emerge to match the tasks at hand.

A single zeolite framework itself contain a range of local void environments, each with distinct reactivity and selectivity; as a result, varying the distribution of protons among these locations within a given framework, selectively adding or removing sites within specific locations, or modifying a given location by partial occlusion of the void space can significantly extend the range of catalytic opportunities for zeolites. Yet, synthetic protocols that purposely direct the location of framework heteroatoms and their balancing cations remain sparse and far from general in applicability. Inferences about the location, and thus the success of synthesis strategies, are possible today only for very distinct environments, allowing knowledge to be brought only into the most egregious differences in environment. The local and selective modification of the void environment near active sites without the introduction of unintended diffusional hurdles remains anecdotal and accidental for those few examples that have seemingly succeeded in practice.

Knowing what to make and for which reactions to make it remains the enduring challenge that precedes the process of learning how to make a structure for a specific purpose; being able to know what one has made remains the ultimate arbiter of success or failure in making that structure. The ubiquitous deployment of a mere handful of zeolites for many practical reactions, among the several hundred known structures attest to the challenges of matching function with structure, and serves to remind us that solutions may lie undiscovered amongst materials already at hand without always requiring the discovery of new frameworks. These sharper methods for searching are based on answering questions about what limits reactivity, and thus selectivity among competing paths; in more colloquial terms, one asks: "what do we measure when we measure a rate." Here, mechanistic interpretations, even incomplete or speculative ones, provide the only reliable method in the search for improvements. These require the dissection of chemical reaction rates into elementary steps, a task that starts with the collection of reliable rate data, the exclusion of (or accounting for) diffusional effects, the spectroscopic and isotopic interrogation of plausible steps and intermediates, and the elimination of implausible mechanistic proposals using theory at the state-of-the-art. The impact of theoretical methods in systems where reactivity is driven by confinement effects has been rather recent, as density functionals and higher levels of theory have become increasingly adept at describing dispersion forces and at handling systems of increasing chemical and structural complexity, a trend that will certainly continue.

Acknowledgments

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