

Emerging solutions (and explanations) for catalysis problems posed long ago: LSAC contributions over the last decade (2014-2023)

This is a summary of the research accomplishments of members of the LSAC group at the University of California at Berkeley. The contributions described below are grouped together by the concepts (and conundrums) that motivated each body of work. The enumeration is presented in a sequence that is unrelated to its significance or impact to avoid the perception (or reality) of personal judgement and taste.

The tone and content of each body of work evolved during this decade -- from inquisitive to explicative, and ultimately, in most cases, to predictive, often based on our earlier work, and with a script punctuated by each manuscript. Along the way, the concepts and the explanations have become more detailed and quantitative, but also, in many cases, simpler in form. To our occasional surprise, some of the knowledge became ultimately useful, often in contexts and for chemistries not meant to be captured by our original intent.

The molecules, reactions, and catalysts differed among these areas, but the methods of inquiry endured throughout:

- (i) let molecules speak through their kinetic trends, descriptors of reactivity, and isotopic effects
- (ii) let the structural uniformity of catalyst architectures bring clarity to the discourse and literacy to the language
- (iii) let the enumeration and identification of active surface structures and bound species e.g., by spectroscopy, titrations during catalysis, ...) guide the search for accurate structures to assess by theory
- (iv) let photons report on intermediates and structure as reactions occur, lest we perturb that which we seek to observe
- (v) let energies (instead of geometries) become the language of descriptors of reactivity, for molecules and surfaces
- (vi) let theory settle the choice of mechanism (among those not clearly contradicted by experiments), discard those blatantly absurd, and confirm descriptors of reactivity and selectivity that would remain phenomenological without theoretical inquiries
- (vii) let thermodynamics guide (and restrict) the boundaries of what dynamics are able to accomplish (and mind fugacities and chemical potentials in non-ideal environments, such as liquids, confined spaces, and dense adlayers)
- (viii) let concepts and answers transcend the specific molecules, catalysts, chemistries, and questions at hand
- (ix) let chemistry be dissected from behind the veils of transport
- (x) let hypotheses be contradicted as soon as possible, so that better hypotheses are forced to emerge

Enrique Iglesia (21 September 2023)

1. Alkane dehydrogenation on “uncovered” Lewis acid-base pairs at surfaces of earth-abundant oxides

Four patent applications (one unpublished) and three manuscripts in draft form describe the use of chemical treatments to remove strongly bound H₂O and CO₂ from the most competent M–O Lewis acid-base site pairs on earth-abundant oxides. These chemically-treated oxides were used in heterolytic C–H activation reactions that mediate the dehydrogenation of alkanes (and in its reverse - alkene hydrogenation) without the sintering and annealing caused by thermal treatments in inert environments, which seek to remove bound titrants, but also decrease both the surface area of the oxides and the areal density of the most competent C–H activation sites. These effects were demonstrated on ZrO₂ (monoclinic and tetragonal), Y₂O₃, CeO_x, and mixed oxide structures thereof. Dimethyl ether and methanol are the most effective chemical treatment agents because they react with surface O–H groups via “reforming” reactions without side reactions that generate unreactive residues; they are able to dehydroxylate surfaces at temperatures (500 K) much lower than those required in treatments with He, O₂, or H₂. These chemical dehydration (and decarboxylation) treatments lead to gravimetric alkane dehydrogenation rates even higher than those on Pt-based materials (and much higher than those on Cr-based catalysts) at 700–900 K for ethane, propane, *n*-butane, and isobutane. The remarkable reactivity chemically treated requires catalytic reactions to be carried out under strictly anhydrous and anaerobic conditions for stable rates, because of the irreversible titration of active sites by H₂O; these findings were then used to accurately measure the number of active sites via titration during catalytic dehydrogenation reactions, thus allowing rigorous measurements of the specific activity of the very reactive sites uncovered by these chemical treatments. These rate enhancements are also observed for the respective reverse reactions (alkene hydrogenation) and their rates can be calculated directly from dehydrogenation rates using the thermodynamic properties of gaseous reactants and products. Kinetic and isotopic data and theoretical models have shown that rates are limited by heterolytic C–H activation (and proton addition to C_nH_{2n+1} anions for hydrogenation); the anionic intermediates involved disfavor C–C cleavage over β-hydride elimination events, leading to dehydrogenation selectivities above 99% at 700-900 K.

Patents (all numbers cited refer to those in the Iglesia CV)

50. Iglesia, E., Dellamorte, J.C., Fu, T., Dutta, B., and Miao, G., **WO2021/194663 (2021)** (“Catalyst Compositions and Methods of Preparation and Use Thereof”)
49. Iglesia, E. and Shangguan, J., **WO2022/132843 (2022)** (“Pre-treating Metal Oxide Catalysts for Alkane Dehydrogenation”)
48. Iglesia, E., Dellamorte, J.C., Fu, T., and Dutta, B., **WO2021/1173333 (2021)** (“Catalyst Compositions and Methods of Preparation Thereof”)

2. Hydrogen spillover” revisited and resolved (hydrogenation and dehydrogenation catalysis)

The significant effects of non-innocent supports on metal-catalyzed hydrogenation rates (for toluene in the specific article listed below) often attributed to the spillover of H-atoms from metal nanoparticles to oxide supports have been shown to arise instead from the scavenging of unreactive, yet desorbable, species formed at metal surfaces via sequential addition of H-atoms to unsaturated substrates. Their diverse coverages and reactivity cause Pt surfaces to become preferentially occupied by less reactive isomers at the expense of the more competent isomers that account for most hydrogenation turnovers. These phenomena were demonstrated through the use of (i) kinetic analysis and theoretical assessment of plausible bound species; (ii) physical mixtures of Al₂O₃, TiO₂, ZrO₂, and MgO with samples consisting of Pt nanoparticles dispersed on inert SiO₂ supports; (iii) the elimination of rate enhancements on physical mixtures by titration of Lewis acid-base pairs on competent supports with added propionic acid; (iv) the demonstrated competence of the active supports in the hydrogenation of analogs to methylcyclohexene and methylcyclohexadiene species desorbed from the less competent intermediates prevalent at metal nanoparticle surfaces.

Such interpretations exclude the (implausible) migration of H-atoms on insulating and semiconducting oxides that have shown the phenomenological rate enhancements attributed to such “hydrogen spillover” phenomena, a moniker that gave birth to five international symposia under the rubric of atomic hydrogen mobility and its role in the “activation” of refractory support surfaces for hydrogenation reactions; in fact such support surfaces are active on their own, but for the hydrogenation (and dehydrogenation) of cyclic alkenes and alkadienes derived from arenes (and cyclic alkanes), but not for the respective reactants in hydrogenation and dehydrogenation catalysis. These observations and interpretations were originally uncovered through a detailed study of the mechanism of toluene hydrogenation on Pt, in which it was shown that high coverages of toluene or partially hydrogenated toluene-derived species are present during reactions and that their “landing ensembles” differ in size. Their extension to dehydrogenation reactions was demonstrated for reactions of alkyl cycloalkanes on Pt and Pd nanoparticles; these molecules and processes are of interest in the emerging applications of organic molecules as liquids that can store, carry, and release hydrogen in their intended markets of use (two manuscript in final draft form).

356. Fischer, A. and Iglesia, E., **Journal of Catalysis** **420** (2023) **68** (“Perspectives on “Hydrogen Spillover”: Site Proximity Effects and Gaseous Intermediates in Hydrogenation Reactions Mediated by Inhibitor-Scavenging Mechanisms”) doi.org: [10.1016/j.jcat.2022.11.013](https://doi.org/10.1016/j.jcat.2022.11.013)

3. Synthesis and structural and functional characterization of monometallic and bimetallic nanoparticles confined within small voids.

The direct confinement of metal and alloy nanoparticles (with >90% encapsulation selectivity) within small-pore and medium-pore zeotypes (aluminosilicates and titanosilicates) was achieved through a combination of hydrothermal methods using protected metal precursors, intrazeolite transformations, and titanosilicate synthesis methods that avoid high framework crystallization temperatures. Selective titration of external nanoparticles and competitive reactions of large and small substrates were used to demonstrate an unprecedented degree of encapsulation. These methods were demonstrated for noble metal (Pt, Pd, Au) and base metal oxide (Co, Ni, Fe) nanoparticles, as well as for the formation of well-mixed and size-uniform bimetallic particles. These nanoparticles locally distort the encapsulating framework with an energy penalty that discourages further growth beyond 2-3 nm. Au precursors are especially susceptible to reduction at the pH and temperature required for zeotype crystallization, especially for titanosilicates (TS-1), which typically require temperatures above 450 K for crystallization; Au nanoparticles were successfully encapsulated within TS-1 to yield active epoxidation catalysts with H₂O-O₂ mixtures as oxidants through the use of S-based ligands and novel TS-1 synthesis protocols; these strategies that have been covered recently in three patents and several publications.

354. Otto, T., Zhou, X., Zones, S.I., and Iglesia, E., **Journal of Catalysis** **410** (2022) **206** (“Synthesis, Characterization, and Function of Au Nanoparticles Encapsulated within TS-1 Zeotype Frameworks as Catalysts for Propene Epoxidation with O₂/H₂O Reactants”) doi.org/10.1016/j.jcat.2022.04.002
313. Otto, T., Zones S., and Iglesia, E., **Journal of Catalysis** **339** (2016) **195** (“Challenges and Strategies in the Encapsulation and Stabilization of Monodisperse Au Clusters within Zeolites”) doi.org/10.1016/j.jcat.2016.04.015
308. Otto, T., Ramallo-Lopez, J.M., Giovanetti, L., Requejo, F.G., Zones, S., and Iglesia, **Journal of Catalysis** **342** (2016) **125** (“Synthesis of Stable Monodisperse AuPd, AuPt and PdPt Bimetallic Clusters Encapsulated with LTA-Zeolites”) doi.org/10.1016/j.jcat.2016.07.017
295. Goel, S., Zones, S., and Iglesia, E., **Chemistry of Materials** **27** (2015) **2056** (“Synthesis of Zeolites via Interzeolite Transformations without Organic Structure-Directing Agents”) doi.org/10.1021/cm504510f
286. Goel, S., Zones, S.I., and Iglesia, E., **Journal of the American Chemical Society** **136** (2014) **15280** (“Encapsulation of Metal Clusters within MFI via Interzeolite Transformations and Catalytic Consequences of Cluster Confinement”) doi.org/10.1021/ja507956m
332. Otto, T., Zones, S.I., and Iglesia, E., **Microporous and Mesoporous Materials** **270** (2018) **10** (“Synthetic Strategies for the Encapsulation of Nanoparticles of Ni, Co, and Fe Oxides within Crystalline Microporous Aluminosilicates”) doi.org/10.1016/j.micromeso.2018.04.045
319. Otto, T., Zones, S., Hong Y., and Iglesia, E., **Journal of Catalysis** **356** (2017) **173** (“Synthesis of Highly-Dispersed Cobalt Oxide Clusters Encapsulated within LTA Zeolites”) doi.org/10.1016/j.jcat.2017.10.017

47. Otto, T., Zones, S.I., and Iglesia, E., **U.S. Patent 10,512,904 (2019)** (“Zeolitic Materials Having Encapsulated Bimetallic Clusters”).
46. Goel, S., Zones, S., and Iglesia, E., **U.S. Patent 9,938,157 (2018)** (“Interzeolite transformation and metal encapsulation in the absence of a structure directing agent”).
45. Goel, S., Zones, S., and Iglesia, E., **U.S. Patent 9,802,831 (2017)** (“Synthesis of high- silica zeolite via interzeolite transformations without organic structure directing agents”).

4. Bimolecular reactions as prevalent reaction channels on surfaces covered by dense adlayers

A body of work initially motivated by CO and NO reactions that occur ubiquitously on surfaces densely covered by CO adlayers led to a general postulate (#297) about the prevalence of bimolecular reactions over unimolecular dissociation routes, previously considered to require special defect sites in an attempt to reconcile catalytic rates with model surface studies and theory focused on nearly bare surfaces. This contrasts the coherence among theory, surface science, and catalytic experiments that prevails in studies of NH₃ synthesis, a reaction that occurs, at conditions of practice, on essentially bare surfaces. These bimolecular channels include the H-assisted dissociation of CO and NO and the CO-assisted dissociation of O₂, among others described in the account cited above.

The CO hydrogenation (Fischer-Tropsch synthesis) work brought this concept into practice (as summarized the Perspective denoted as #352) through the demonstration that:

- (i) CO dissociation occurs predominantly after the addition of one or two H-atoms at the C and O atoms of CO, thus resolving long-standing mechanistic inconsistencies between theory, model surfaces, and experiments at conditions of practice.
- (ii) Chains grow very long through rapid C-C bond formation because growing chains locally disrupt dense CO adlayers, thus creating “spaces” that allow H-assisted CO dissociation events (without requiring the desorption of chemisorbed CO to create such spaces) at sites vicinal to growing chains because they locally disrupt dense CO adlayers.
- (iii) Repulsive interactions within dense CO adlayers destabilize bound CO species, thus allowing their desorption to create “landing ensembles” that can stabilize the CO dissociation transition states; as CO adlayers densify with increasing CO pressure repulsive effects affect the transition state more weakly than the chemisorbed CO molecules that must be removed, thus leading to CO hydrogenation rates higher than predicted from Langmuirian kinetic models.
- (iv) Previously unexplained effects of H₂O in enhancing rates and chain growth selectivity were shown to involve proton-coupled electron transfer events that increase the rate of H addition to bound CO through a combination of theoretical treatments and mechanistic analysis of measured isotope effects and kinetic trends.

Most recently (#350), these concepts were demonstrated also for CO₂ hydrogenation catalysis on Ru, Co, and Ni nanoparticles on which CO₂ dissociation is fast and quasi-equilibrated and the formation of hydrocarbons proceeds through reactions of CO intermediates on dense CO adlayers, such as those previously uncovered for reactions of CO-H₂ mixtures. These findings and mechanistic interpretations have led to novel bifunctional routes and reactor operating strategies to form either CO or hydrocarbons.

352. Iglesia E. and Hibbitts, D., **Journal of Catalysis** **405** (2022) **614** (“The Fischer-Tropsch synthesis: Some Enduring Mechanistic Conundrums Revisited”) doi.org/10.1016/j.jcat.2021.10.033
326. Liu, J., Hibbitts, D., and Iglesia, E., **Journal of the American Chemical Society** **139** (2017) (11789) (“Dense CO Adlayers as Enablers of CO Hydrogenation Turnovers on Ru Surfaces”) doi.org/10.1021/jacs.7b04606
316. Hibbitts, D.D., Dybeck, E., Lawlor, T., Neurock, M., and Iglesia, E., **Journal of Catalysis** **337** (2016) **91** (“Preferential Activation of Carbon Monoxide near Hydrocarbon Chains during Fischer-Tropsch Synthesis on Ru”) doi.org/10.1016/j.jcat.2016.01.010
277. Loveless, B., Buda, C., Neurock, M., and Iglesia, E., **Journal of the American Chemical Society**, **135** (2013) **6107** (“CO Chemisorption and Dissociation at High Coverages during CO Hydrogenation on Ru Catalysts”) doi.org/10.1021/ja311848e
273. Hibbitts, D., Loveless, B., Neurock, M., and Iglesia, E., **Angewandte Chemie**, **52** (2013) **12273** (“Mechanistic Role of Water on the Rate and Selectivity of Fischer-Tropsch Synthesis on Ruthenium Catalysts”) doi.org/10.1002/anie.201304610
350. Mansour, H. and Iglesia, E., **Journal of the American Chemical Society** **143** (2021) **11582** (“Mechanistic Connections between CO₂ and CO Hydrogenation on Dispersed Ruthenium Nanoparticles”) doi.org/10.1021/jacs.1c04298
297. Hibbitts, D.D. and Iglesia, E., **Accounts of Chemical Research** **48** (2015) **1254** (“The Prevalence of Bimolecular Routes in the Activation of Diatomic Molecules with Strong Chemical Bonds on Catalytic Surfaces”) doi.org/10.1021/acs.accounts.5b00063

5. The mechanism of formation of filamentous carbon species and the role of “reaction-derived organic residues” as previously unrecognized organocatalysts for alkane dehydrogenation rates

These findings are covered in two articles that address (i) the mechanism of formation of filamentous carbon on Ni nanoparticles, relevant to deactivation processes in methane reforming reactions and to the purposeful formation of carbon nanotubes; and (ii) the unrecognized role of reaction-derived organic residues in mediating alkane dehydrogenation reactions that are distinct in mechanism but are as functionally competent as Brønsted acid sites that catalyze alkane dehydrogenation reactions via carbonium-ion transition states.

The diffusion-reaction processes required for filament growth from CH₄-H₂O-CO₂ reactants as they undergo catalytic reforming reactions on Ni nanoparticles are reported based on real-time analysis of filament growth and CH₄ reforming rates as a function of the chemical potential of chemisorbed carbon intermediates during steady-state catalysis; the mechanistic analysis of these filament formation processes requires non-equilibrium thermodynamic formalisms of both chemical reactions and diffusion processes. The results provide predictive descriptions of the conditions that prevent filament growth, but also of those that lead to different selectivities for the formation of filamentous or onion-like encapsulating carbon structures. In doing so, these treatments describe the requirements for stable operation, deactivation, and bed/pore plugging in methane reforming reaction, as well as several strategies for the purposeful formation of carbon nanotubes.

The other study (#344) resolved long-standing inconsistencies in reported alkane dehydrogenation turnover rates by recognizing, detecting the presence of reaction-derived organic residues (and measuring their rates of formation), and establishing their significant role in the formation of alkenes, via processes previously presumed to occur only at Brønsted acid sites. In doing so, these measurements showed how the temporal and spatial “history” of the sample, and specifically the presence of H₂, whether formed as a product of the reaction or added to inlet streams, influences alkane dehydrogenation rates. Such organocatalyst-mediated rates were directly associated with the amount and type of the organic residues and showed kinetic trends that were detectably distinct from those of dehydrogenation events on zeolitic protons (e.g., H₂ inhibits rates on organic-derived species, but not on protons). These organocatalysts are proposed to function via sequential H-transfer from alkenes and the subsequent evolution of H₂ from such organic residues to restore their ability to abstract H-atoms from alkanes.

348. Leung, S. L., Wei, J., Holstein, W. L., Avalos-Borja, M., and Iglesia, E., **Journal of Physical Chemistry C** **124** (2020) **20143** (Dynamics and Mechanism of Carbon Filament Formation during Methane Reforming on Supported Nickel Clusters”). doi.org/10.1021/acs.jpcc.0c05590
344. Kester, P.M., Gounder, R., and Iglesia, E., **Journal of Physical Chemistry C** **124** (2020) **15839** (“Alkane Dehydrogenation Catalyzed by Brønsted Acidic and Reaction-Derived Carbonaceous Active Sites in Zeolites”) doi.org/10.1021/acs.jpcc.0c01808

6. Reactivity (and selectivity) descriptors in oxidation (#311) and (Brønsted) acid (#287, #310, #346) catalysis

These studies report synergistic combinations of theory and experiments to assess the relevant molecular and catalyst descriptors of reactions catalyzed by redox-active oxides and Brønsted acids. They demonstrate how frequently proposed independent descriptors of the stability of the relevant transition states fail to account for how the organic and inorganic moieties perturb each other as they interact in forming adducts at such transition states.

The activation of C-H bonds via H-abstraction from alkanes, alkenes, alkanols, and alkanals by O-atoms in redox active oxides forms radical-like species and is mediated by transition states with energies that depend on the C-H homolytic dissociation energy for each distinct C-H bond in these

reactants. These transition states exhibit di-radical moieties with organic and inorganic components that feature, respectively, nearly-cleaved C–H bonds and nearly-formed O–H bonds; the radical interactions between these components resemble those encountered in molecular magnets. The relevant catalyst descriptor is, therefore, the hydrogen addition energy (HAE; the energy of formation of the O–H bond at oxide surfaces); when combined with molecular descriptors, HAE provides an accurate description for each type of C–H bonds, but fails to provide a combined descriptor that captures the reactivity of different types of C–H bonds. The reactivity of these different types of C–H bonds (primary, secondary, tertiary C–H bonds, allylic and carbonyl C–H bonds) can be predicted using more complete descriptors that incorporate a diradical interaction energy that depends on the substitution at the C-atom bearing the unpaired electron, which, for non-allylic C–H bonds, interacts with the OH group more strongly at the transition state as the organic radical becomes more stable. Radicals formed by C–H activation in allylic C–H bonds gain stability by resonance mediated delocalization of the unpaired electrons that interact with the OH group more weakly than the non-allylic radical of the same stability.

In the case of Brønsted acid catalysis, the respective molecular and catalyst descriptors are the proton affinity (PA) of the transition state analog and the deprotonation energy of the solid acid (DPE), which provide complete descriptors of reactivity (and selectivity) for each “family” of reactions on each family of catalysts. The incompleteness of such combinations of descriptors reflects the extent to which transition state analogs and the conjugate anion of the Brønsted acid balance the respective energies required to reorganize their charges in order to maximize electrostatic interactions at ion-pair transition states. For the organic portion, this can be described by properties specific to each family of reactions, and for the inorganic, by the covalent and ionic components of DPE. These more complete descriptors bring the qualitative concepts of hard-soft acid-base interactions in the context of the transition states that determine reactivity and selectivity for solid acid catalysis in unprecedented quantitative form.

346. Deshlahra, P., and Iglesia, E., **Chem. Comm. (Feature Article) 56 (2020) 7371** (“Reactivity Descriptors in Acid Catalysis: Acid Strength, Proton Affinity and Host-Guest Interactions”) doi.org/10.1039/d0cc02593c
311. Deshlahra, P., and Iglesia, E., **Journal of Physical Chemistry C, 120 (2016) 16741** (“Reactivity and Selectivity Descriptors for the Activation of C–H Bonds in Hydrocarbons and Oxygenates on Metal Oxides”) doi.org/10.1021/acs.jpcc.6b04604
310. Deshlahra, P. and Iglesia, E., **ACS Catalysis, 6 (2016) 5386** (“Toward More Complete Descriptors of Reactivity in Catalysis by Solid Acids”) doi.org/10.1021/acscatal.6b01402
287. Deshlahra, P., Carr, R.T, and Iglesia, E., **Journal of the American Chemical Society 136 (2014) 15229** (“Ionic and Covalent Stabilization of Intermediates and Transition States in Catalysis by Solid Acids”). doi.org/10.1021/ja506149c

7. The role of non-polar liquids in entry and exit elementary steps: Implications for reactivity and selectivity in oligomerization catalysis

This study revealed the remarkable effects of the formation of an intrapore non-polar liquid phase and on the stability of Ni-based catalysts and on the selectivity to primary dimers in alkene (C₂–C₄) dimerization. The catalyst half-lives increased abruptly from less than 5 h to more than 600 h as the pressure of a given alkene (or an inert alkane) approaches its vapor pressure at the prevalent reaction temperature. Specifically, this pressure range coincides (precisely) with that required for each given alkene (or inert alkane) to condense within the cylindrical channels of porous MCM-41 solids. Such strategies led to materials that remained inherently stable and catalyzed alkene dimerization at subambient temperatures with turnover rates (e.g., 40,000 h⁻¹ at 243 K) much higher than those reported for heterogeneous or molecular catalysts at even higher temperatures and without the co-catalysts and activators required for the latter. Their remarkable stability allowed mechanistic studies that were previously infeasible and demonstrated the exclusive involvement of grafted (NiOH)⁺ monomers that stoichiometrically replaced protons in Al-MCM-41 precursors. These single-site structures remain essentially uncovered even at cryogenic temperatures. The kinetically-relevant C-C bond formation steps are mediated by bimolecular transition states that are stabilized weakly by non-polar liquids. This stands in contrast with the much stronger stabilization of desorption transition states, which leads to the desorption of dimers before subsequent chain growth events, thus inhibiting further chain growth processes that lead to loss of selectivity and of active sites. Subsequent DFT treatments confirmed these conclusions; they demonstrated the involvement and kinetic competence of (NiOH)⁺ monomers, in a previously unrecognized dimerization mechanism, distinct from Cossee-Arlman and metallacycle routes. The novel routes uncovered in this body of work involve the concerted polarization of two bound alkenes by a Lewis acid (H) and a Lewis base (O) in (NiOH)⁺ sites at the C-C bond formation transition state. A later study extended these intrapore liquid effects to another C-C bond formation reaction (acetone condensation) on mesoporous TiO₂, also leading to significant enhancements in rates, selectivity to primary products, and unprecedented stability.

358. Jaegers, N. R. and Iglesia, E., **Journal of the American Chemical Society** **145** (2023) **5989**. (“Theoretical Assessment of the Mechanism and Active Sites in Alkene Dimerization on Ni Monomers Grafted onto Aluminosilicates: (Ni-OH)⁺ Centers and C-C Coupling Mediated by Lewis Acid-Base Pairs”) DOI: [10.1021/jacs.2c13487](https://doi.org/10.1021/jacs.2c13487)
343. Aguirrezabal, I., and Iglesia, E., **Journal of Catalysis** **389** (2020) **690** (“Mechanistic insights and consequences of an intrapore liquid phase in ethane, propene, and butane dimerization on Ni(II) cations grafted within ordered aluminosilicate mesopores”) doi.org/10.1016/j.jcat.2020.06.038
324. Agirrezabal-Telleria, I. and Iglesia, E., **Journal of Catalysis** **352** (2017) **505** (“Stabilization of active, selective, and regenerable Ni-based dimerization catalysts by condensation within ordered mesopores”) doi.org/10.1016/j.jcat.2017.06.025
355. Kadam, S.A., Hwang, A., and Iglesia, E., **ChemCatChem** **14** (2022) **e202200059** (“Consequences of Intrapore Liquids on Reactivity, Selectivity, and Stability for Aldol Condensation Reactions on Anatase TiO₂ Catalysts”) doi.org/10.1002/cctc.202200059

8. Revisiting the binding and reactivity of chemisorbed hydrogen atoms: Isotherms, H₂-D₂ exchange, and the consequences of a liquid water phase for binding and hydrogenation reactions

Studies of H-binding on metal nanoparticle surfaces (Pt reported, unpublished results with similar conclusions on Ru and Ir) using appropriate adsorption isotherms and H-D exchange rates in H₂-D₂-H₂O mixtures ultimately came together to describe the processes by which mobile adlayers can catalyze H-H bond activation through local displacements that create landing ensembles for incoming H₂ molecules. The effects of pressure and temperature on H₂ uptakes were analyzed using a novel approach that is agnostic to the nature of the adlayer. The adsorption entropies extracted from such data were compared with those expected from specific adlayer descriptions to demonstrate that chemisorbed H-atoms form a mobile adlayer, even at near ambient temperatures and coverages near saturation; they can be accurately described as a non-interacting two-dimensional gas with excluded volume, instead of the Langmuir isotherms typically used to describe such processes. The mobility of H-atoms becomes essential to account for how H₂-D₂ and H₂O-D₂ isotopic exchange can occur without requiring the formation of landing ensembles for H₂ dissociation by the recombinative desorption of H-atoms from dense adlayers. Exchange occurs instead by local disruption to mobile adlayers, which momentarily create “landing spots” for the binding and reactions of H₂ molecules that exchange via reactions with chemisorbed D*.

Such a mechanistic assessment was extended to the isotopic exchange between D₂ and H₂O, thus making it possible to examine the effects of the formation of an intrapore liquid water phase (via capillary condensation) on exchange rates. As expected from the channels involved in isotopic exchange and of the dense H-atom adlayers prevalent during such processes, no effects were evident in kinetic trends, exchange rates, or mechanism as the physical form of water evolved from gaseous to physisorbed to an extended liquid phase. These data and mechanistic interpretations contradict previous studies, which concluded that the presence of liquid water influences D₂-H₂O exchange rates by significantly weakening H-binding. These previous inferences seem to reflect the consequences of traces of dissolved CO₂ in liquid water and its reactions that form chemisorbed CO titrants of Pt surface atoms, an artifact that was detected through painstaking experimentations and eliminated through exhaustive purification of the water reagents used in our studies.

341. Garcia-Dieguez, M., Hibbitts, D., and Iglesia, E., **Journal of Physical Chemistry C**, **123** (2019) **8447** (“Hydrogen Chemisorption Isotherms on Pt Particles at Catalytic Temperatures: Langmuir and Two-Dimensional Gas Models Revisited”) doi.org/10.1021/acs.jpcc.8b10877
353. Leung, S.L., Garcia-Dieguez, M., Hibbitts, D., and Iglesia, E., **Journal of Physical Chemistry C** **126** (2022) **3923** (“H₂-D₂ Isotopic Exchange Pathways and Thermodynamic Isotope Effects for Hydrogen Chemisorption on Pt Nanoparticles”) doi.org/10.1021/acs.jpcc.1c09131
361. Leung, S.L., Chen, S., and Iglesia, S., **Journal of Physical Chemistry C** (accepted) (“Elementary steps in D₂-J₂O and H₂-D₂-H₂O exchange reactions on Pt nanoparticles and the consequences of liquid water for the binding and reactivity of chemisorbed hydrogen”)

9. The mechanism of O₂ activation and diffusion in redox-active oxides: Outer and inner sphere channels and consequences for oxidation selectivity

Theory and experiment were combined in these studies to probe O₂ activation channels at reduced centers present in nearly isolated form in redox-active metal oxides, which act as reaction intermediates in Mars-van Krevelen catalytic cycles. Kinetic analysis, including the effects of water and the scavenging of electrophilic O-species by alkenes (via epoxidation events) demonstrated the involvement of two activation routes, historically denoted as inner-sphere and outer-sphere routes. Inner-sphere routes involve the formation of dioxygen species at reduced centers with subsequent removal of one of the O-atoms via electrophilic insertion into C-H bonds in reactants (alkanes or alkanols), oxidative dehydrogenation (to form alkenes and alkanals), or added scavengers (alkenes). O₂ can instead react at vicinal OH pairs formed via H₂O dissociation at reduced centers via outer sphere routes to form H₂O₂ and a nucleophilic lattice O-atom, with the latter ultimately removed via subsequent C-H activation events. The H₂O₂ formed then diffuses to react with a distant reduced center to form a lattice O-atom or with a lattice O-atoms to form O₂* species.

These processes, previously proposed for molecular catalysts and liquid phase oxidations on polyoxometalates, were conjectured without theoretical or experimental verification in prior studies of redox-active oxides. Theoretical treatments confirmed the routes proposed from experimental observations and are consistent with the relative rates of these two O₂ activation routes, as well as with the effects of redox properties and H₂O binding energies for different oxide structures and compositions on the relative rates of inner and outer sphere O₂ activation channels.

The original premise and motivation, as well as the foundational concepts and the conundrum about how an O₂ molecule can carry out a two-electron oxidation of an isolated reduced center, emerged from our earlier work on the reactivity of O₂-derived species for CH₄ activation, in which Pd nanoparticles underwent a reversible phase transition between Pd to PdO (#257). These concepts underpin our current research in propene epoxidation on Au nanoclusters confined within titanosilicates (#354), ethylene oxide synthesis on Ag-based catalysts, and alkane oxidative dehydrogenation (ODH) on dicopper centers grafted onto exchange sites within zeotype voids. In the latter case, inner sphere O₂ activation routes provide electrophilic oxygens that insert into a C-H bond in alkanes to form alkanols, via channels reminiscent of methane monooxygenases. Ethanol (in the case of ethane) is “protected” via dehydration to ethene on residual acid sites within zeotypes, thus discouraging combustion cascades from H-abstraction from ethanol by the other (nucleophilic) O-atom (present as dicupric μ-oxo species); this has led to ethene selectivities that increase as ratios of acid to redox rates increase. Rates are limited by O₂ activation steps, in contrast with ODH reactions on metal oxide domains, and are accurately described by Langmuirian treatments because of the single-site nature of the redox and acid functions.

Such Langmuirian constructs fail for bulk semiconducting oxide crystallites, such as the Ce-Zr oxides used in oxygen storage/release and chemical looping applications. This reflects redox thermodynamics that depend strongly on the extent of reduction, as O-atoms are removed or restored (#359). Consequently, descriptions of kinetic trends and temporal evolution of O-addition/removal and catalytic oxidation rates require transition state formalisms that account for the non-ideal character of oxide crystals. These crystals remain spatially uniform in oxygen

chemical potential (because of fast O-diffusion), but exhibit dynamics, for diffusion and reactions that vary strongly even for small changes in O-content. Such effects of extreme thermodynamic non-idealities on reactivity and diffusion have not been part of previous attempts to describe and manage the capture, release, and transport of O-atoms in oxides used in emissions control, chemical looping, and ion-transport membranes.

340. Kwon, S., Deshlahra, P., and Iglesia, E., **Journal of Catalysis**, **377** (2019) **692** (“Reactivity and Selectivity Descriptors of Dioxygen Activation Routes on Metal Oxides”) doi.org/10.1016/j.jcat.2019.07.048
336. Kwon, S., Deshlahra, P., and Iglesia, E., **Journal of Catalysis** **364** (2018) **228** (“Dioxygen Activation Routes in Mars-van Krevelen Redox Cycles Catalyzed by Metal Oxides”) doi.org/10.1016/j.jcat.2018.05.016
359. Hwang, A. Wu, J., Getsoian, A.B., and Iglesia, E., **Journal of Physical Chemistry C** **127** (2023) **2923** (“Kinetic Relevance of Surface Reactions and Lattice Diffusion in the Dynamics of Ce–Zr Oxides Reduction–Oxidation Cycles”) DOI: [10.1021/acs.jpcc.2c08117](https://doi.org/10.1021/acs.jpcc.2c08117)
301. Chin, Y.-H., García-Diéguez, M. and Iglesia, E., **Journal of Physical Chemistry C** **120** (2016) **1446** (“Dynamics and Thermodynamics of Pd-PdO Phase Transition: Effects of Pd Cluster Size and Kinetic Implications for Catalytic Methane Combustion”) doi.org/10.1021/acs.jpcc.5b06677
276. Chin, Y.-H., Buda, C., Neurock, M., and Iglesia, E., **Journal of the American Chemical Society**, **135** (2013) **15425** (“Consequences of Metal-Oxide Interconversion for C-H Bond Activation during CH₄ Reactions on Pd Catalysts”) doi.org/10.1021/ja405004m

10. Myths and challenges in the interpretation of reactivity and selectivity within voids of molecular dimensions: Acid strength, the elusive transition state selectivity, and the illusions of pore mouth catalysis

The sieving and confinement phenomena that confer remarkable functional diversity on solids with voids of molecular dimensions also act to obscure the chemical origins of the molecular transformations that occur within their voids. The mechanistic conjectures imposed by such hurdles to direct observations of chemical events are considered in this body of work through theory and experiments of evolving precision and fidelity. These studies have focused on acid catalysis, because of its ubiquitous use of microporous solids, but the myths and challenges are evident for most reactions occurring within small voids, irrespective of the nature of the active sites. Selectivity and reactivity differences among heterosilicates that differ in void topology are frequently ascribed to their diverse acid strength, but such properties are, in fact, similar for different framework structures (#294). Instead, their different catalytic properties reflect confinement effects that favor specific transition states, often combined with the preferential diffusion of certain molecules through small apertures based on their size.

Deprotonation energy (DPE) is the precise (and sole) descriptor of acid strength and the rigorous measure of the stability of the conjugate anion in solid acids; it cannot be measured, but it can be calculated using theoretical methods for solid acids with well-defined known structures. The strength of Brønsted acid sites in aluminosilicates is similar when protons reside within different void

topologies, but it varies as Al is replaced isomorphously by other trivalent cations (e.g., Ga, Fe, B) in microporous heterosilicates.

Acid strength influences turnover rates because it determines the stability of anion at ion-pair transition states (#292, #333). The effects are strongest as the amount of charge and the extent to which it is localized differs between a transition state and its relevant precursors. In voids of molecular dimensions, the consequences of acid strength are inextricably linked with host-guest non-covalent van der Waals interactions that depend on the size and shape of transition states, relevant precursors, and inorganic voids. Such interactions are most effective when the host and guest maximize their fit (#285). The interconnections among these voids also restrict diffusional egress of guest molecules (#333, #339). Therefore, reaction-transport formalism are required to dissect the effects of intracrystal gradients of reactants and products, which preclude the interpretation of kinetic trends solely in terms of chemical events. For instance, β -scission reactions during alkene/alkane isomerization occurs most selectively on weaker acid sites (#333); yet, measured β -scission selectivities are higher on stronger acids, a consequences of intracrystal gradients of slow-diffusing and highly reactive branched alkenes that form at higher rates on stronger acids. Such diffusional enhancements of secondary reaction mimic primary pathways favored by stronger acids, an inaccurate attribution that persists in the literature.

Similar diffusional barriers lead to isomers with a strong preference for terminal methyl groups during n-alkane isomerization, especially on medium-pore one-dimensional zeolites, an observation quaintly attributed to “pore mouth catalysis”. These trends merely reflect the preferential sieving of quasi-equilibrated skeletal isomers by apertures of molecular dimensions (#339), instead of any selective entry of the reactants partly into channels, the visual depiction that birthed the moniker. In spite of the persistence of such paradigms, the selectivity for more “demanding” (i.e., slower) reactions is not inherently favored by stronger acids and strong acids are not essential to activate H₂ and CH₄ reactants in alkene hydrogenations or alkene-CH₄ alkylations, respectively. The clarity that emerges from dissecting chemistry from transport (and binding from solvation) is enabled by an increasingly seamless theory-experiment nexus; such clarity is essential to design novel solids that exploit synergies between binding sites and their outer sphere environments, without the misleading guidance of earlier paradigms.

339. Noh, G., Zones, S.I., and Iglesia, E., **Journal of Catalysis**, **377** (2019) **255** (“Isomer Sieving and the Prevalence of Terminal Methyl Branches in Reactions of Linear Alkanes Within Small Voids Containing Acid Sites”) doi.org/10.1016/j.jcat.2019.07.022
333. Noh, G., Zones, S.I., and Iglesia, E., **Journal of Physical Chemistry C** **122** (2018) **25475** (“Consequences of acid strength and diffusional constraints for alkane isomerization and β -scission turnover rates and selectivities on bifunctional metal-acid catalysts”) doi.org/10.1021/acs.jpcc.8b08460
294. Jones, A. and Iglesia, E., **ACS Catalysis** **5** (2015) **5741** (“The Strength of Brønsted Acids Sites in Zeolites”) doi.org/10.1021/acscatal.5b01133
292. Jones, A., Carr, R., Zones, S., and Iglesia, E., **Journal of Catalysis** **312** (2014) **58** (“Acid Strength and Solvation in Catalysis by MFI Zeolites and Effects of the Identity, Concentration and Location of Framework Heteroatoms”) doi.org/10.1016/j.jcat.2014.01.007

285. Jones, A., Zones, S.I., and Iglesia, E., **Journal of Physical Chemistry C**, **118** (2014) **17787** (“Implications of Transition State Confinement within Small Voids for Acid Catalysis”). doi.org/10.1021/jp5050095
282. Jones, A. and Iglesia, E., **Angewandte Chemie Int. Ed.** **126** (2014) **12177** (“Kinetic, Spectroscopic, and Theoretical Assessment of Associative and Dissociative Methanol Dehydration Routes in Zeolites”) doi.org/10.1002/anie.201406823

11. C-C bond formation on Brønsted acids: Consequences of size (of voids and transition states), acid strength, and diffusion-enhanced secondary reactions on alkene oligomerization rates and selectivity

Alkene conversion on solid Brønsted acids occurs via concurrent oligomerization, isomerization, β -scission, hydride transfer, and cyclization reactions, all of which are mediated by ion-pair transition states. The relative stability of these ion-pairs is caused, in part, by: (i) van der Waals interactions conferred by the geometry of the anion environment (confinement) and (ii) the anion's willingness to accept the negative charge (acid strength) and to interact electrostatically with the organic cation. These confinement and electrostatic effects on rates and selectivities were examined in this work using reactions of light alkene and alkanes mediated by transition states that differ in size, shape, and/or charge from each other and from their relevant kinetic precursors. Specifically, this work investigates turnover rates (per proton) for C₂-C₄ alkene oligomerization reactions and for the incorporation of C₄-C₅ alkanes via hydride transfer on acids of different acid strength and confining environments (TON, MFI, BEA, MOR, FAU zeolites; amorphous silica-alumina (SiAl), Keggin polyoxometalate (POM) clusters on SiO₂).

C-C bond formation and hydride transfer rates show that kinetically-relevant steps involve reactions of an alkane or alkene with alkene-derived alkoxides present at saturation coverages, consistent with *in-situ* infrared spectra and DFT estimates of activation free energy barriers and of the stability of alkoxide intermediates. The rate constants for oligomerization and hydride transfer increase exponentially as the deprotonation energy of the solid acid decreases, reflecting DFT-derived transition states that differ in charge from their covalent alkoxide precursors. These rates constants also typically increase as either void size decreases or transition states become larger, because of more effective contact with the void walls, and the greater stability of the larger carbenium ions involved as transition states. DFT treatments show that zeolite frameworks distort locally, so as to enhance van der Waals contacts at the expense of a slight distortion of the framework lattice; such distortions ultimately become too costly as transition states approach the size of the confining void space. These energy compromises are also critical in alkoxide formation, where DFT-calculated alkoxide energies indicate that bulkier alkoxides distort the framework more in smaller concave environments (TON) than for larger voids (MOR, HPW).

Skeletal and double bond isomerization results in equilibrated alkene pools of a given carbon number on all catalysts, consistent with rapid hydride and methyl shifts of alkoxide intermediates and with their rapid adsorption/desorption. Different solid acids, however, generate different products during alkene oligomerization, not because of voids that preferentially “solvate” C-C bond formation transition states, but because of undulations in the void spaces, which allow the

formation of oligomers that are unable to egress through the interconnecting voids without C-C β -scission events, thus influencing the relative rates of formation of oligomerization and β -scission products. The relevant selectivity for a given solid acid catalyst is the true oligomer selectivity, defined as the fraction of products that egress as true oligomers (C_{3n} for propene) as opposed to smaller alkenes formed via β -scission. Three-dimensional zeolites contain voids larger than the smallest aperture where chain growth forms products that must undergo β -scission to egress through the crystal as smaller species. The relative ratio of the size of these voids to their subsequent channels dictates the selectivity of oligomerization to β -scission products; lack of this undulation leads to species remaining intact, as observed in 1-D microporous and mesoporous samples. By developing descriptors that relate reactivity and selectivity to transition state properties (intrinsic stability of the organic cation, electrostatic interaction with the anion (acid strength) and stabilization via confinement provided by the flexible inorganic framework), this work has provided previously unavailable guidance for designing acids with the most effective strength and location of protons in a way that allows rigorous extrapolations to molecules of size and structure different from those examined here.

Hydride transfer (HT) from alkanes causes the desorption of alkoxides as alkanes with the concurrent formation of alkane-derived alkoxides that can then form new C-C bonds via reactions with alkenes. The transition state structures that mediate HT and oligomerization are both fully-formed ion-pairs, leading to turnover rates that vary to similar extents for both reactions with changes in acid strength. The transition state structures for HT from a given H-donor to each given alkoxide are, however, significantly larger than those involved in dimerization events that formed the alkoxide; this leads to a preference for HT over dimerization as the size of the confining voids increase and to the observed minor HT contributions in reactions within medium-pore zeolites. HT rate constants increase with the size and extent of branching of the alkoxide acceptors; the equilibrated nature of the bound alkoxide isomers allowed the accurate and direct assessment of their relative reactivity in HT reactions of any given H-donor alkanes with each of the alkene isomers formed in oligomerization reactions. The stability of oligomerization and HT transition states was shown to depend on the proton affinity (PA) of the alkene that forms the alkoxide involved in both reactions, but the HT transition state stability also reflects the energy required to donate a hydride from the alkane (dehydrogenation energy; DHE). DHE and PA depend, in turn, on the size and backbone structure of the alkene and alkane reactants, with larger and more highly branched species forming the more stable carbenium ions.

331. Sarazen, M. and Iglesia, E., **ChemCatChem** **10** (2018) **4028** (“Effects of Charge, Size, and Shape of Transition States, Bound Intermediates, and Confining Voids in Reactions of Alkenes on Solid Acids”) doi.org/10.1002/cctc.201800401
328. Sarazen, M.L. and Iglesia, E., **Journal of Catalysis** **354** (2017) **287** (“Experimental and Theoretical Assessment of the Mechanism of Hydrogen Transfer in Alkane-Alkene Coupling on Solid Acids”) doi.org/10.1016/j.jcat.2017.08.002
322. Sarazen, M.L. and Iglesia, E., **Proceedings of the National Academy of Sciences** **114** (2017) **E3900** (“Stability of Bound Species during Alkene Reactions on Solid Acids”) doi.org/10.1073/pnas.1619557114

302. Sarazen, M.L., Dorskocil, E., and Iglesia, E., *ACS Catalysis*, **6** (2016) 7059 (“The Effects of Void Environment and Acid Strength on Alkene Oligomerization Selectivity”) doi.org/10.1021/acscatal.6b02128

12. C-H activation and C-C bond formation from oxygenate reactants catalyzed by Lewis acid-base pairs and Bronsted acids

This series of articles describe and support through theory and experiment a unifying conceptual framework for describing reactivity and selectivity in C-H activation and C-C formation steps that mediate reactions of alkenes, alkanals, alkanones, and carboxylic acids. These reactions involve the cleavage of C-H bonds at the α -position to the carbonyl moiety and are denoted as aldol condensation and ketonization. They are catalyzed by Lewis acid-base pairs at oxide surfaces, with anatase TiO₂ and tetragonal ZrO₂ among the most active reported catalysts. Their practical use was precluded by their poor selectivity to primary products and by the deactivation caused by their further growth; both hurdles were circumvented in these studies through the use of a second site (Cu nanoparticles dispersed on inert supports and present as physical mixtures) and H₂, a strategy that also allowed the use of alkanols as reactants through their fast equilibration with their carbonyl analogs at the Cu function.

The remarkable stability conferred by these strategies allowed previously inaccessible mechanistic inquiries and the elucidation of the nature and coverage of the relevant intermediates and of the kinetically-relevant steps. In aldol condensations, both TiO₂ and ZrO₂ surfaces remained essentially bare during catalysis and rates are limited by the formation of bound enolates through concerted interactions with the Lewis acid and base centers at Ti-O or Zr-O pairs; the fast subsequent C-C bond formation occurs via nucleophilic attack by the enolate at the electrophilic C-atom in a coadsorbed carbonyl reactant. DFT-derived energies are consistent with the observed reactivity trends and C-C formation selectivities for a broad range of alkanal and alkanone substrates (and their mixtures) and with the kinetic relevance of enolate formation steps. The latter is also consistent with measured and DFT-derived kinetic isotope effects and with measured infrared spectra during reaction. The ketonization elementary steps resemble those for condensation, but differ in their relative kinetic relevance; they also involve initial C-H activation steps that form hydroxy-enolates via concerted interactions with Lewis acid-base pairs. In contrast with aldol condensation, these species are present at detectable coverages, such that the subsequent C-C bond formation step becomes the kinetically-relevant step, as shown by kinetic trends, isotope effects, infrared spectra of bound species during reaction, and theoretical treatments for both ZrO₂ and TiO₂ catalysts.

Prins condensation between isobutanal and isobutene forms C-C bonds at locations that lead to a mixture of allenes and alkadienes with 2,6-dimethyl-C₆ backbones; these species act as precursors to p-xylene during Prins condensation or via subsequent cyclization processes. Prins condensation reactions are catalyzed by zeotypes in their acid forms, polyoxometalate acids, and mesoporous aluminosilicates. Weaker acids (e.g., Al-zeolites vs. phosphotungstic acids) favor Prins condensation over competitive isobutene oligomerization events. DFT-derived energies show that such selectivities reflect transition states for C-C bond formation in Prins condensation reactions

that do not require the full transfer of the acid proton (and are thus less positively charged) than those for dimerization. The rates of both reactions are significantly increased by confinement, but to similar extents because of the similar size and shape of the two relevant transition states.

330. Wang, S. and Iglesia, E., **Journal of the American Chemical Society** **140** (2018) **775** (“Entropy-Driven High Reactivity of Formaldehyde in Nucleophilic Attack by Enolates on Oxide Catalysts”) doi.org/10.1021/jacs.7b11749
327. Wang, S. and Iglesia, E., **Journal of Physical Chemistry C** **121** (2017) **18030** (“Experimental and Theoretical Evidence for Reactivity of Bound Intermediates in Ketonization of Carboxylic Acids and Consequences of Acid-base Properties of Oxide Catalysts”) doi.org/10.1021/acs.jpcc.7b05987
325. Wang, S. and Iglesia, E., **Journal of Catalysis** **352** (2017) **415** (“Catalytic Diversity Conferred by Confinement of Protons within Porous Aluminosilicates in Prins Condensation Reactions”) doi.org/10.1016/j.jcat.2017.06.012
320. Wang, S. and Iglesia, E., **Journal of Catalysis** **345** (2017) **183** (“Experimental and Theoretical Assessment of the Mechanism and Site Requirements for Ketonization of Carboxylic Acids on Oxides”) doi.org/10.1016/j.jcat.2016.11.006
312. Wang, S. and Iglesia, E., **Journal of Catalysis**, **340** (2016) **302** (“Condensation and Esterification Reactions of Oxygenates on TiO₂: Elementary Steps, Site Requirements, and Synergistic Effects of Bifunctional Strategies”) doi.org/10.1016/j.jcat.2016.05.026
305. Wang, S. and Iglesia, E., **ACS Catalysis**, **6** (2016) **7664** (“Mechanism of Isobutanol-Isobutene Prins Condensation on Solid Bronsted Acids”) doi.org/10.1021/acscatal.6b02171
303. Wang, S. and Iglesia, E., **Journal of Physical Chemistry C**, **120** (2016) **21589** (“Substituent Effects and Molecular Descriptors of Reactivity in Condensation and Esterification Reactions of Oxygenates on Acid-Base Pairs at TiO₂ and ZrO₂ Surfaces”) doi.org/10.1021/acs.jpcc.6b07304
321. Wang, S., Agirrezabal-Telleria, I., Bhan, A., Simonetti, D., Takanabe, K., and Iglesia, E., **Faraday Discussions** **197** (2017) **9** (“Catalytic Routes to Fuels from C₁ and Oxygenate Molecules”) doi.org/10.1039/C7FD00018A

13. Entropy and enthalpy effects in C-C hydrogenolysis rates and selectivity on metal nanoparticles

This body of work assesses (through theory and experiment and for diverse acyclic and cyclic alkanes) the identity and kinetic relevance of the bound intermediates and elementary steps that mediate C-C cleavage steps that require several preceding C-H cleavage events. Kinetic analysis and statistical mechanics treatments of the entropies of bound species, as well as those of plausible transition states, demonstrated how the location of the C-C cleavage events and their temperature dependence reflect the rotational degrees of freedom of the alkyl groups (R' and R'') attached to each of the two C-atoms involved in the R'C-CR'' cleavage transition state. The transition states for C-C cleavage at substituted C-atoms are more extensively dehydrogenated, but often require C-H activation events at more distant C-atoms; as a result, rates of cleavage at

such locations show higher activation barriers and stronger H₂ inhibition effects than for the cleavage of C-C bonds at less substituted positions.

The preeminent role of entropy and of the H-content of the relevant intermediates for the stability of relevant transition states dictate the rate and location of cleavage events among endocyclic and exocyclic C-C bonds and their H₂ kinetic trends. These mechanism-based insights also account for why hydrogenolysis reactions (with 200-250 kJ mol⁻¹ activation barriers) proceed with practical rates at modest temperatures (500-600 K), because of the (unusual) positive activation entropies conferred by the evolution of H₂ molecules to form the unsaturated intermediates that undergo C-C cleavage at kinetically-relevant transition states.

The ability to predict the effects of C-atom connectivity in (cyclo)alkanes and of H₂ pressure and temperature effects on the rate and location of C-C cleavage was demonstrated for several noble metals (Pt, Ir, Ru, Rh) without reliance on theoretical methods beyond classical statistical mechanics. They were subsequently confirmed using density functional theory treatments, which identified specific structures for transition states and their relevant precursors and the sequence, location, and quasi-equilibrated nature of C-H bond activation steps. Measured and DFT-derived barriers and entropies were in excellent agreement. These mechanistic tenets and predictive models are being extensively cited in studies of hydrogenolytic deconstruction of polyolefins and in ring-opening strategies for cycloalkane moieties, in practical applications that were never envisioned as part of the original motivation and intent of this body of work.

317. Hibbitts, D.D., Flaherty, D.W., and Iglesia, E., **ACS Catalysis** **6** (2016) **469** (“Role of Branching on the Rate and Mechanism of C-C Cleavage in Alkanes on Metal Surfaces”) doi.org/10.1021/acscatal.5b01950
314. Hibbitts, D.D., Flaherty, D.W., and Iglesia, E., **Journal of Physical Chemistry C** **120** (2016) **8125** (“Effects of Chain Length and van der Waals Interactions on the Mechanism and Rates of Metal-Catalyzed Hydrogenolysis of n-Alkanes”) doi.org/10.1021/acs.jpcc.6b00323
298. Flaherty, D., and Iglesia, E., **Journal of Physical Chemistry C** **119** (2015) **2597** (“Catalytic Ring Opening of Cycloalkanes on Ir Clusters: Alkyl Substitution Effects on the Structure and Stability of C-C Bond Cleavage Transition States”) doi.org/10.1021/jp511688x
289. Flaherty, D.W., Hibbitts, D.D., and Iglesia, E., **Journal of the American Chemical Society**, **136** (2014) **9664** (“Metal-Catalyzed C-C Bond Cleavage in Alkanes: Effects of Methyl Substitution on Transition State Structures and Stability”) doi.org/10.1021/ja5037429
275. Flaherty, D. and Iglesia, E., **Journal of the American Chemical Society** **135** (2013) **18586** (“Transition State Enthalpy and Entropy Effects on Reactivity and Selectivity in Hydrogenolysis of n-Alkanes”) doi.org/10.1021/ja4093743