

Mechanism of Isobutanal–Isobutene Prins Condensation Reactions on Solid Brønsted Acids

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S Supporting Information

ABSTRACT: The selectivity to 2,5-dimethyl-hexadiene isomers (2,5-DMH) via acid-catalyzed isobutanal-isobutene Prins condensation is limited by isobutene oligomerization reactions (to 2,4,4-trimethyl-pentene isomers) and by skeletal isomerization and cyclization of the primary 2,5-DMH products of Prins condensation. Experiment and theory are used here to assess and interpret acid strength effects on the reactivity and selectivity for isobutanal-isobutene Prins condensation routes to 2,5-DMH, useful as precursors to pxylene. Non-coordinating 2,6-di-tert-butylpyridine titrants fully suppress reactivity on Keggin heteropolyacids, niobic acid, and mesoporous and microporous aluminosilicates, indicating that



Prins condensation, parallel isobutene oligomerization, and secondary skeletal isomerization and cyclization of primary 2,5-DMH products occur exclusively on Brønsted acid sites. The number of titrants required to suppress rates allows site counts for active protons, a requirement for comparing reactivity among solid acids as turnover rates, as well as for the rigorous benchmarking of mechanistic proposals by theory and experiment. Kinetic and theoretical treatments show that both reactions involve kinetically relevant C-C bond formation elementary steps mediated by cationic C-C coupling transition states. Transition state charges increase with increasing acid strength for Prins condensation, becoming full carbenium-ions only on the stronger acids. Oligomerization transition state structures, in contrast, remain full ion-pairs, irrespective of acid strength. Turnover rates for both reactions increase with acid strength, but oligomerization transition states preferentially benefit from the greater stability of the conjugate anions in the stronger acids, leading to higher 2,5-DMH selectivities on weaker acids (niobic acid, aluminosilicates). These trends and findings are consistent with theoretical estimates of activation free energies for Prins condensation and oligomerization elementary steps on aluminosilicate slab and Keggin heteropolyacid cluster models. High 2,5-DMH selectivities require weak acids, which do not form a full ion-pair at transition states and thus benefit from significant stabilization by residual covalency. These trends demonstrate the previously unrecognized consequences of incomplete proton transfer at oxygencontaining transition states in dampening the effects of acid strength, which contrast the full ion-pair transition states and stronger acid strength effects in hydrocarbon rearrangements on solids acids of catalytic relevance. These mechanistic conclusions and the specific example used to illustrate them led us to conclude that reaction routes involving O-containing molecules become prevalent over hydrocarbon rearrangements on weak acids when parallel routes are accessible in mixtures of oxygenate and hydrocarbon reactants.

KEYWORDS: isobutene, isobutanal, Prins reaction, oligomerization, 2,5-dimethyl-hexadienes, solid acid, acid strength, density functional theory

1. INTRODUCTION

The acid-catalyzed electrophilic addition of alkanals to alkenes, known as the Prins reaction,¹ selectively forms C-C bonds between the terminal C atoms in the two reactants to form specific C_n skeletal structures (n > 4); these backbone structures are not accessible via C-C bond formations in aldol condensation² nor oligomerization³ reactions. For isobutanal-isobutene mixtures, which can be derived from isobutanol,^{4,5} Prins condensation reactions form 2,5-dimethylhexadiene (2,5-DMH) molecules⁶⁻⁹ that are convenient precursors to *p*-xylene^{10,11} (Scheme 1), a chemical precursor to terephthalic acid.¹² Isobutanol can be formed from

carbohydrates via fermentation, 13 from ethanol-methanol mixtures via aldol condensation, 14 or from CO-H $_2$ mixtures via sequential hydrogenation and condensation reactions on bifunctional catalysts (e.g., Cu/MgCeO_x,¹⁵ Cu/ZnO/Cr₂O₃,¹⁶ and Pd/ZrO₂/ZnO/MnO¹⁷). The successful deployment of active, selective, and stable Prins condensation catalysts would create alternate routes to p-xylene and its derivatives and could do so entirely from renewable resources.

Received: July 30, 2016 **Revised:** September 19, 2016 Scheme 1. Proposed Pathways for *p*-Xylene Synthesis from Isobutanol



Solid acids, such as $Nb_2O_5 \cdot nH_2O_5^{6,7,18}$ $WO_3/TiO_{2,7}^{7,7}$ heterosilicates, ^{8,9,19,20} and zirconium and niobium phosphates,²¹ catalyze alkanal-alkene Prins condensation in parallel with alkene oligomerization²² and isomerization, cyclization, and β -scission of the primary products formed via Prins condensation reactions.^{3,23,24} Formaldehyde–isobutylene condensation to isoprene occurs more selectively on H-B-MFI than on stronger acids (i.e., H-Al-FAU and H-Al-MFI),¹⁹ indicating that these undesired reactions may be suppressed relative to condensation reactions on weaker acids. Previous studies, however, have remained silent about the number or type of catalytically relevant acid sites, and their reactivity has not been rigorously reported as turnover rates.⁶⁻⁹ Such details are required for benchmarking density functional theory (DFT) and experiments based on activation free energies. Such benchmarking allows, in turn, rigorous assessments of the identity and kinetic relevance of elementary steps involved, of the fundamental underpinnings for the effects of acid strength, and of the most appropriate descriptors of reactivity and selectivity for these types of reactions.

We show here that isobutanal–isobutene condensation to form 2,5-DMH is favored over sequential skeletal isomerization or cyclization reactions of 2,5-DMH and parallel isobutene oligomerization on weaker acids, such as aluminosilicates and Nb₂O₅·nH₂O; the latter reactions occur preferentially on stronger SiO₂-supported Keggin heteropolytungstic acids. On all catalysts, Prins condensation, oligomerization, isomerization, and cyclization reactions were fully suppressed by the selective titration of Brønsted acid sites with non-coordinating 2,6-di*tert*-butylpyridine titrants, indicative of the sole involvement of protons as active sites for all reactions. The turnover rates were higher on stronger acids for all reactions, but such rate enhancements were greater for oligomerization and skeletal isomerization than for Prins condensation reactions at all temperatures (473–633 K).

DFT treatments show that Prins condensation and oligomerization rates are limited by C–C bond formation steps mediated by cationic transition states (TS). The charge in the isobutanal-isobutene C–C coupling TS for Prins condensation increases as the acid becomes stronger, as a result of the more stable conjugate anions of stronger acids; their smaller deprotonation energies (DPE) lead to the more complete proton transfer to isobutanal at the TS on stronger acids. In contrast, fully formed carbenium ions are involved in the C–C coupling TS for isobutene oligomerization, irrespective of the DPE values of solid acids. As a result, weaker acids, with less stable conjugate anions, are less consequential for Prins TS structures than for those involved in oligomerization steps, which also retain significant covalency at the TS on the weaker acids. These mechanistic findings show

that Prins condensation rates and selectivities can be systematically controlled through changes in the strength of solid acids; these findings, illustrated here for 2,5-DMH synthesis from isobutanal—isobutene mixtures, should apply generally to alkanal—alkene reactions that uniquely form products with C– C bonds between their respective terminal C atoms.

2. METHODS

2.1. Catalyst Preparation and Characterization. Mesoporous H-Al-MCM-41 (Si/Al = 39.5, 970 m² g⁻¹, 2.5–3 nm pore size) and amorphous $SiO_2 - Al_2O_3$ (H-ASA, Si/Al = 30, 440 $m^2 g^{-1}$) samples were obtained from Sigma-Aldrich. Chemically dealuminated H-FAU (H-CD-FAU, Si/Al = 7.5) without extra framework Al was obtained in its NH₄⁺ form via chemical dealumination of H-USY (Union Carbide, Si/Al = 2.9) in aqueous $(NH_4)_2SiF_6$ solutions at 323 K.²⁵ The numbers of proton sites on these aluminosilicate samples are 0.35 for H-Al-MCM-41, 0.025 for H-ASA, and 0.37 for H-CD-FAU (Table S1 in the Supporting Information (SI)), which are determined by titrations using 2,6-di-tert-butylpyridine (DTBP) during catalysis (described in section 2.3), whereas the Lewis acid sites on these samples are 0.65, 0.975, and 0.63, respectively (Table S1, SI). Niobic acid (Nb₂O₅·nH₂O; Nb₂O₅/H₂O = 5.1 molar, 118 m² g⁻¹) was obtained from CBMM (Companhia Brasileira de Metallurgia e Mineração). The H₃PW₁₂O₄₀/SiO₂ catalyst (5% wt. POM, 0.04 POM nm⁻²) was prepared by incipient wetness impregnation of SiO₂ (Cab-O-Sil HS-5, 310 m² g⁻¹) with an ethanolic solution of H₃PW₁₂O₄₀ (Sigma-Aldrich, reagent grade).³

H-Al-MCM-41, H-ASA, and H-CD-FAU were treated in flowing dry air (Praxair, 99.999%, 1.67 cm³ g⁻¹ s⁻¹) by heating to 823 K (at 0.025 K s⁻¹) and holding for 5 h; Nb₂O₅·nH₂O and 5% wt. H₃PW₁₂O₄₀/SiO₂ were treated similarly but at lower temperatures (573 K) in order to prevent structural degradation. All catalyst samples were then pressed, crushed, and sieved to retain 106–180 μ m aggregates. X-ray diffraction (XRD) measurements (Bruker D8 Advance; Cu K α radiation, λ = 0.15418 nm, 40 kV, 40 mA) were used to confirm their respective crystal structures; diffractograms were measured in the 5–60° range of 2 θ using a scan rate of 0.033° s⁻¹ and finely ground powders held onto quartz slides.

2.2. Catalytic Rates and Selectivities. Steady-state rates of isobutanal—isobutene reactions were measured in a tubular quartz reactor with plug-flow hydrodynamics at 453-633 K. Samples (0.020-0.6 g) were held as a packed-bed and treated in flowing air (Praxair, 99.999%, 1.67 cm³ g⁻¹ s⁻¹) by heating to the required reaction temperature (at 0.0833 K s⁻¹) and holding for 4 h before rate measurements. Temperatures were controlled using a resistively heated furnace and a temperature controller (Watlow, Series 988) and measured using a K-type thermocouple (0.05 cm diameter, 16 cm length, Omega) held against the outer reactor wall at the location of the catalyst bed.

Isobutanal (Sigma-Aldrich, \geq 99%) was fed using a syringe pump (Cole Parmer, 74900 series) into isobutene (Praxair, 99%) and He (Praxair, 99.999%) flows that were metered by mass flow controllers (Porter, Model 201). Transfer lines after the liquid injection point were held at 433 K using heating tape (Omega) to prevent condensation of reactants or products. The concentrations of reactants and products were measured by online gas chromatography (Agilent 6890) using a methyl silicone capillary column (Agilent HP-1, 50 m, 0.32 mm ID; 1.05 um film) and flame ionization detection. Known standards and speciation by mass spectrometry after chromatographic



Scheme 2. Extraction of a 4-Layer Silicate Slab (Si₆₀O₁₂₄H₈) from a MCM-41 Parent Structure





^aProtons that constitute the active sites in DFT calculations are indicated.

separations (HP 5972 GC/MS) using a similar column and similar heating protocols were applied to confirm the identity and to determine the detector response factors for all species present in effluent streams. Isomers with different C==C bond positions (i.e., alkenes and alkadienes) were separable by chromatographic retention time but could not be individually identified because of their identical mass spectra; these isomers were lumped together in reporting rates and selectivities. All reported rates were measured at differential reactant conversions (<5%) and corrected for any intervening deactivation by rates periodically measured at a reference condition (1.0 kPa isobutene, 2.0 kPa isobutanal, 473 K).

2.3. Selective Titrations of Brønsted Acid Sites by 2,6-Di-tert-butylpyridine during Catalysis. Protons on H-Al-MCM-41, H-ASA, Nb₂O₅·nH₂O, and H₃PW₁₂O₄₀/SiO₂ were titrated using 2,6-di-*tert*-butylpyridine (DTBP; Aldrich, > 97%) during reactions of isobutanal–isobutene reactant mixtures (1.0 kPa isobutene, 2.0 kPa isobutanal, 473 K). In these experiments, Prins condensation and alkene oligomerization rates were measured for about 1 h before the introduction of DTBP, and the reactant mixture was then replaced with one containing DTBP in the liquid isobutanal/DTBP = 200–1000 molar) to give a DTBP pressure of 2–10 Pa. The concentrations of the reactants, products, and titrant were measured using the chromatographic protocols described above. The number of accessible protons in each sample was determined from titrant uptakes required to fully suppress isobutanal–isobutene reactions (assuming a 1:1 DTBP/H⁺ adsorption stoichiometry²⁶). The proton density of H-CD-FAU (0.37 H⁺/Al) was measured from the DTBP titration during CH₃OH dehydration (0.5 kPa CH₃OH, 0.1 kPa DTBP, 433 K) using methods described elsewhere.²⁵

2.4. Density Functional Theory Methods. The energetics of the elementary steps involved in acid-catalyzed isobutanal-isobutene Prins condensation and isobutene oligomerization reactions were examined using periodic plane-wave DFT as implemented in the Vienna ab initio simulation package (VASP).^{27–30} All calculations were performed using the Perdew-Burke-Ernzerhof (PBE) exchange-correlation functional^{31,32} and projector augmented wave (PAW) pseudopotentials (energy cutoff 396 eV).^{33,34} Convergence criteria were 1×10^{-6} eV for energies and 0.05 eV Å⁻¹ for forces on all atoms. The van der Waals interactions between atoms were taken into account by including Grimme's D3BJ dispersion corrections after each step in the energy minimization algorithm.^{35,36}

DFT calculations were carried out using model solids consisting of amorphous aluminosilicate slabs and Keggin POM clusters. The aluminosilicate slabs were built based on reported pure Si MCM-41 silanol-terminated surfaces.³⁷ These model surfaces exhibit isolated silanols with vibrational frequencies around 3740 cm⁻¹ and a range of diverse H-bonded silanols with vibrational frequencies centered at 3550 cm⁻¹; these DFT estimates are consistent with those observed on pure silica MCM-41 materials (3745 and 3536 cm⁻¹, respectively).³⁷ A four-layer silicate slab of 1.2 nm thickness $(Si_{60}O_{124}H_8 \text{ per unit cell}; Scheme 2)$ was extracted from the channel wall of the Si MCM-41 model (0.24 surface silanol nm^{-2}); the lateral dimensions of the cell are 1.3 nm \times 1.3 nm (Scheme 2), which are large enough to avoid repulsive lateral interactions between reactants or transition states in vicinal cells (the distance between organic moieties in vicinal cells above 0.9 nm; an example of the Prins condensation C-C coupling TS is shown in Figure S1, SI). A Si atom on the top surface was then replaced by an Al atom, and an extra H atom was attached to one of the O atoms bound to the Al atom to maintain charge neutrality (Si₅₉AlO₁₂₄H₉ per unit cell; Scheme 3a). Periodic images of this aluminosilicate slab were separated by a 4.0 nm vacuum region in the z-direction: dipole and quadrupole interactions between images along this direction were corrected during each geometric optimization step.³⁸ A 2 $\times 2 \times 1$ Monkhorst–Pack k-point mesh³⁹ was used to sample the first Brillouin zone for simulations using this aluminosilicate slab.

Full Keggin clusters (H_{8-n}Xⁿ⁺W₁₂O₄₀, Xⁿ⁺ = S⁶⁺, P⁵⁺, Si⁴⁺, Al³⁺, 1.1 nm diameter; Scheme 3b) were constructed as in previous studies.^{40,41} In these structures, one heteroatom (S, P, Si, and Al) was placed at the center of a W₁₂O₄₀⁻⁸ cage, and the charge-balancing (8-n) H atoms were placed at bridging or terminal O atoms in the cage's outer surface to obtain the minimum energy. Geometry optimizations were performed at the center of a 2.0 × 2.0 × 2.0 nm³ unit cell with a (1 × 1 × 1) Γ -centered k-point mesh; dipole and quadrupole moments were calculated to correct for long-range interactions between neighboring unit cells.

Deprotonation energies (DPE) of Brønsted acids (HZ) are defined as those required to separate protons (H^+) from their conjugate anions (Z^-) to non-interacting distances:

$$DPE = E_{Z^{-}} + E_{H^{+}} - E_{HZ}$$
(1)

where E_{Z^-} , E_{H^+} , and E_{HZ} are respective electronic energies of Z^- , the gaseous H⁺, and HZ; DPE rigorously accounts for acid strength and has been previously reported for microporous aluminosilicates⁴² and Keggin polyoxometalates (POM)^{40,41} and used as a descriptor of their catalytic properties for alkene isomerization³ and alkanol dehydration reactions.^{40,41,43} The DPE value for the proton of the amorphous aluminosilicate slab model used here was calculated from a Si₄₇AlO₁₂₂H₅₃ cluster, which was extracted from this slab (Figure S2, SI), because dipole and quadrupole energy corrections are inaccurate for slab models with net charges.⁴⁴ A Si₄₇AlO₁₂₂H₉ cluster was first extracted from a unit cell of the aluminosilicate slab, and 44 H atoms were then attached to the peripheral dangling O atoms along the orientation of the cut Si-O bonds to obtain a neutral cluster (Si₄₇AlO₁₂₂H₅₃). This Si₄₇AlO₁₂₂H₅₃ cluster was placed in the center of a 4.0 \times 4.0 \times 4.0 nm³ unit cell, and a (1 \times 1 \times 1) Γ -centered k-point mesh was used to sample the first Brillouin zone. All atoms in the H^+ -[Al(OSiO₃H)₂(OSiO₃)₂]⁻ structure that reside at the center of the cluster model (Figure S3, SI) were allowed to relax during geometry and energy optimizations of the cluster and its conjugate anion, while the other Si, O, and H atoms were held to retain the local coordination environment of the extended parent surface. Dipole and quadrupole interactions among neighboring unit

cells were taken into account in these geometry and energy optimizations.

The calculated DPE values for this proton on the $Si_{47}AIO_{122}H_{53}$ cluster using PBE and revised-PBE⁴⁵ (RPBE) functionals were 1204 and 1212 kJ mol⁻¹, respectively (Table 1); the different mathematical formalisms that describe the

Table 1. DFT-Derived Deprotonation Energies (DPE) for the Aluminosilicate Slab and Keggin W Polyoxometalate Cluster Models^a

functional	PBE	RPEB
aluminosilicate slab	1204	1212
$H_5AlW_{12}O_{40}$	1123	1137
$H_4SiW_{12}O_{40}$	1109	1121
$H_{3}PW_{12}O_{40}$	1087	1101
$H_2SW_{12}O_{40}$	1073	1089

^{*a*}Unit: kJ mol⁻¹; protons involved in the calculations are indicated in Scheme 3.

electron exchange interactions in these functionals account for the slightly different DPE values, as also observed for Keggin POM clusters (Table 1). The good agreement between the DPE value of the Si₄₇AlO₁₂₂H₅₃ cluster (1212 kJ mol⁻¹, RPBE) and those reported for microporous aluminosilicates (1201 \pm 11 kJ mol⁻¹, RPBE)⁴² is consistent with the lack of any effects of the local structure/coordination on DPE values for aluminosilicates 42,46-48 and also indicates that this construct of the aluminosilicate slab provides a practical and computationally tractable model to examine the acid strength and reactivity of unconfined aluminosilicate protons. DFT-derived DPE values were 1073-1204 kJ mol⁻¹ (PBE; Table 1) for the Keggin clusters and aluminosilicate slab models; their broad range allows the systematic examination of the effects of acid strength on reactivity for isobutanal-isobutene Prins condensation and isobutene oligomerization reactions.

Transition state (TS) structures for all elementary steps were first optimized using the nudged elastic band (NEB) method^{49,50} with convergence criteria of 1×10^{-5} eV for energies and of 0.2 eV Å⁻¹ for the forces on each atom. Converged TS structures were then optimized using the dimer method⁵¹ with more stringent convergence criteria for electronic energies (1×10^{-6} eV) and forces (0.05 eV Å⁻¹). A frequency analysis (calculation parameters described below) was used to confirm that the TS structure exhibited a single imaginary frequency, characteristic of the molecular vibration along the reaction coordinate. Löwdin population analyses^{52,53} using localized quasiatomic minimal basis orbitals (QUAM-BO)⁵⁴ were performed to examine the charge distribution in all reactants and TS structures.

Enthalpies, entropies, and Gibbs free energies of stable and TS structures were determined from statistical mechanics formalisms using DFT-derived vibrational frequencies.⁵⁵ The vibrational frequencies for each optimized structure were obtained from the diagonalization of the mass-weighted Hessian matrix using one irreducible k point at the Γ -point. Each atom was perturbed in all three Cartesian directions with displacements of ± 0.015 Å for the calculation of energy gradients.⁵⁶ Low-frequency modes (<60 cm⁻¹) involved in weakly bound adsorbates were treated as rotations similar to those in gaseous molecules,⁵⁷ instead of treating them as harmonic oscillators that can lead to significant underestimation of entropies.

Equilibrium constants between regioisomers involved in isobutanal–isobutene Prins condensation and isobutene oligomerization products (i.e., C_8 dienes and alkenes) were estimated from DFT-derived free energies of formation for these unsaturated C_8 hydrocarbons. Such free energies of formation were calculated using the G4MP2 composite theoretical method⁵⁸ implemented in the Gaussian 09 program⁵⁹ to reach accuracy within 4 kJ mol^{-1.60,61}

3. RESULTS AND DISCUSSION

3.1. Effects of Acid Strength on the Selectivities of Isobutanal–Isobutene Reactions on Solid Acids. The Prins condensation reactions of isobutanal–isobutene mixtures led to 2,5-dimethyl-hexadiene isomers (2,5-DMH henceforth; consisting of isomers with different C=C bond positions, e.g., 2,5-dimethyl-hexa-2,4-diene and *cis/trans-2,5*-dimethyl-hexa-1,3-dienes) on all solid acid catalysts (Keggin H₃PW₁₂O₄₀/SiO₂, H-Al-MCM-41, H-ASA, H-CD-FAU, and Nb₂O₅·nH₂O). Isobutene oligomerization products, predominantly consisting of 2,4,4-trimethyl-pentene positional isomers (2,4,4-TMP), isomerization products of 2,5-DMH to dienes with different skeletal backbones (2,4-DMH and 3,4-DMH), and cyclization products of 2,5-DMH to 1,4-dimethyl-cyclohexene (1,4-DMCH) (Scheme 4) were also detected. As in the case of

Scheme 4. Reaction Network of Isobutanal–Isobutene Mixtures on Solid Acids



2,5-DMH, the skeletal isomerization and cyclization reactions of the other products (e.g., 2,4,4-TMP, 2,4-DMH, and 3,4-DMH) were also observed but at rates that were 10-fold smaller than those for the other reactions. These products are lumped with their respective precursors in the mechanistic discussions that follow. The formation rate ratios of regioisomers with a given skeletal backbone for each diene/alkene product (e.g., between 2,5-dimethyl-hexa-2,4-diene and trans-2,5-dimethylhexa-1,3-diene and between 2,4,4-trimethyl-pent-1-ene and 2,4,4-trimethyl-pent-2-ene, which are the predominant regioisomers for the isobutanal-isobutene Prins condensation and isobutene oligomerization products, respectively) did not depend on residence time or conversion (Section S4, SI); these constant rate ratios are similar to DFT-derived equilibrium constants (e.g., 0.044 ± 0.003 vs 0.022 for the rate ratios of trans-2,5-dimethyl-hexa-1,3-diene to 2,5-dimethyl-hexa-2,4diene; 0.56 ± 0.01 vs 0.47 for the rate ratios of 2,4,4trimethyl-pent-2-ene to 2,4,4-trimethyl-pent-1-ene; 473 K; section S4, SI), indicating that H-shifts required for doublebond isomerization are fast at all conditions and that the interconversions among these double bond isomers are equilibrated. All regioisomers with a given skeleton can thus be rigorously treated as lumped chemical species in all kinetic treatments.

Figure 1a shows that 2,5-DMH selectivities decreased from 55.2% to 19.3% as the isobutene conversion increased from 2.1% to 14.2% (through changes in residence time) on H₃PW₁₂O₄₀/SiO₂ (473 K; 2.0 kPa isobutanal; 1.0 kPa isobutene). The respective selectivities to skeletal isomers and cyclization products of 2,5-DMH primary products increased from 21.3% to 54.5% and from 1.9% to 3.8%, while the selectivity of 2,4,4-TMP remained relatively constant (~23%). The ratio of the total Prins condensation products, defined here as the sum of 2,5-DMH positional isomers and its skeletal and cyclization isomers, to 2,4,4-TMP products did not depend on conversion $(3.3 \pm 0.2;$ Figure 1a), consistent with the primary nature of both Prins condensation and oligomerization reactions of isobutanal-isobutene reactants. Similar selectivity trends were also observed on aluminosilicates (H-Al-MCM-41 20 ± 1 , Figure 1b; H-CD-FAU 18 ± 1 , Figure 1c; H-ASA 19 \pm 1, section S5, SI) and on Nb₂O₅ \cdot nH₂O (9.6 ± 0.5 , Figure 1d), indicative of a similar reaction network on all solid acids. Condensation/oligomerization selectivity ratios are significantly higher on the weaker aluminosilicate acids (DPE 1204 kJ mol⁻¹, Table 1) than on $H_3PW_{12}O_{40}$ acids (1087 kJ mol⁻¹); these effects of acid strength are discussed based on the elementary steps and transition states involved in section 3.6. They appear to indicate that the strength of the acid sites in Nb2O5.nH2O is intermediate between those of the acid sites present in aluminosilicates and H3PW12O40, an inference that cannot be confirmed by DFT methods because the uncertain structure of the conjugate anion in Nb2O5.nH2O solids precludes any reliable structural models on which to estimate DPE values. Selectivities to products of skeletal isomerization and cyclization reactions of 2,5-DMH on aluminosilicates and $Nb_2O_5 \cdot nH_2O$ (<15% and 2% at 8–10% isobutene conversion, respectively; Figure 1b-d) were also much lower than on $H_3PW_{12}O_{40}/SiO_2$ (54% and 3%, respectively, Figure 1a), indicative of the stronger dependence on acid strength of these reactions relative to the Prins condensation steps that form 2,5-DMH. These data show that the rates of all reactions decrease with increasing DPE values of solid acids but that Prins condensation reactions are more weakly affected than oligomerization or secondary reactions, leading to a preference for 2,5-DMH Prins condensation products over those of oligomerization, skeletal isomerization, and cyclization on weaker acids.

3.2. Site Titrations during Isobutanal-Isobutene Reactions on Solid Acids. Non-coordinating 2,6-di-tertbutylpyridine (DTBP) titrants were introduced during isobutanal-isobutene reactions to determine the number and type of acid sites responsible for the products observed. DTBP is irreversibly protonated on Brønsted acids but cannot coordinate with Lewis acid centers because of the significant steric hindrance at its N atom.²⁶ Titration with DTBP fully suppressed rates for Prins condensation reactions (r_{prins} , defined as the combined formation rates of 2,5-DMH and the products of its skeletal isomerization and cyclization reactions hereinforth) and for oligomerization reactions (r_{oligo}) in a concurrent manner on all solid acids (e.g., H₃PW₁₂O₄₀/SiO₂ and H-Al-MCM-41 in Figure 2; H-ASA and Nb₂O₅·nH₂O in section S6, SI). These data show that both reactions occur exclusively on the same Brønsted acid sites present on each solid acid. The number of these active protons is given by the amount of DTBP required to fully suppress each of two rates. These proton counts are reported in Table 2 for each sample and are used to calculate turnover rates, a measure of the



Figure 1. Selectivities of 2,5-DMH (\bullet) and the respective skeletal (\Box) and cyclized (Δ) isomers and 2,4,4-TMP (\diamond) as a function of isobutene conversion on (a) H₃PW₁₂O₄₀/SiO₂, (b) H-Al-MCM-41, (c) H-CD-FAU, and (d) Nb₂O₅·nH₂O (473 K; 2.0 kPa isobutanal; 1.0 kPa isobutene). The dashed curves indicate trends.



Figure 2. Isobutanal–isobutene Prins condensation (r_{prins}) and isobutene oligomerization (r_{oligo}) rates as a function of cumulative 2,6-di-*tert*butylpyridine (DTBP) uptakes on (a) H₃PW₁₂O₄₀/SiO₂ and (b) H-Al-MCM-41 (473 K; 2.0 kPa isobutanal; 1.0 kPa isobutene; DTBP 2.0 Pa for H₃PW₁₂O₄₀/SiO₂ and 2.5 Pa for H-Al-MCM-41). The dashed lines represent linear regression fits.

Table 2. Proton Densities, Turnover Rates for Isobutene Oligomerization (r_{oligo}) and for Isobutanal–Isobutene Prins Condensation (r_{prins}) , and Ratios of the Two Rates on Solid Acid Catalysts^{*a*}

catalyst	Н	I ₃ PW ₁₂ O ₄₀ / SiO ₂	Nb ₂ C nH ₂) ₅ . O	H-CD- FAU	H-Al- MCM-4	1 H-ASA
H ⁺ density (mmol g ⁻¹)	1	0.049	0.01	7	1.4	0.15	0.064
		Turnover H	Rate (k	cs ⁻¹ p	er H+)		
r _{oligo}		11.2	2.3		1.0	0.8	0.8
r _{prins}		35.6	20.6		18.1	14.8	14.3
r _{2,5-DMH}		23.1	19.2		16.9	14.1	13.5
r _{skeletal}		11.6	1.1		1.0	0.7	0.7
r _{cyclic}		1.0	0.2		0.2	0.1	0.1
$r_{\rm prins}/r_{\rm oligo}$		3.2	9.0		18	20	19
^a 473 K, 2.	0 kPa	isobutanal,	1.0	kPa	isobutene	e, 3%	isobutene

conversion; $r_{\rm prins}$ is the sum of formation rates of 2,5-DMH ($r_{2,5-\rm DMH}$) and the products of its skeletal isomerization ($r_{\rm skeletal}$) and cyclization ($r_{\rm cyclic}$).

intrinsic reactivity of the Brønsted acid sites in each sample. The accurate assessment of turnover rates allows, in turn, rigorous comparisons among catalyst samples and also between measured rates and those derived from DFT treatments of plausible elementary steps for Prins condensation and oligomerization catalytic sequences (section 3.6).

3.3. Turnover rates of Isobutanal–Isobutene Reactions on Solid Acids. Both isobutanal–isobutene Prins condensation and isobutene oligomerization rates (r_{prins} ; r_{oligo}) on solid acids decreased with time on stream ($H_3PW_{12}O_{40}/$ SiO₂ and H-Al-MCM-41 as illustrative examples shown in section S7, SI), but the $r_{\text{prins}}/r_{\text{oligo}}$ ratios remained essentially unchanged throughout (3.5 ± 0.2 for $H_3PW_{12}O_{40}/SiO_2$; 21 ± 2 for H-Al-MCM-41; section S7, SI), consistent with the involvement of the same Brønsted acid sites in both reactions (section 3.2) and with deactivation processes that merely remove sites instead of changing their reactive properties. $H_3PW_{12}O_{40}/SiO_2$ and H-Al-MCM-41 showed similar deactivation rate constants (0.12 vs 0.16 ks⁻¹, section S7, SI) but distinct selectivities to Prins condensation and oligomerization products (r_{prins}/r_{oligo} 3.5 ± 0.2 vs 21 ± 2), indicating that the deactivation rates do not depend sensitively on the prevalent concentration of any specific products but are likely to reflect instead intrinsic side reactions from common precursors involved in Prins condensation and oligomerization pathways. All rate data reported herein were corrected for deactivation by periodically returning to standard conditions as described in section 2.2 when measuring Prins condensation and oligomerization rates at different reactant pressures or temperatures.

Table 2 depicts turnover rates for isobutanal-isobutene Prins condensation and isobutene oligomerization reactions on all solid acid catalysts examined in this study (473 K; 2.0 kPa isobutanal; 1.0 kPa isobutene). The turnover rates for both reactions were higher on H₃PW₁₂O₄₀/SiO₂ than on weaker acids (Nb₂O₅·nH₂O, H-CD-FAU, H-Al-MCM-41, and H-ASA), indicating that both reactions are mediated by cationic TS, which contain conjugate anionic moieties that become more stable with increasing acid strength.⁴¹ In contrast, r_{prins}/ r_{oligo} ratios were larger on weaker acids (Table 1), as also evident in their selectivities at all isobutene conversions (0-15%; Figure 1). These trends indicate that the charge difference between the cationic transition states for Prins condensation (TS_{prins}) and oligomerization (TS_{oligo}) is larger on the weaker acids. DFT treatments show that the extent of protonation of the isobutanal-derived moiety involved in TS_{prins} increases as the acid becomes stronger, leading to a concomitant increase in the charge of the TS_{prins} structure with increasing acid strength (+0.73 on aluminosilicates; + 0.94 on $H_3PW_{12}O_{40}$; section 3.6); in contrast, fully formed carbenium ions are present at TS_{oligo} structures, irrespective of the acid strength, leading to charges of TS_{oligo} structures close to unity on all acid catalysts, as also observed in previous studies.^{3,22} As a result, TS_{oligo} benefits



Figure 3. Effects of temperature on the (a) rates of isobutanal-isobutene Prins condensation (r_{prins}) and isobutene oligomerization (r_{oligo}) and (b) selectivities of isobutanal-isobutene reactant mixtures at 10% isobutene conversion (H-Al-MCM-41; 20 kPa isobutanal; 20 kPa isobutene). The dashed curves indicate trends. Solid lines represent exponential regression fits. Activation enthalpies (ΔH^{\ddagger}) for Prins condensation and oligomerization reactions at 473 K were calculated from the exponential regression fits according to the Arrhenius equation ($E_a = -R \frac{d \ln(r)}{d(1/T)}$, where E_a is the activation energy, r is the reaction rate; $\Delta H^{\ddagger} = E_a + RT$) and were shown beside the respective rate data.



Figure 4. Effects of (a) isobutene pressure and (b) isobutanal pressure on isobutanal-isobutene Prins condensation rates (H-Al-MCM-41; 473 K; 0-5 kPa isobutanal; 0-5 kPa isobutene). The dashed lines represent regressed fits to the functional form of eq 2.



Figure 5. Effects of (a) isobutene pressure and (b) isobutanal pressure on isobutene oligomerization rates (H-Al-MCM-41; 473 K; 0-5 kPa isobutanal; 0-5 kPa isobutene). The dashed lines represent regressed fits to the functional form of eq 3.

more significantly from the stability conferred by the more stable conjugate anions of the stronger acids than TS_{prins} , causing the selectivity to Prins reaction products to increase as acid sites weaken. Such effects of acid strength ultimately weaken for stronger acids because both TS_{Prins} and TS_{oligo} structures become full ion-pairs and similarly sensitive to the stability of the conjugate anions at the TS. Fully formed carbenium ions are also involved in the transition states that mediate secondary isomerization and cyclization reactions of primary 2,5-DMH products;³ stronger acids thus favor these transition states over the less charged TS structures that mediate the primary formation of the 2,5-DMH Prins reaction products (Table 1). These effects of acid strength on reactivity and selectivity are confirmed in section 3.6 using density functional theory (DFT) calculations.

The strength of Brønsted acid sites in aluminosilicates is essentially independent of the framework structure and similar in crystalline and amorphous solids (section 2.4).^{42,46–48} The higher r_{prins} and r_{oligo} values observed on microporous H-CD- FAU relative to mesoporous H-Al-MCM-41 and H-ASA samples (Table 2), taken together with their similar $r_{\rm prins}/r_{\rm oligo}$ ratios (18–20, Table 2), indicate that the van der Waals stabilization conferred by the confining voids in these samples is similar for Prins condensation and oligomerization transition states. We note that alternate proposals that would implicate differences in acid strength to account for the different reactivities on H-CD-FAU, H-Al-MCM-41, and H-ASA would be inconsistent with their similar $r_{\rm prins}/r_{\rm oligo}$ ratios.

Isobutanal–isobutene reaction rates and selectivities were measured over a broad range of temperature (473–633 K) and at higher reactant pressures (20 kPa isobutanal; 20 kPa isobutene) on H-Al-MCM-41 to explore the effects of the higher reactant conversions and temperatures envisioned in practice. The data in Figure 3a show that r_{prins} and r_{oligo} both exhibit Arrhenius-type temperature dependences with a slightly lower activation enthalpy for the isobutanal–isobutene Prins condensation than for isobutene oligomerization (36 ± 1, 43 ± 2 kJ mol⁻¹; Figure 3a). These small differences led to a slight decrease in $r_{\rm prins}/r_{\rm oligo}$ ratios from 10.6 (at 473 K) to 7.4 (at 633 K) with increasing temperature (Figure 3a). Higher temperatures also favored the formation of skeletal isomers and cyclic products via secondary reactions of the 2,5-DMH primary products of Prins condensation (Figure 3b), but the sum of the selectivities to these products remains below 20% (at 10% isobutene conversion) on these weaker acids at temperatures below 600 K.

3.4. Effects of Isobutene and Isobutanal Pressures on Prins Condensation and Oligomerization Turnover **Rates.** The rate of Prins condensation reactions (r_{prins}) of isobutanal-isobutene mixtures on H-Al-MCM-41 increased monotonically with isobutene and isobutanal pressures (Figure 4), but such linear increases at low pressures became weaker as pressure increased. These prevalent effects of the pressures of both reactants on r_{prins} are consistent with the formation of 2,5-DMH products via kinetically relevant C–C bond coupling between isobutene and isobutanal⁶⁻⁹ on proton sites, which become increasingly covered by adsorbed species derived from one or both reactants as their respective pressures increase. In contrast, isobutene oligomerization rates (r_{oligo}) showed a stronger than linear dependence on isobutene pressure (Figure 5a), and these rates decreased with increasing isobutanal pressure (Figure 5b). These trends indicate that the formation rate of 2,4,4-TMP is limited by steps that are mediated by bimolecular transition states involving two isobutene molecules on protons partially occupied by isobutanal-derived bound species. The proportional dependence of $r_{\rm prins}/r_{\rm oligo}$ on isobutanal/isobutene reactant ratios (Figure 6) indicates that



Figure 6. Effects of isobutanal/isobutene reactant ratio on ratios of isobutanal–isobutene Prins condensation and isobutene oligomerization rates (H-Al-MCM-41 (\diamond); H-CD-FAU (Δ); 5% wt. H₃PW₁₂O₄₀/SiO₂ (O); 473 K; 0–5 kPa isobutanal; 0–5 kPa isobutene). The dashed lines represent linear regression fits.

the rate equations for both reactions share a common denominator term, which reflects the relative coverages of various species at protons and the common involvement of protons of uniform acid strength as the active sites for both reactions.

The observed effects of isobutene and isobutanal pressures on Prins condensation and oligomerization rates on $H_3PW_{12}O_{40}/SiO_2$ (Figures 7 and 8) and H-CD-FAU resemble those observed on H-Al-MCM-41 (Figures 4 and 5), indicative of Prins condensation and oligomerization elementary steps that are similar on all acids, irrespective of the number or acid strength of their active protons (Tables 1 and 2). The ratio of Prins condensation and oligomerization rates on $H_3PW_{12}O_{40}/SiO_2$ and H-CD-FAU is also strictly proportional to isobutanal/ isobutene reactant ratios (Figure 6), confirming that both reactions occur on the same proton sites, as also found on H-Al-MCM-41. The slopes of these linear trends reflect the intrinsic selectivities of Prins condensation and oligomerization reactions. Such intrinsic selectivities depend on acid strength, as discussed in section 3.3 and as interpreted mechanistically by DFT treatments of the proposed elementary steps in section 3.6.

Scheme 5 depicts a plausible sequence of elementary steps for Prins condensation and oligomerization reactions using isobutanal and isobutene as illustrative coreactants on Brønsted acid sites. These elementary steps are consistent with the observed effects of isobutene and isobutanal pressures on Prins condensation and oligomerization rates (Figures 4-8) and with the DFT-derived free energies described in section 3.6. In these steps, isobutanal first binds to protons via H-bonding between its carbonyl O atom or via H-transfer to form 1-hydroxy-isobutoxides (steps 1-2, Scheme 5a). Isobutene, in contrast, binds by forming a π -complex, an iso-butoxide, or a *tert*-butoxide at Brønsted acid sites (steps 1'-3', Scheme 5b).²² Each bound species can react with either isobutanal or isobutene to form the respective dimers (steps 3-4, Scheme 5a; steps 4'-5', Scheme 5b). Some of these dimer species could be present at kinetically relevant coverages on catalysts that contain protons within voids of molecular dimensions (e.g., H-MFI, H-BEA), which preferentially stabilize these dimers over monomer species via van der Waals stabilization, because of their larger size and more effective contacts with the void walls.²³

The C–C bond formation in Prins condensation reactions occurs via nucleophilic attack by the terminal C atom in the C=C bond of a gaseous isobutene molecule at the carbonyl C atom of a H-bonded isobutanal molecule to form γ -hydroxy-C₈ alkoxides (step 5, Scheme 5a). These alkoxides subsequently undergo concerted elimination and deprotonation (step 6, Scheme 5a) and dehydration (step 7, Scheme 5a) to form 2,5-DMH. Oligomerization reactions form C–C bonds via nucleophilic attack by the same terminal C atom in a gaseous isobutene molecule at the tertiary C atom of *tert*-butoxides (step 6', Scheme 5b) to form C₈ alkoxides that subsequently deprotonate to form 2,4,4-TMP (step 7', Scheme 5b).

These elementary steps (Scheme 5), taken together with the assumption that all bound monomer and dime species derived from isobutanal—isobutene reactants may exist at kinetically significant coverages, led to rate equations for isobutanal—isobutene Prins condensation (r_{prins}) and isobutene oligomerization (r_{oligo}):

$$r_{\rm prins} = \frac{k_{\rm prins} P_{\rm al} P_{\rm ene}}{1 + K_{\rm al} P_{\rm al} + K_{\rm ene} P_{\rm ene} + K_{\rm al-ene} P_{\rm al} P_{\rm ene} + K_{\rm al-al} P_{\rm al}^{2} + K_{\rm ene-ene} P_{\rm ene}^{2}}$$
(2)
$$r_{\rm oligo} = \frac{k_{\rm oligo} P_{\rm ene}^{2}}{1 + K_{\rm al} P_{\rm al} + K_{\rm ene} P_{\rm ene} + K_{\rm al-ene} P_{\rm al} P_{\rm ene} + K_{\rm al-al} P_{\rm al}^{2} + K_{\rm ene-ene} P_{\rm ene}^{2}}$$
(3)

These two rates share a common denominator. The k_{prins} and k_{oligo} parameters denote the respective second-order rate constants for Prins condensation and oligomerization, and P_{al} and P_{ene} are the isobutanal and isobutene pressures; the K_{al}



Figure 7. Effects of (a) isobutene pressure and (b) isobutanal pressure on isobutanal–isobutene Prins condensation rates (5% wt. $H_3PW_{12}O_{40}/SiO_{2}$; 473 K; 0–5 kPa isobutanal; 0–5 kPa isobutene). The dashed lines represent regressed fits to the functional form of eq 2.



Figure 8. Effects of (a) isobutene pressure and (b) isobutanal pressure on isobutene oligomerization rates (5% wt. $H_3PW_{12}O_{40}/SiO_2$; 473 K; 0–5 kPa isobutanal; 0–5 kPa isobutene). The dashed lines represent regressed fits to the functional form of eq 3.

 $K_{ene'}$, $K_{al-al'}$, and $K_{ene-ene}$ parameters represent the lumped adsorption equilibrium constants; the lumping strategy is meant to account for all distinct adsorbed configurations that can form as bound monomers or dimers upon adsorption of isobutanal, isobutene, isobutanal–isobutene pairs, isobutanal–isobutanal pairs, and isobutene–isobutene pairs on protons.

The parity plots of predicted and measured rates (section S8, SI; using the regressed parameters in Table 3) show that eqs 1 and 2 accurately describe all Prins condensation and oligomerization rate data on H-Al-MCM-41 (Figures 4 and 5) and H₃PW₁₂O₄₀/SiO₂ (Figures 7 and 8) over a broad range of conditions. These equations also describe the observed effects of isobutanal/isobutene reactant ratios on $r_{\rm prins}/r_{\rm oligo}$ ratios (Figure 6):

$$\frac{r_{\rm prins}}{r_{\rm oligo}} = \frac{k_{\rm prins}P_{\rm al}}{k_{\rm oligo}P_{\rm ene}} \tag{4}$$

The slope for the data shown in Figure 6 reflects the ratio of the second-order rate constants (k_{prins}/k_{oligo}) and thus the intrinsic selectivities for Prins condensation and oligomerization on protons present in a given solid acid. Such mechanistic interpretations of the reactivity and selectivity of isobutanal– isobutene reactants allow a rigorous assessment of the validity of this proposal and of the implications of this mechanistic proposal for the consequences of acid strength and confinement using DFT methods (section 3.6).

3.5. Effects of Acid Strength on Prins Condensation and Oligomerization Turnover Rates. The second-order Prins condensation rate constant (k_{prins} ; eq 2) depends on the activation free energy ($\Delta G^{\ddagger}_{prins}$) for the kinetically relevant elementary step:

$$k_{\rm prins} = \frac{k_{\rm B}T}{h} \exp(-\Delta G^{\dagger}_{\rm prins}/RT)$$
(5)

The value of $\Delta G^{\ddagger}_{\text{prins}}$ is the free energy of the C–C coupling TS ($G^{\ddagger}_{\text{prins}}$) referenced to those of gaseous reactants and a bare

Scheme 5. Proposed Reaction Pathways for (a) Isobutanal–Isobutene Prins Condensation and (b) Isobutene Oligomerization on Solid Brønsted Acids (Shown for Aluminosilicates As an Illustrative Example)^a

(a) Isobutanal-isobutene Prins reaction



^aQuasi-equilibrated steps are noted by a circle over double arrows.

Table 3. Rate Constants and Adsorption Constants Obtained from Regression Fits of Prins Condensation and Oligomerization Rate Data (at 473 K) to the Respective Functional Forms of Eqs 2 and 3 for H-Al-MCM-41 and SiO₂-Supported H₃PW₁₂O₄₀

catalyst	H-Al-MCM-41 ^a	H ₃ PW ₁₂ O ₄₀ ^b
$k_{\rm prins}~({\rm ks^{-1}~kPa^{-2}~per~H^+})$	12 ± 2	25 ± 1
k _{oligo} (ks ⁻¹ kPa ⁻² per H ⁺)	1.2 ± 0.3	12 ± 1
$K_{\rm al}~({\rm kPa}^{-1})$	0.3 ± 0.1	0.12 ± 0.02
$K_{\rm ene}~({\rm kPa}^{-1})$	0.3 ± 0.1	< 0.01
$K_{\text{al-ene}} \ (\text{kPa}^{-2})$	0.17 ± 0.02	0.06 ± 0.01
$K_{\rm al-al}~({\rm kPa^{-2}})$	<0.01	< 0.01
$K_{\rm ene-ene}~({\rm kPa}^{-2})$	<0.01	< 0.01
^{<i>a</i>} From data in Figures 4 and 5.	^b From data in Fig	ures 7 and 8.

surface site; in this case, such species are one gaseous isobutanal molecule (G_{al}) , one gaseous isobutene molecule (G_{ene}) , and a proton (G_{H}) , as inferred from the schematic reaction

coordinate diagram for Prins condensation elementary steps (Scheme 6):

$$\Delta G^{\ddagger}_{\text{prins}} = G^{\ddagger}_{\text{prins}} - G_{\text{al}} - G_{\text{ene}} - G_{H} \tag{6}$$

The value of the oligomerization rate constant (k_{oligo}) reflects its corresponding activation free energy $(\Delta G^{\ddagger}_{\text{oligo}}; \text{ eq } 3)$:

$$k_{\rm oligo} = \frac{k_{\rm B}T}{h} \exp(-\Delta G^{\ddagger}_{\rm oligo}/RT)$$
⁽⁷⁾

The value of $\Delta G^{\ddagger}_{oligo}$ is given by the free energy difference between the oligomerization C–C coupling TS (G^{\ddagger}_{oligo}) and two gaseous isobutene reactants (G_{ene}) and a bare proton (G_{H}) as illustrated in Scheme 6:

$$\Delta G^{\dagger}_{\text{oligo}} = G^{\dagger}_{\text{oligo}} - 2G_{\text{ene}} - G_H \tag{8}$$

Measured $\Delta G^{\ddagger}_{\text{prins}}$ and $\Delta G^{\ddagger}_{\text{oligo}}$ values on H-Al-MCM-41 were 107 \pm 1 and 116 \pm 1 kJ mol⁻¹ (473 K; Table 4, 1 bar reference state), respectively, in agreement with their respective

Scheme 6. Schematic Reaction Coordinate Diagram for Isobutanal–Isobutene Prins Condensation and Isobutene Oligomerization Reactions from Gaseous Isobutanal–Isobutene Reactants on a Bare Proton Site^a



Reaction coordinate

 ${}^{a}\Delta G^{\dagger}_{\text{prins}}$ and $\Delta G^{\dagger}_{\text{oligo}}$ represent respective experimentally accessible free energy barriers for isobutanal–isobutene Prins condensation (eq 5) and for isobutene oligomerization (eq 7).

Table 4. Measured Free Energy Activation Barriers for Isobutanal–Isobutene Prins Condensation ($\Delta G^{\dagger}_{prins}$) and Isobutene Oligomerization ($\Delta G^{\dagger}_{oligo}$) and Adsorption Energies for Isobutanal ($\Delta G_{ads,al}$) and Isobutene ($\Delta G_{ads,ene}$) on H-Al-MCM-41 and SiO₂-Supported H₃PW₁₂O₄₀^{*a*}

	H-Al-MCM-41	$H_{3}PW_{12}O_{40}$		
$\Delta G^{\ddagger}_{\text{prins}}$ (kJ mol ⁻¹)	107 ± 1	104 ± 1		
$\Delta G^{\ddagger}_{oligo}$ (kJ mol ⁻¹)	116 ± 1	107 ± 1		
$\Delta G_{ m ads,al}~(m kJ~mol^{-1})$	-13 ± 2	-10 ± 1		
$\Delta G_{ m ads,ene}~(m kJ~mol^{-1})$	-13 ± 2	>0		
a 473 K, 1 bar; from data in Table 3.				

DFT estimates using model aluminosilicate slab surfaces (109 and 124 kJ mol⁻¹; section 3.6). Measured $\Delta G^{\ddagger}_{\text{prins}}$ and $\Delta G^{\ddagger}_{\text{oligo}}$ values on H₃PW₁₂O₄₀/SiO₂ (104 ± 1 and 107 ± 1 kJ mol⁻¹; 473 K; Table 4) were lower than their respective values on H-Al-MCM-41, as a result of the smaller DPE values of POM clusters compared with H-Al-MCM-41 (1087 and 1204 kJ mol⁻¹; Table 1). Such effects of acid strength are consistent with those determined from DFT-derived free energies on aluminosilicate slab and H₃PW₁₂O₄₀ cluster models (section 3.6). These data confirm that the C–C coupling transition states involved in Prins condensation and oligomerization reactions both become more stable with increasing acid strength as a result of the more stable conjugate anions prevalent in stronger acids.⁴¹

The ratio of the $k_{\text{prins}}/k_{\text{oligo}}$ parameters reflects the difference between $\Delta G^{\ddagger}_{\text{prins}}$ and $\Delta G^{\ddagger}_{\text{oligo}}$ values ($\Delta \Delta G^{\ddagger}_{\text{prins-oligo}}$) (Scheme 6):

$$\frac{k_{\text{prins}}}{k_{\text{oligo}}} = \exp(-\Delta\Delta G^{\ddagger}_{\text{prins-oligo}}/RT)$$
$$= \exp[-(\Delta G^{\ddagger}_{\text{prins}} - \Delta G^{\ddagger}_{\text{oligo}})/RT]$$
(9)

$$\Delta \Delta G^{\dagger}_{\text{prins-oligo}} = G^{\dagger}_{\text{prins}} - G^{\dagger}_{\text{oligo}} - G_{\text{al}} + G_{\text{ene}}$$
(10)

1

These ratios are thus determined by the free energy differences between the two C–C coupling transition states, which depend on the identity of the solid acids, specifically on their acid strength and on any relevant effects of confinement imposed by voids of molecular dimensions,²⁵ and between their respective

isobutanal and isobutene gaseous reactants, which reflect catalyst-independent properties of the gaseous reactants (eq 10). Measured $\Delta\Delta G^{\ddagger}_{\text{prins-oligo}}$ values for H-Al-MCM-41 and H₃PW₁₂O₄₀ were -9 ± 1 and -3 ± 1 kJ mol⁻¹ (473 K; Table 4), respectively, in agreement with the trends derived from DFT treatments (-15 and -4 kJ mol⁻¹; section 3.6). The different $\Delta\Delta G^{\ddagger}_{\text{prins-oligo}}$ values on H-Al-MCM-41 and H₃PW₁₂O₄₀ indicate that the stability of the oligomerization C-C coupling TS depends more sensitively on acid strength than for the Prins condensation C-C coupling TS. Such different sensitivities reflect, in turn, differences in the partial charge at these two cationic TS structures, a conclusion confirmed by DFT-derived energies and TS structures for the elementary steps that mediate oligomerization and Prins condensation catalytic sequences (section 3.6).

3.6. Theoretical Treatments of Adsorbed Species and Elementary Steps and Their Kinetic Relevance in Prins Condensation and Oligomerization Catalytic Sequences. DFT methods are used in this section to confirm the mechanistic details inferred from measured rates and selectivities and to interpret the effects of acid strength on reactivity and selectivity for Prins condensation and oligomerization reactions. These calculations were carried out on model aluminosilicate slabs and POM clusters with W addenda atoms and S, P, Si, or Al central atoms (section 2.4). These materials provide a broad range of DPE values (1204 kJ mol⁻¹ for the aluminosilicate slab; 1073–1123 kJ mol⁻¹ for W-based POM clusters; Table 1) appropriate to probe the effects of acid strength on reactivity and selectivity.

The structure and binding energy of monomeric adsorbed species derived from isobutanal (H-bonded isobutanal and 1-hydroxy-iso-butoxide; steps 1 and 2, Scheme 5a) and isobutene (π -complex, iso-butoxide and *tert*-butoxide; steps 1'-3', Scheme 5b) via interactions with protons were first examined on aluminosilicate slab surfaces. The regressed adsorption constants obtained from rate data on H-Al-MCM-41 (eq 2; Table 3) show that monomeric species derived from isobutanal and isobutene are present at higher coverages than for the various dimer species derived from isobutanal—isobutene reactants, indicating that such monomeric species are the most abundant adsorbed intermediates during catalysis. DFT treatments allow assessments about the prevalent forms of the

Scheme 7. DFT-Optimized Structures of Adsorbed Species Formed from Isobutanal ((a) H-Bonded Isobutanal and (b) 1-Hydroxy-iso-butoxide) and Isobutene ((c) π -Complex, (d) Iso-butoxide, and (e) *tert*-Butoxide) on Proton Sites and Their Respective Adsorption Enthalpies (ΔH_{ads}) and Adsorption Free Energies (ΔG_{ads})^{*a*}



^aAluminosilicate (Si₅₉AlO₁₂₄H₉) slabs, PBE+D3BJ; 473 K, 1 bar; relative to a bare surface and respective gaseous reactants.

monomers derived from either isobutanal or isobutene and about the involvement of their stable and unstable forms in subsequent reactions that lead to the kinetically relevant transition states for Prins condensation and oligomerization reactions; the relative stabilities and involvement of these distinct forms of each monomer or dimer species, differing in structure and reactivity, but not in stoichiometry, cannot be discerned from experiments.

Isobutanal can bind at a proton site via its O atom to form Hbonded species with O–H distances of 0.155 nm (Scheme 7a). H-transfer can form 1-hydroxy-iso-butoxides with the carbonyl C atom bound to a lattice O atom ($d_{C-O} = 0.154$ nm, Scheme 7b) and the proton residing at the carbonyl O atom ($d_{\rm H-O}$ = 0.098 nm, Scheme 7b). H-bonded isobutanal and 1-hydroxyiso-butoxide show similar adsorption enthalpies (ΔH_{ads} ; -68 and -62 kJ mol⁻¹, Scheme 7; 473 K henceforth), but the slight enthalpic preference for H-bonded species becomes much more consequential for its prevalence when its greater entropy is taken into account, which leads to free energies that make Hbonded isobutanal the most abundant isobutanal-derived adsorbed species (ΔG_{ads} -8 vs +20 kJ mol⁻¹). Such entropy differences reflect the suppression of free rotations upon formation of the strong covalent bond between the carbonyl C atom and the framework O atom in 1-hydroxy-iso-butoxide, leading to a preference for H-bonded isobutanal that becomes even stronger at higher temperatures because of the preeminence of entropy as the determinant of Gibbs free energies at higher temperatures. Such differences in stability lead to a coverage ratio of 1200 between H-bonded isobutanal and 1hydroxy-iso-butoxide at 473 K on aluminosilicate slab surfaces. The predominant presence of H-bonded species on such

surfaces is also consistent with measured ΔG_{ads} values (-13 ± 2 kJ mol⁻¹, Table 4) that resemble DFT-derived values for Hbonded isobutanal (-8 kJ mol⁻¹, Scheme 7a) but differ significantly from those calculated for 1-hydroxy-iso-butoxide species (+20 kJ mol⁻¹, Scheme 7b).

The DFT-derived structure of the π -complex of adsorbed isobutene shows the proton aligned with the π orbital at the C=C bond at 0.195 and 0.233 nm from the primary and tertiary C atoms in isobutene, respectively (Scheme 7c). Htransfer to the tertiary C atom forms an iso-butoxide (Scheme 7d), while transfer to the primary C atom forms a *tert*-butoxide (Scheme 7e). The C-O bond is longer in the tert-butoxide than in the terminal iso-butoxide (0.155 vs 0.149 nm, Schemes 7d,e), indicative of steric hindrance at the tertiary C atom. DFT-derived ΔH_{ads} and ΔG_{ads} for *tert*-butoxide (-81 and -10 kJ mol⁻¹, Scheme 7e) were more negative than the respective values for π -complexes (-64 and -4 kJ mol⁻¹, Scheme 7c) or iso-butoxides (-72 and 0 kJ mol⁻¹, Scheme 7d), reflecting the prevalence of tert-butoxides among isobutene-derived monomer species. As in the case of isobutanal-derived species, these DFT-derived ΔG_{ads} values for *tert*-butoxides (-10 kJ mol⁻¹, Scheme 7e) agree with those measured from the denominator term corresponding to isobutene-derived monomers in eq 2 $(-13 \pm 2 \text{ kJ mol}^{-1}, \text{ Table 4})$, which are significantly more negative than DFT estimates for iso-butoxides or π -complexes of isobutene. Such benchmarking of theoretical and experimental ΔG_{ads} estimates provides confirmatory evidence for the adequacy of the aluminosilicate slab models used in describing the binding properties of the active protons in H-Al-MCM-41.37

Scheme 8. DFT-Optimized Structures of Adsorbed Species Formed from Isobutanal ((a) H-Bonded Isobutanal and (b) 1-Hydroxy-iso-butoxide) and Isobutene ((c) π -Complex, (d) Iso-butoxide, and (e) *tert*-Butoxide) on Proton Sites and Their Respective Adsorption Enthalpies (ΔH_{ads}) and Adsorption Free Energies (ΔG_{ads})^{*a*}



^aH₃PW₁₂O₄₀ clusters, PBE+D3BJ; 473 K, 1 bar; relative to a bare cluster and respective gaseous reactants.

The structure and stability of the monomeric adsorbed species derived from isobutanal and isobutene reactants (steps 1,2 and steps 1'-3', Scheme 5) were also examined on H₃PW₁₂O₄₀ clusters. Specifically, the adsorption constant regressed from measured rates (eq 2; Table 3) indicate that isobutanal-derived monomers are the most abundant adsorbed intermediates and that isobutene-derived monomers are present at much lower coverages on $H_3PW_{12}O_{40}$ (K_{al} 0.12 ± 0.02 kPa⁻¹, $K_{ene} < 0.01$ kPa⁻¹, Table 3). DFT-optimized structures for H-bonded isobutanal are similar to those on aluminosilicate slabs, but proton distances from the carbonyl O atom are slightly shorter on H₃PW₁₂O₄₀ than on aluminosilicate slabs (0.150 and 0.155 nm, Schemes 7a and 8a), as expected from their difference in acid strength (Table 1). In contrast, the C-O bond between 1-hydroxy-iso-butoxides and framework O atoms is longer on $H_3PW_{12}O_{40}$ than on aluminosilicates (0.160 vs 0.155 nm, Schemes 7b and 8b), reflecting the more ionic character of this bond on stronger acids. These trends with acid strength are also observed for the monomeric species derived from isobutene (i.e., π -complex, isobutoxide, and *tert*-butoxide; Scheme 8). The π -complexes reside closer to the protons on $H_3PW_{12}O_{40}$ clusters than on aluminosilicates, with the proton located 0.189 nm (Scheme 8c) and 0.195 nm (Scheme 7c) away from the terminal C atom in isobutene, respectively. In contrast, iso-butoxides and tertbutoxides bind to the conjugate anions of H₃PW₁₂O₄₀ clusters with slightly longer C-O bonds (0.150 and 0.158 nm, Scheme 8d,e) than to aluminosilicates (0.149 and 0.155 nm, Scheme 7d,e).

As in the case of isobutanal interactions with aluminosilicate slabs, H-bonded isobutanal is more stable than 1-hydroxy-isobutoxide on $H_3PW_{12}O_{40}$ clusters (ΔG_{ads} -12 vs +27 kJ mol⁻¹, Scheme 8a,b) and their ΔG_{ads} values agree with those regressed from rate data $(-10 \pm 1 \text{ kJ mol}^{-1}, \text{ Table 4})$. DFT-derived ΔG_{ads} values for π -complexes, iso-butoxides, and *tert*-butoxides on $H_3PW_{12}O_{40}$ clusters were -1, +17, and +41 kJ mol⁻¹, respectively, indicating that these species are less stable than isobutanal-derived monomers, as also concluded from the regression of all rate data to the functional form of eq 2 (ΔG_{ads} > 0 kJ mol⁻¹, Table 4). The different stability of *tert*-butoxides on aluminosilicate slabs and $H_3PW_{12}O_{40}$ clusters (ΔG_{ads} -10 vs +41 kJ mol⁻¹, Schemes 7e and 8e) predominantly reflects enthalpic effects (ΔH_{ads} –81 vs –47 kJ mol⁻¹, Schemes 7e and 8e) resulting from steric hindrance imposed by the two terminal lattice O atoms adjacent to the bound tert-butoxides on H₃PW₁₂O₄₀ clusters. This enthalpic difference is much smaller for protonated isobutene bound through its less substituted primary C atom (to from iso-butoxide species) on both aluminosilicate slabs and $H_3PW_{12}O_{40}$ clusters (ΔH_{ads} -72 vs –65 kJ mol⁻¹, Schemes 7d and 8d), consistent with the preeminence of steric effects as descriptors of stability for bound alkoxides. DFT-derived binding energies show that H-bonded isobutanals are also the predominant adsorbed species on other POM clusters ($H_5AlW_{12}O_{40}$, $H_4SiW_{12}O_{40}$, and $H_2SW_{12}O_{40}$; section S9, SI); their stability increases slightly as the DPE values of the POM clusters decrease (e.g., H₅AlW₁₂O₄₀, -9 kJ mol^{-1} , $H_2SW_{12}O_{40}$, -13 kJ mol^{-1} , section S9, SI).

Nucleophilic attack by gaseous isobutene molecules at the carbonyl C atom in H-bonded isobutanal leads to C-C bond

Scheme 9. DFT-Derived Structures of Reactants, Transition States, and Products Involved in the C–C Bond Formation Elementary Steps for (a) Isobutanal–Isobutene Prins Condensation (Step 5, Scheme 5a) and (b) Isobutene Oligomerization (Step 6', Scheme 5b)^a





(b) C-C bond formation between tert-butoxide and isobutene (isobutene oligomerization)



"Aluminosilicate (Si₅₉AlO₁₂₄H₉) slabs were used for the DFT calculations (PBE+D3BJ); distances are reported in nm.

Scheme 10. DFT-Derived Charge Distributions and van der Waals Volumes for the C–C Bond Formation Transition State Structures Involved in Isobutanal–Isobutene Prins Condensation and Isobutene Oligomerization Pathways (Aluminosilicate $(Si_{59}AlO_{124}H_9)$ Slabs, and PBE+D3BJ)



formation (step 5, Scheme 5a). DFT treatments of this step on aluminosilicate slabs show that the H-bonded isobutanal becomes partially protonated as the primary C atom in isobutene approaches the carbonyl C atom to form an incipient C–C bond at the TS (Scheme 9a). Such charge transfer is evident from the distance between the proton and the carbonyl O atom, which is much shorter at the Prins TS (TS_{prins}; 0.109 nm, Scheme 9a) than in H-bonded isobutanal (0.153 nm, Scheme 9a) but slightly longer than that in the O–H bond at the product state (0.099 nm, Scheme 9a). The extent of charge transfer at the TS_{prins} was probed using the QUAMBO method

(section 2.4), which estimates the most likely Lewis electronic structures for periodic systems and combines the electron densities within the structures to calculate charges. The estimated charge of the cationic TS_{prins} structure was +0.73 (Scheme 10a), confirming its cationic character but without the full protonation of the isobutanal moiety at the TS on aluminosilicates. In contrast, the DFT-derived TS structure that mediates C–C bond formation in isobutene oligomerization (TS_{oligo}) on aluminosilicates involves a *tert*-butoxide species that forms a full carbenium ion as the terminal C atom in the C=C bond in a gaseous isobutene molecule attacks the tertiary



Figure 9. DFT-derived reaction free energy diagrams of (a) isobutanal-isobutene Prins condensation and (b) isobutene oligomerization pathways (aluminosilicate (Si₅₉AlO₁₂₄H₉) slabs, PBE+D3BJ; 473 K, 1 bar). TSj and Pj represent the respective transition state and product of Step j in Scheme 5; AL and ENE represent gaseous isobutanal and isobutene, respectively. Energies are relative to a bare surface and respective gaseous reactants.

Scheme 11. DFT-Derived Structures of Reactants, Transition States, and Products Involved in the C-C Bond Formation Elementary Steps for (a) Isobutanal-Isobutene Prins Condensation (Step 5, Scheme 5a) and (b) Isobutene Oligomerization (Step 6', Scheme 5b)^{*a*}



 ${}^{a}H_{3}PW_{12}O_{40}$ clusters were used for the DFT calculations (PBE+D3BJ); distances are reported in nm.

C atom in *tert*-butoxide (step 6', Scheme 5b). The formation of a full carbenium ion at TS_{oligo} is also evident from the distances between the tertiary C atom and the framework O site in *tert*butoxides (0.155 nm, Scheme 9b) and in TS_{oligo} (0.333 nm, Scheme 9b). The estimated partial charge at the cationic TS_{oligo} structure was +0.92 (Scheme 10b), consistent with these conclusions; such fully formed carbenium ions are typical of the cationic transition states that mediate acid-catalyzed oligomerization, isomerization, and β -scission reactions of hydrocarbons^{3,40-44} and contrast the less pronounced charge (+0.73, Scheme 10a) separation at the oxygen-containing transition states that mediate C–C bond formation in Prins condensation reactions on aluminosilicates.

The C-C bond formation steps involved in Prins condensation lead to γ -hydroxy-C₈ alkoxides (Step 5, Scheme 5a) that convert to 2,5-DMH via concerted elimination-deprotonation and subsequent dehydration steps (steps 6–7, Scheme 5a). 2,4,4-TMP molecules form via deprotonation of C₈ alkoxides (step 7', Scheme 5b), which are formed from the C-C bond formation TS that mediates oligomerization reactions. The DFT-derived Gibbs free energies for these elementary steps in the Prins condensation and oligomerization catalytic sequences are depicted in the reaction coordinate diagram of Figure 9 (473 K, 1 bar) on aluminosilicates. All free energies are referenced to a bare aluminosilicate surface and their respective gaseous isobutanal or isobutene reactants; the corresponding enthalpy components of these free energies are reported in the SI (section S10).

The isobutanal-isobutene and isobutene-isobutene C-C coupling transition states represent the steps with the highest free energies along the Prins condensation and oligomerization reaction coordinates, respectively, reflecting their sole kinetic relevance in the formation of their respective reaction products. DFT-derived $\Delta G^{\dagger}_{\text{prins}}$ (eq 6) and $\Delta G^{\dagger}_{\text{oligo}}$ (eq 8) values on aluminosilicate slabs were 109 and 124 kJ mol⁻¹, respectively (473 K, 1 bar; Figure 9), in good agreement with values determined from measured turnover rates on H-Al-MCM-41 (107 ± 1 and 116 ± 1 kJ mol⁻¹; Table 4). These data confirm that acid-catalyzed Prins condensation and oligomerization reactions are mediated by cationic C-C coupling transition states with different charges, thus allowing the use of weaker acid catalysts to maximize the selectivity to Prins condensation products, as shown in section 3.5.

In contrast with these findings on aluminosilicate slabs, DFTderived isobutanal–isobutene TS_{prins} structures on $H_3PW_{12}O_{40}$ clusters show that the H-bonded isobutanal moiety is fully protonated at the TS; the distance between the proton and the carbonyl C atom is nearly identical to that in the γ -hydroxy-C₈ alkoxide products (0.099 vs 0.097 nm, Scheme 11) and the charge in the cationic TS_{prins} is near unity (+0.94, Figure 11). This greater extent of charge transfer reflects stronger acid sites in $H_3PW_{12}O_{40}$ clusters than in aluminosilicates (DPE 1087 and 1204 kJ mol⁻¹, Table 1). The more stable conjugate anion on stronger acids thus favors a full proton transfer at the TS. The incipient C-C bond at TS_{prins} is shorter on H₃PW₁₂O₄₀ than on aluminosilicates (0.183 vs 0.196 nm, Schemes 9a and 11a), indicative of transition states that occur later along the reaction coordinate on stronger acids. The isobutene-isobutene TS_{oligo} also involves a fully formed carbenium ion on H₃PW₁₂O₄₀ clusters, evident from the charge of the cationic $\mathrm{TS}_{\mathrm{oligo}}$ structure close to unity (+0.93, Figure 11), as also found for the weaker aluminosilicate acids (+0.92, Figure 11). TS_{oligo} structures on H₃PW₁₂O₄₀, however, exhibit shorter distances between the

tertiary C atom in *tert*-butyl carbenium ions and the conjugate O-anion than on aluminosilicate slabs (0.281 vs 0.333 nm, Schemes 9b and 11b) and much longer incipiently formed C–C bonds (0.346 vs 0.194 nm, Schemes 9b and 11b). These differences in bond distances indicate that the C–C coupling transition states for oligomerization occur earlier along the reaction coordinate on stronger acids, indicative of less endothermic formation of the *tert*-butyl carbenium ions on stronger acids as a result their more stable conjugate anions. Such fully formed cations at the C–C coupling transition states involved in the Prins condensation and oligomerization reactions are also observed for H₅AlW₁₂O₄₀, H₄SiW₁₂O₄₀, and H₂SW₁₂O₄₀ clusters (Figure 10), all of which are stronger acids



Figure 10. DFT-derived electronic charges for C–C coupling transition states involved in isobutanal–isobutene Prins condensation (TS_{prins}) and isobutene oligomerization (TS_{oligo}) as a function of deprotonation energy of solid acids (PBE+D3BJ). The solid lines represent trends.

than aluminosilicates (DPE 1073–1123 vs 1204 kJ mol⁻¹, Table 1). These results show that the cationic TS_{prins} and TS_{oligo} structures have similar charges on strong acids, reflecting a weak dependence of the relative stabilities of TS_{prins} and TS_{oligo} on the acid strength for strong acids, as we discuss in detail below.

As for aluminosilicate slab models, DFT-derived free energies for C-C coupling transition states for Prins condensation and oligomerization reactions on Keggin clusters (H_{8-n}Xⁿ⁺W₁₂O₄₀, $X^{n+} = S^{6+}, P^{5+}, Si^{4+}, and Al^{3+}$ are higher than other transition states or intermediates along the respective reaction coordinates (section S11, SI), indicative of the general kinetically relevance of these C-C bond formation elementary steps for both Prins condensation and oligomerization reactions. $\Delta G^{\ddagger}_{prins}$ (eq 6) and $\Delta G^{\ddagger}_{oligo}$ (eq 8) values estimated from DFT treatments for $H_3PW_{12}O_{40}$ clusters were 96 and 100 kJ mol⁻¹ (473 K, 1 bar; Figure 11a), respectively, in reasonable agreement with those measured values (104 \pm 1 and 107 \pm 1 kJ mol⁻¹, Table 4) and confirming that these POM cluster models can describe the reactivities of Prins condensation and oligomerization reactions correctly. DFT-derived enthalpy components involved in these $\Delta G^{\ddagger}_{\text{prins}}$ and $\Delta G^{\ddagger}_{\text{oligo}}$ (i.e., $\Delta H^{\ddagger}_{\text{prins}}, \Delta H^{\ddagger}_{\text{oligo}}$ for $H_3 PW_{12}O_{40}$ clusters were -46 and -39 kJ mol⁻¹, respectively (Figure 11b), reflecting the cationic



Figure 11. DFT-derived (a) activation free energies $(\Delta G^{\dagger}_{\text{prins}} \text{ and } \Delta G^{\dagger}_{\text{oligo}})$ and (b) their enthalpy components for isobutanal-isobutene C-C coupling steps involved in Prins condensation (\bullet) and isobutene-isobutene C-C coupling steps involved in isobutene oligomerization (\bigcirc) as a function of the deprotonation energy of solid acids (PBE+D3BJ; referenced to a bare proton site and respective gaseous reactants; 473 K, 1 bar). The solid lines represent trends.



Figure 12. DFT-derived (a) $\Delta\Delta G^{\dagger}_{\text{prins-ologo}}$ and (b) respective enthalpy components ($\Delta\Delta H^{\dagger}_{\text{prins-ologo}}$) as a function of deprotonation energy of solid acids (PBE+D3BJ; referenced to a bare proton site and respective gaseous reactants; 473 K, 1 bar). The solid lines represent trends.

 TS_{prins} and TS_{oligo} structures are enthalpically more stable than the respective referenced gaseous reactants, which are imparted by the stable conjugate anions of strong acids⁴¹ as also observed for $H_2SW_{12}O_{40}$, $H_4SiW_{12}O_{40}$, and $H_5AIW_{12}O_{40}$ clusters (Figure 11b).

DFT-derived $\Delta G^{\ddagger}_{prins}$ and $\Delta G^{\ddagger}_{oligo}$ for POM clusters both increase monotonically as the DPE values increase with changes in the central atom (Figure 11a), consistent with the lower stability of the conjugate anions in weaker acids and with the cationic character of both C–C coupling transition states, which contain the conjugate anion interacting with the organic cation. Linear trends are also evident between the activation enthalpies ($\Delta H^{\ddagger}_{prins} \Delta H^{\ddagger}_{oligo}$) and the DPE value of each acid (Figure 11b). These relationships highlight the predominant role of enthalpic stabilization in the higher reactivity conferred upon stronger acids by their more stable conjugate anions. Such stabilization becomes more consequently as the cation and anion at the TS acquire a more significant charge. The TS_{prins} and TS_{oligo} structures on the stronger acids, illustrated here by the POM clusters, have similar charges (+0.92-+0.94, Figure 10); their $\Delta G^{\dagger}_{prins}$ and $\Delta G^{\dagger}_{oligo}$ values thus lie along similar trend lines as a function of DPE values (Figure 11a). Selectivity, in this case reflected in the k_{prins}/k_{oligo} ratios (eq 9), therefore becomes independent of acid strength, as previously shown for other catalytic reactions in which parallel routes are mediated by TS structures of similar charge.³

 $\Delta G^{\ddagger}_{\text{prins}}$ and $\Delta G^{\ddagger}_{\text{oligo}}$ for aluminosilicate slab models deviate from their linear trends with DPE values on the stronger POM acids (Figure 11a). The deviation for $\Delta G^{\ddagger}_{\text{oligo}}$ values arises mainly from the entropy component in $\Delta G^{\ddagger}_{\text{oligo}}$; weaker acids lead to TS_{oligo} structures with higher entropy because the fully formed *tert*-butyl carbenium ion and gaseous isobutene species are more tightly bound at the later TS_{oligo} on weaker acids (Scheme 9) than the respective moieties at the earlier TS_{oligo} on stronger acids (Scheme 11). Figure 11b shows that $\Delta H^{\ddagger}_{oligo}$ values for the aluminosilicate slab lie along the linear trend of $\Delta H^{\ddagger}_{oligo}$ with DPE values set by the POM acids, as expected from the full ion-pair character of TS_{oligo} structures on both aluminosilicate slab and POM cluster models (+0.92-+0.94, Figure 10), thus confirming that entropic effects account for the lower than predicted $\Delta G^{\ddagger}_{oligo}$ values for aluminosilicates.

The $\Delta H^{\ddagger}_{\text{prins}}$ values on aluminosilicate slabs (-52 kJ mol⁻¹, Figure 11b), however, are much lower than expected from the $\Delta H^{\ddagger}_{\text{prins}}$ -DPE trends given by the POM clusters (-3 kJ mol⁻¹, Figure 11b). These differences account for the lower $\Delta G^{\ddagger}_{\text{prins}}$ values on aluminosilicate slabs, which also lie below these linear trends (109 kJ mol⁻¹ (calculated) vs 148 kJ mol⁻¹ (expected), Figure 11b). These more negative $\Delta H^{\ddagger}_{\text{prins}}$ values reflect, in part, TS_{prins} structures that are less sensitive to the less stable nature of the conjugate anions as acids weaken because of their lower charges on aluminosilicates than on POM clusters (+0.72 vs +0.94, Figure 10); they also reflect the additional stabilization imparted by the partially covalent O–H bond that remains at the solid acid moiety because of the incomplete transfer of the proton at the TS_{prins} on aluminosilicate slabs (O–H distance 0.139 nm (at TS) vs 0.104 nm (in the TS precursor), Scheme 9a).

On stronger acids $(H_{8-n}X^{n+}W_{12}O_{40}, X^{n+} = S^{6+}, P^{5+}, Si^{4+}, and$ Al³⁺ POM), TS_{prins} and TS_{oligo} are both fully protonated as discussed above (+0.92-+0.94, Figure 10); Prins condensation and oligomerization reactions thus depend similarly on acid strength, as evident from the similar differences between $\Delta G^{\ddagger}_{\text{prins}}$ and $\Delta G^{\ddagger}_{\text{oligo}}$ values on these solid acids $(\Delta \Delta G^{\ddagger}_{\text{prins-oligo}}; (-2 \text{ to } -7) \text{ kJ mol}^{-1}, \text{ Figure 12a})$ over a broad range of DPE values (1073–1123 kJ mol⁻¹, Table 1). On weaker acids, such as aluminosilicates (DPE 1204 kJ mol⁻¹, Table 1), TS_{prins} and TS_{oligo} differ significantly (+0.72 vs +0.92, Figure 10) because of the incomplete proton transfer at TS_{prins}; as a result, the TS_{prins} structures are less destabilized by greater instability of the conjugate anions and the greater residual covalency as acids weaken. Such trends lead, in turn, to more negative $\Delta\Delta G^{\ddagger}_{\text{prins-oligo}}$ values (-15 kJ mol⁻¹, Figure 12a) on aluminosilicates than on stronger POM acids and thus to the observed preference for the formation of 2,5-DMH over isobutene oligomers or products of secondary isomerization of 2,5-DMH; the latter also involve full ion-pairs at their TS structures on all solid acids.³ The pre-eminence of enthalpic stabilization in determining the selectivity to 2,5-DMH is evident from DFT-derived $\Delta\Delta H^{\dagger}_{\text{prins-oligo}}$ components that show similar trends with DPE values as $\Delta\Delta G^{\dagger}_{\text{prins-oligo}}$ estimates (Figure 12b).

DFT-derived entropy components $(T\Delta S^{\ddagger})$ in the free energies of Prins condensation and oligomerization transition states $(TS_{prins}; TS_{oligo})$ are shown in section S12 of the SI. These entropy components are similar for the TS_{prins} and TS_{oligo} structures on the POM clusters and the TS_{oligo} structure on the aluminosilicate slab (-131 to -142 kJ mol⁻¹, Figure S10a, SI), which consist of full ion-pairs at the TS, but more negative for the TS_{prins} structure on the aluminosilicate slab (-161 kJ mol⁻¹, Figure S10a, SI), because of the residual covalent bond that exists between the TS_{prins} and the conjugate anion of the proton site as discussed above. The differences in the entropy components between the TS_{prins} and TS_{oligo} structures ($T\Delta\Delta S^{\ddagger}_{prins-oligo}$) reflect the entropy contributions to the free energy difference between these two transition states, which determine Prins condensation to oligomerization rate ratios. The $T\Delta\Delta S^{\ddagger}_{\text{prins-oligo}}$ values for the POM clusters (-2 to -3 kJ mol⁻¹, Figure S10b, SI) and the aluminosilicate slab (-30 kJ mol⁻¹, Figure S10b, SI) were all less negative than the respective $\Delta\Delta H^{\ddagger}_{\text{prins-oligo}}$ values (Figure 12b), further confirming that the Prins condensation and oligomerization selectivities for a proton site are predominately determined by the different enthalpies of their TS structures.

Finally, we examine the expectations for how confinement within voids of molecular dimensions is likely to influence reactivity and selectivity in alkanal-alkene reactions on solid acids. The van der Waals volumes for TS_{prins} and TS_{oligo} structures (calculated from solvent-excluded surfaces using a sphere (of solvent) with a radius of 0.14 nm)⁶² on aluminosilicate slabs were 0.153 nm³ and 0.144 nm³ respectively (Scheme 10). These transition states are expected to become stable relative to their respective H-bonded isobutanal and bound alkoxides when the confining voids are of similar volume and dimensions, as observed experimentally from the higher turnover rates on microporous H-CD-FAU relative to mesoporous H-Al-MCM-41 of similar acid strengths $(r_{\text{prins}} \ 18.1 \text{ vs } \ 14.8 \text{ ks}^{-1} \text{ per } \text{H}^+; r_{\text{oligo}} \ 1.0 \text{ vs } \ 0.8 \text{ ks}^{-1} \text{ per } \text{H}^+;$ Table 2). The similar size of the TS_{prins} and TS_{oligo} structures makes $k_{\text{prins}}/k_{\text{oligo}}$ ratios $(\Delta\Delta G^{\ddagger}_{\text{prins-oligo}}; \text{ eq } 10)$ essentially independent of the void size in aluminosilicates $(k_{prins}/k_{oligo} 9.7)$ \pm 0.3 (H-CD-FAU) vs 10.3 \pm 0.2 (H-Al-MCM-41); 473 K; Figure 6) because both TS structures are stabilized to the same extent by van der Waals contacts with the walls of the confining voids. Such confinement effects on reactivity and selectivity are consistent with measurements on microporous aluminosilicates with smaller voids (e.g., H-BEA, H-MOR, H-TON, and H-FER) as will be shown in a later report that focuses on the appropriate descriptor of size and reactivity for protons confined within voids of molecular dimensions.

These mechanistic interpretations, underpinned by consistent experimental and theoretical evidence, illustrate how the incompleteness of charge separation at transition states on weak acids can be used for significant selectivity benefits in reactions, in which oxygenates act as electrophiles in the presence of hydrocarbons as coreactants or products. In practice, these findings provide guidance in the design of solids with acid strength that leads to optimal selectivities for such general families of useful catalytic reactions.

4. CONCLUSIONS

Isobutanal and isobutene form 2,5-dimethyl-hexadienes (2.5-DMH) via Prins condensation reactions on Brønsted solid acids (Keggin heteropolyacids, Nb₂O₅·nH₂O, and mesoporous and microporous aluminosilicates). The selectivity to 2,5-DMH, a precursor to p-xylene, is limited by parallel isobutene oligomerization and sequential isomerization reactions. The suppression of the Prins condensation and oligomerization rates by non-coordinating titrations showed that both reactions occur only on Brønsted acid sites, and their accurate counting allows rigorous reactivity comparisons among these acids based on turnover rates and the accurate benchmarking of mechanistic conclusions between theory and experiment. Turnover rates for both reactions $(r_{prins} \text{ and } r_{oligo})$ were higher on H₃PW₁₂O₄₀/SiO₂ than on weaker acids (Nb₂O₅·nH₂O and mesoporous and microporous aluminosilicates), whereas the $r_{\rm prins}/r_{\rm oligo}$ ratios were much higher on the weaker acids instead. Measured activation enthalpies for the isobutanal-isobutene Prins condensation on mesoporous aluminosilicates were

slightly lower than that for isobutene oligomerization $(36 \pm 1 \text{ vs } 43 \pm 2 \text{ kJ mol}^{-1})$, consistent with a minor decrease in $r_{\text{prins}}/r_{\text{oligo}}$ ratios (10.6–7.4) with increasing temperature (473–633 K).

Kinetic and theoretical assessment showed that (i) Prins condensation and oligomerization reactions are mediated by the respective C-C bond formation steps of gaseous isobutene with partly or fully protonated isobutanal and tert-butyl carbenium ions formed from protonation of isobutene; (ii) active proton sites present on the solid acids have uniform acid strength and are predominantly covered by H-bonded isobutanal and isobutene in the form of tert-butoxide (for mesoporous aluminosilicates) or by H-bonded isobutanal solely (for $H_3PW_{12}O_{40}/SiO_2$). Measured free energy barriers for these C-C bond formation steps involved in Prins condensation $(\Delta G^{\ddagger}_{\text{prins}})$ and oligomerization $(\Delta G^{\ddagger}_{\text{oligo}})$ reactions were both higher on mesoporous aluminosilicates (107 \pm 1 and 116 \pm 1 kJ mol⁻¹; 523 K) than on $H_3PW_{12}O_{40}/SiO_2$ (104 ± 1 and 107 \pm 1 kJ mol⁻¹; 523 K), whereas the difference between $\Delta G^{\ddagger}_{\text{prins}}$ and $\Delta G^{\ddagger}_{\text{oligo}}$ ($\Delta \Delta G^{\ddagger}_{\text{prins-oligo}}$), which determines the intrinsic selectivities to the Prins condensation and oligomerization products, was more negative on mesoporous aluminosilicates $(-9 \pm 2 \text{ kJ mol}^{-1}; 523 \text{ K})$ than on H₃PW₁₂O₄₀/SiO₂ (-3 ± 2; 523 K); these data are consistent with theoretical estimates using aluminosilicate slab and Keggin H3PW12O40 cluster models and confirm that mesoporous aluminosilicates with the acid strength weaker than for H₃PW₁₂O₄₀ are less reactive but more selective to the Prins condensation products.

Theoretical treatments unveiled that the C-C bond formation transition states for Prins condensation (TS_{prins}) and oligomerization (TS_{oligo}) reactions are both cationic and have similar charges on stronger acids (+0.94 vs +0.93; on $H_3PW_{12}O_{40}$), while the charge of the TS_{prins} is lower than that for TS_{oligo} on weaker acids (+0.73 vs +0.92; on aluminosilicates), as a result of the incomplete protonation of isobutanal at the $TS_{prins}.$ The cationic nature of TS_{prins} and TS_{oligo} leads to the decrease of their stability with increasing deprotonation energies (DPE) for solid acids, as acid sites weaken and their conjugate anions become less stable, but the stability of the TS_{prins} depends less sensitively on acid strength than for the TS_{oligo} because of the concomitant decrease of the TS_{prins} charge with decreasing acid strength. Such different dependences of the TS stability on DPE values, taken together with an additional stabilization for TS_{prins} on weaker acids imparted by the partially covalent O-H bond remained in the solid acid as a result of the incomplete proton transfer at the TS_{prins}, account for the preferential stabilization of TS_{prins} over TS_{oligo} on weaker acids, which allows to mediate $r_{\rm prins}/r_{\rm oligo}$ ratios for alkanalalkene reactant pairs by choosing solid acids with the proper acid strength. The TS_{prins} and TS_{oligo} structures on aluminosilicates have similar sizes (0.153 and 0.144 nm³), which makes these structures stabilized similarly by van der Waals contacts with the walls of confining voids differing in size but containing protons of similar acid strength, in consistence with the observed similar $r_{\rm prins}/r_{\rm oligo}$ ratios for mesoporous and microporous aluminosilicates.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acscatal.6b02171.

Number of proton and Lewis acid sites on aluminosilicate samples; top views of aluminosilicate slabs; structure of aluminosilicate clusters; effects of space velocity on selectivities to regioisomers of diene/alkene products; conversion-selectivity relations on H-ASA; site titrations of H-ASA and Nb₂O₅·nH₂O during catalysis; deactivation of sold acids during catalysis; parity plots of predicted and measured rates; and summary of DFTderived enthalpies, entropies, and free energies for intermediates and transition states involved in Prins condensation and oligomerization elementary steps on aluminosilicates and POM clusters (PDF)

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Notes

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