

Hydrogen Generation from Alcohols Catalyzed by Ruthenium–Triphenylphosphine Complexes: Multiple Reaction Pathways

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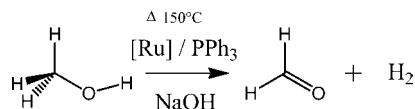
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Abstract: We report a comprehensive density functional theory (DFT) study of the mechanism of the methanol dehydrogenation reaction catalyzed by $[\text{RuH}_2(\text{H}_2)(\text{PPh}_3)_3]$. Using the B97-D dispersion-corrected functional, four pathways have been fully characterized, which differ in the way the critical β -hydrogen transfer step is brought about (e.g., by prior dissociation of one PPh_3 ligand). All these pathways are found to be competitive ($\Delta G^\ddagger = 27.0\text{--}32.1$ kcal/mol at 150 °C) and strongly interlocked. The reaction can thus follow multiple reaction channels, a feature which is expected to be at the origin of the good kinetics of this system. Our results also point to the active role of PPh_3 ligands, which undergo significant conformational changes as the reaction occurs, and provide insights into the role of the base, which acts as a “co-catalyst” by facilitating proton transfers within active species. Activation barriers decrease on going from methanol to ethanol and 2-propanol substrates, in accord with experiment.

Introduction

Generation of hydrogen from renewable resources still represents a challenging task in the larger framework of sustainable power management. Currently, hydrogen is mainly generated from fossil fuel (e.g., natural gas, liquid hydrocarbons, and coal),¹ thereby releasing massive amounts of CO_2 during the production process. On the other hand, an increasing interest has emerged in the use of renewable biomass and its fermentation products (i.e., mainly alcohols) as an alternative to fossil feedstocks, which allows for an almost closed carbon cycle, thanks to the CO_2 -consuming photosynthesis reaction occurring within plants. In particular, the use of alcohols as initial substrates has stimulated an important research effort, aiming ultimately to develop efficient catalytic systems to produce hydrogen on an industrial scale. Whereas some interesting heterogeneous catalysts are being developed,² the design of efficient homogeneous catalysts still remains in its infancy.³ Pioneering studies revealed the possibility of producing hydrogen from alcohols using rhodium⁴ and ruthenium⁵ precursors, and despite significant subsequent research progress⁶ the obtained turnover frequencies (TOF) are generally low. The first efficient homogeneous catalytic system was developed in the late 1980s by Cole-Hamilton et al.,⁷ where high turnover frequencies (TOFs; up to 520 h^{-1} for butanol) are achieved at 150 °C and in the presence of a ruthenium catalyst and

Scheme 1. Methanol Dehydrogenation Catalyzed by $[\text{RuH}_2(\text{H}_2)(\text{PPh}_3)_3]$ (1)



triphenylphosphine ligands (PPh_3 ; see Scheme 1). Subsequent studies have focused on the development of more efficient catalysts, active under milder conditions⁸ and free of phosphorus atoms.⁹

However, little is known about the mechanism of these reactions, since it is not easy to obtain detailed mechanistic insights from experiments. However, some valuable information can be gained, for example, by analyzing the initial reaction rate upon the addition of different catalyst ligands¹⁰ or by

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spectroscopic characterization of selected resting states.¹¹ However, a full elucidation of catalytic cycles, including the characterization of relevant transition states and short-lived intermediates, is scarcely possible. In such a situation, computer modeling contributes profoundly to our understanding of reaction mechanisms. Density functional theory (DFT) is well-suited to provide reliable structural and energetic data, thereby allowing for robust predictions on uncharacterized intermediates and transition states. An early theoretical study of methanol dehydrogenation catalyzed by ruthenium in the presence of phosphine and acetate ligands has been performed by Itagaki et al.,¹² investigating the mechanism initially proposed by Saito et al.^{6g} However, this system is not very active and has now been surpassed by the more recently developed systems cited above.^{7–9} To the best of our knowledge, the latter have not been investigated so far computationally. On the other hand, we note that the reverse hydrogenation¹³ and the closely related hydrogen-transfer¹⁴ reactions have gained more attention.

This led us to undertake a density functional theory study on the classic Morton and Cole-Hamilton system,^{7a} which is found to be reasonably active and for which some experimental mechanistic information are available in the literature. This system is based on a $[\text{RuH}_2(\text{X}_2)(\text{PPh}_3)_3]$ ($\text{X}_2 = \text{N}_2, \text{PPh}_3$) catalyst precursor, and the well-known ruthenium tetrahydride complex^{11b,15} $[\text{RuH}_2(\text{H}_2)(\text{PPh}_3)_3]$ (**1**) is expected to be a key active species. Moreover, this reaction requires the presence of a base (NaOH) and occurs at a moderately high temperature (150 °C; see Scheme 1). A preliminary mechanism has been proposed, in which all steps involve intermediates retaining their three coordinated triphenylphosphine ligands, as found in **1**.^{7a} However, this system was further investigated by Shinoda et al.,^{10,16} who found that the addition of free PPh_3 ligands retards the reaction, a feature which suggests the presence of a phosphine dissociation pre-equilibrium. Moreover, the understanding of this catalytic system is complicated by the presence of side reactions, in particular alcohol decarbonylation,¹⁷ which can be competitive with the dehydrogenation reaction and can lead to catalyst deactivation upon formation of the $[\text{RuH}_2(\text{CO})(\text{PPh}_3)_3]$ complex.⁷

Following a computational protocol that we have established recently (see Methods),¹⁸ we first investigate the mechanism initially proposed by Morton and Cole-Hamilton^{7a} (hereafter noted pathway **A**), using methanol as substrate. Next, three other possible reaction channels (pathways **B–D**) are proposed, guided by computational evidence (reaction free energies between intermediates and free energies of activation) and inspired by other mechanistic reports on closely related reactions found in the literature.¹⁹ Our results reveal that the studied reaction can follow multiple reaction channels, since these four mechanisms are found to be competitive and strongly interlocked, a feature which may be at the origin of the good kinetics of this system. The influence of the alcohol substrate on the dehydrogenation mechanism(s), the role of the base, and the importance of steric effects are also investigated and discussed herein.

Methods

We have recently established a cost-effective protocol¹⁸ allowing us to compute accurate reaction free energies in solution and to consider the actual PPh_3 ligands which are critically needed in order to properly account for their electronic and steric effects. Briefly, our approach is based on geometry optimizations and computation of thermochemistry corrections at a fairly low computational level, whereas refined energies are obtained using a larger basis set in conjunction with the recently developed B97-D functional.²⁰ The latter allows us to account for the critical noncovalent interactions involved in this system.²¹ Solvent effects are also taken into account via the use of a continuum model. In detail, the following steps are involved:

Geometries and Thermodynamic Corrections. Geometries of complexes **1–18** were fully optimized at the RI-BP86/ECP1 level, i.e. employing the exchange and correlation functionals of Becke²² and Perdew,²³ respectively, in conjunction with the SDD basis on Ru, denoting the small-core Stuttgart-Dresden relativistic effective core potential (ECP) together with its valence basis set,²⁴ and the standard 6-31G(d,p) basis for all other elements, except the C and H atoms of phenyl rings on which the smaller 3-21G basis were used,²⁵ and suitable auxiliary basis sets for the fitting of the Coulomb potential.²⁶ Harmonic frequencies were computed analytically and were used without scaling to obtain enthalpic and entropic

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(25) Structures have been determined without corrections for the basis set superposition error (BSSE), since the latter is found to have only a slight influence on geometries. This feature has been investigated in our previous study on a similar tris(triphenylphosphine) complex, and only small structural differences have been obtained when going from ECP1 to the larger ECP2 basis set, where BSSE is expected to be smaller.¹⁸ On the other hand, we note that the influence of the BSSE on reaction energies has been carefully considered herein, and counterpoise energy corrections have been made for each investigated step.

(26) Generated automatically according to the procedure implemented in Gaussian 03.

corrections at the experimentally used temperature of 423 K.^{7a} The corresponding correction terms δE_G were estimated at the RI-BP86/ECP1 level and have been obtained as the difference of the reaction energy of a given step ($\Delta E_{\text{RI-BP86/ECP1}}$) and the corresponding free energy ($\Delta G_{\text{RI-BP86/ECP1}}$):

$$\delta E_G = \Delta G_{\text{RI-BP86/ECP1}} - \Delta E_{\text{RI-BP86/ECP1}} \quad (1)$$

The entropic contributions have been evaluated at a pressure of 1354 atm in order to model the changes in entropy for a condensed phase.²⁷ The corresponding correction terms (δE_G) for each step of the catalytic cycles are gathered in Tables 1 and 2 along with other correction terms (vide infra).

The transition states (denoted TS_{x-y}) were characterized by a single imaginary frequency and visual inspection of the corresponding vibrational mode ensured that the desired minima \mathbf{x} and \mathbf{y} were connected. The reaction pathways have been investigated more closely by following the intrinsic reaction coordinate (IRC)²⁸ starting from TS_{x-y} and leading to the intermediates \mathbf{x} and \mathbf{y} .

All potential energy profile calculations have been performed at the same RI-BP86/ECP1 level and are computed by gradually increasing the metal–ligand distance by 0.1 Å and optimizing the remaining geometric parameters using loose convergence criteria.

The initial structures of the complexes were derived from that of **1b**, which was constructed by hand from the Ru(PPh_3)₃ moiety as found in the X-ray structure of $[\text{RuCl}_2(\text{PPh}_3)_3]$.²⁹ As tris(triphenylphosphine) complexes are quite flexible, a systematic conformational search on complex **1b** has been performed by optimizing 27 conformers obtained by rotations of the 9 phenyl rings of the ligands around their P–C bonds. The outcome of this search revealed that the most stable complex corresponds to that where all triphenylphosphine ligands adopt propeller-like conformations,³⁰ more or less distorted due to interactions between the positively charged phenyl hydrogens and the negatively charged hydride ligands. The other complexes have been constructed by hand, following the reaction path: i.e., starting from the structure of the previous step and keeping the conformation of the PPh_3 ligands unaltered. Such a procedure is therefore consistent with a reaction following a least-motion pathway. Concerning Ru complexes possessing only two PPh_3 ligands in axial positions, a regular propeller conformation can be easily adopted by both ligands due to the lack of steric interaction between them. However, two conformational diastereoisomers can be obtained for these complexes by inversion of the propeller configuration of one phosphine. The latter are therefore labeled “pp” and “pm”, following the notation adopted by Davies et al. in ref 31 (see Figure S1 in the Supporting Information). The relative energies between the pp and pm conformers are shown to be quite small (see Table S1 in the Supporting Information), and the pm conformers are generally found to be more stable. We therefore only considered pm intermediates and transition states in the investigated pathways **C** and **D** (vide infra), and the pm labels are omitted for clarity.

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Table 1. Reaction Energies (ΔE), Correction Terms for BSSE (δE_{BSSE}), Solvation (δE_{Solv}), and Thermochemistry (δE_G), and Resulting Reaction Free Energies (ΔG) in kcal/mol^a

	ΔE	δE_{BSSE}	δE_{Solv}^b	δE_G	ΔG
Global					
MeOH \rightarrow H ₂ + HCHO	24.0	0.0	0.5	-12.4	12.1
Pathway A					
1b \rightarrow 2 + H ₂	16.7	-0.9	-0.1	-11.6	4.2
2 + MeO ⁻ \rightarrow 3	-51.3	5.3	42.3	14.7	11.1
2 + MeOH \rightarrow 6	-11.0	4.4	4.7	17.7	15.8
6 + MeO ⁻ \rightarrow 3 + MeOH	-40.3	0.0	37.6	-2.9	-5.6
3 \rightarrow 4	11.5	0.0	-6.1	-1.6	3.8
4 \rightarrow 5 + HCHO	15.0	-3.0	0.4	-12.1	0.3
5 + MeOH \rightarrow 1b + MeO ⁻	32.1	0.0	-36.1	-1.9	-5.8
1b \rightarrow TS_{1b-2}	15.5	0.0	0.3	-6.5	9.4
3 \rightarrow TS_{3-4}	24.1	0.0	-7.5	0.1	16.6
Pathway B					
3 + MeOH \rightarrow 3Hb + MeO ⁻	45.2	0.0	-37.7	0.1	7.6
3Hb \rightarrow 7 + H ₂	2.2	-1.0	0.0	-8.5	-7.3
7 \rightarrow 8	4.7	0.0	-1.4	-1.1	2.2
8 \rightarrow 9	-4.9	0.0	0.7	-1.5	-5.6
9 \rightarrow 10	12.6	0.0	0.8	-1.4	12.0
10 \rightarrow 2 + HCHO	15.6	-3.7	-4.2	-14.8	-7.2
3Hb \rightarrow TS_{3Hb-7}	9.4	0.0	0.1	0.0	9.5
7 \rightarrow TS_{7-8}	6.4	0.0	-1.2	0.7	5.9
8 \rightarrow TS_{8-9}	2.7	0.0	0.3	-0.7	2.3
9 \rightarrow TS_{9-10}	20.2	0.0	0.6	-0.3	20.6
2 + MeOH \rightarrow 6	-11.0	4.4	4.7	17.7	15.8
6 \rightarrow 3Hb	4.8	0.0	-0.1	-2.8	1.9
6 \rightarrow TS_{6-3Hb}	17.5	0.0	-0.3	-2.9	14.3
Pathway C					
3 \rightarrow 11 + PPh_3	48.2	-10.2	-13.6	-20.9	3.5
11 \rightarrow 12	3.4	0.0	-0.4	1.5	4.5
12 \rightarrow 13	-8.5	0.0	-1.4	1.1	-8.8
13 \rightarrow 14	27.0	0.0	-0.9	-5.5	20.6
14 \rightarrow 15 + HCHO	14.4	-3.2	-6.3	-13.1	-8.1
15 + PPh_3 \rightarrow 5	-58.0	9.2	16.8	23.3	-8.8
11 \rightarrow TS_{11-12}	4.9	0.0	0.3	-0.5	4.6
12 \rightarrow TS_{12-13}	1.8	0.0	-0.9	0.0	0.9
13 \rightarrow TS_{13-14}	28.5	0.0	-0.7	-5.1	22.7
Pathway D					
15 + MeOH \rightarrow 15H + MeO ⁻	24.2	0.0	-24.8	-1.5	-2.0
15H + MeOH \rightarrow 16Hb	-20.1	3.9	4.7	15.8	4.3
16Hb \rightarrow 17 + H ₂	18.5	-0.7	-0.3	-10.2	7.3
17 + MeO ⁻ \rightarrow 11 + MeOH	-35.0	0.0	29.9	-0.5	-5.6
16Hb \rightarrow $\text{TS}_{16Hb-17}$	16.9	0.0	0.3	-8.1	9.1

^a B97-D/ECP2 energies. $\Delta G = \Delta E + \delta E_{\text{BSSE}} + \delta E_{\text{Solv}} + \delta E_G$.
^b MeOH has been used as solvent.

Energies. Refined energies were obtained from single-point calculations (on the RI-BP86/ECP1 geometries) using the same SDD ECP on Ru²⁴ and a larger basis set (hereafter noted ECP2), namely 6-311+G(d,p), on all elements except for all the C and H phenyl atoms, where the 6-31G(d,p) basis was used. The B97-D functional²⁰ has been used in conjunction with the ECP2 basis set, as this method has been shown to lead to the most accurate binding enthalpy of PPh_3 to an analogous Ru complex.^{18,32} This functional follows the DFT-D general approach of Grimme,^{20,33} in which the functional energies are corrected by an atomic pairwise additive term accounting for the long-range noncovalent interactions. The corresponding interatomic C_6^{ij} terms are calculated as the geometric mean of the standard C_6 atomic coefficients.²⁰ We note that B97-D has also been successfully employed to study a parent Ru-catalyzed reaction.³⁴

Energies have been corrected for the basis set superposition error (BSSE) using the counterpoise method.³⁵ The BSSE energy corrections (denoted δE_{BSSE}) are gathered in Table 1. Estimates of the solvation effects were computed using the conductor-like screening model (COSMO),³⁶ with a dielectric constant $\epsilon = 32.63$ to model the experimentally used methanol solvent. Dielectric

Table 2. Refined Free Energies (in kcal/mol, at the B97-D/ECP3 Level) for Initiation Steps and Overall Activation Barriers of Pathways A–D

pathway		ΔE	$\delta E'_{\text{BSSE}}$	δE_{solv}	δE_{G}	ΔG
Initiation Free Energies ^a						
B	1b → 2 + H ₂	16.6	−0.5	−0.2	−11.6	4.3
D	1b → 15H + PPh ₃	46.3	−7.0	−5.5	−22.9	10.9
Overall Free Energy Barriers						
Methanol ^a						
A	1b + MeO [−] → TS _{3–4} + H ₂	−15.4	5.0	36.6	3.2	29.4
B	2 + MeOH → TS _{3Hb-7}	5.2	6.9	5.1	14.9	32.1
C	1b + MeO [−] → TS _{13–14} + H ₂ + PPh ₃	28.2	−5.2	28.6	−20.3	31.3
D	13 + 2 + MeOH → TS _{16Hb-17} + HCHO + MeO [−]	68.4	0.3	−29.4	−12.4	27.0
Ethanol ^b						
A	1b + EtO [−] → TS _{3–4} + H ₂	−13.6	4.3	33.0	4.3	28.0
B	2 + EtOH → TS _{3Hb-7}	3.6	6.2	5.0	14.5	29.3
C	1b + EtO [−] → TS _{13–14} + H ₂ + PPh ₃	25.6	−4.9	26.6	−18.6	28.7
D	13 + 2 + EtOH → TS _{16Hb-17} + MeCHO + EtO [−]	58.0	0.2	−28.0	−12.1	18.1
2-Propanol ^c						
A	1b + ⁱ PrO [−] → TS _{3–4} + H ₂	−11.7	3.9	31.5	3.8	27.5
B	2 + ⁱ PrOH → TS _{3Hb-7}	1.1	6.0	4.9	15.0	27.0
C	1b + ⁱ PrO [−] → TS _{13–14} + H ₂ + PPh ₃	27.5	−4.7	24.9	−18.4	29.3
D	15H + ⁱ PrO [−] → TS _{13–14} + H ₂	−18.8	2.3	30.2	4.4	18.2

^a Model solvent MeOH. ^b Model solvent EtOH. ^c Model solvent ⁱPrOH.

constants of 24.55 and 20.18 have been used to model ethanol and 2-propanol, respectively (see Table 2 and the Discussion). Unless otherwise indicated, methanol was used as the solvent. We defined the δE_{solv} energy correction as the difference between the reaction energy in the continuum (ΔE_{COSMO}) and that in the gas phase (ΔE), at the B97-D/ECP2 level:

$$\delta E_{\text{solv}} = \Delta E_{\text{COSMO}} - \Delta E \quad (2)$$

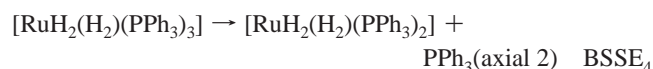
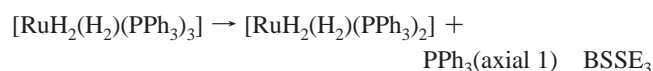
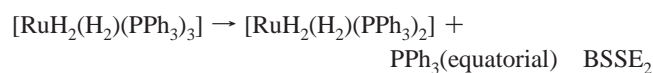
Both counterpoise and COSMO corrections were calculated by performing single-point calculations at the B97-D/ECP2 level on the BP86/ECP1 geometries. The final ΔG values are calculated as a sum of all energy correction terms, added to the raw B97-D/ECP2 gas-phase reaction energies (ΔE):

$$\Delta G = \Delta E + \delta E_{\text{solv}} + \delta E_{\text{BSSE}} + \delta E_{\text{G}} \quad (3)$$

where ΔE , δE_{solv} and δE_{BSSE} are computed at the B97-D/ECP2 level and δE_{G} is computed at the RI-BP86/ECP1 level (vide supra).

In order to compare the kinetics of the four investigated pathways in a consistent manner, it is necessary to overcome the ambiguity stemming from the BSSE counterpoise correction when more than

one ligand is coordinated/decoordinated during a given reaction. For that purpose, the initiation energies and activation barriers have been recomputed using a more elaborated BSSE correction and using a larger basis set (hereafter noted ECP3), where all P, O, C, and H atoms are described by the 6-311+G(d,p) basis set (and the same SDD ECP on Ru). In this approach, the intermolecular BSSE for a given reaction (e.g., $\text{RuL}_n\text{L}' \rightarrow \text{RuL}_n + \text{L}'$) is estimated as a difference of the intramolecular BSSEs of the intermediates and transition states involved (i.e., $\text{RuL}_n\text{L}'$ and RuL_n). The intramolecular BSSE (noted $E_{\text{intra-BSSE}}$) of a given complex is estimated as the sum of counterpoise corrections associated to the dissociation of each ligand separately. The counterpoise corrections associated with hydride ligand dissociation is postulated to be 0. For instance, for complex **1b**



and $E_{\text{intra-BSSE}}(\mathbf{1b}) = \text{BSSE}_1 + \text{BSSE}_2 + \text{BSSE}_3 + \text{BSSE}_4$.

The corresponding intermolecular correction term ($\delta E'_{\text{bsse}}$) e.g. for the reaction **1b** → **2** + H₂ is therefore obtained as $\delta E'_{\text{bsse}} = E_{\text{intra-BSSE}}(\mathbf{2}) - E_{\text{intra-BSSE}}(\mathbf{1b})$, where $E_{\text{intra-BSSE}}(\mathbf{2})$ is computed in a similar manner considering complex **2**.

The gas-phase energies (ΔE^{ECP3}) and the corresponding solvation ($\delta E_{\text{solv}}^{\text{ECP3}}$) and BSSE ($\delta E'_{\text{BSSE}}^{\text{ECP3}}$) correction terms are gathered in Table 2, whereas the values of the BSSE_n and $E_{\text{intra-BSSE}}$ terms are gathered in Table S3 in the Supporting Information.

All the RI-BP86/ECP1 calculations were performed using the Gaussian03 program,³⁷ whereas the B97-D/ECP2 and B97-D/ECP3 calculations were performed with the Turbomole package (version

- (32) (a) Following the comment of a reviewer, we tested the influence of the density functional on the initiation and activation energies of pathways A–D with the BP86, B3LYP, BP86-D, B3LYP-D, and M06-L functionals (see Table S2). We found that B97-D and M06-L give similar activation barriers (within ± 2.6 kcal/mol on the average), whereas the traditional BP86 and B3LYP functionals lead to inconsistent results due to a lack of description of noncovalent interactions. BP86-D and B3LYP-D indeed give more consistent results; however, our previous study¹⁸ revealed that B97-D is the best suited functional to model the key PPh₃ dissociation step. More problematic is the case of H₂ dissociation, where B97-D leads to a lower dissociation energy compared to M06-L. Comparison with the experimental enthalpy of activation for this process reported by Halpern et al.^{32b} shows that, for this particular step, M06-L would be more suited, since the B97-D value is underestimated by ca. 5.2 kcal/mol ($\Delta H^{\text{exp}} \approx 17.9$ kcal/mol; $\Delta H^{\text{calc}} = 12.7$ kcal/mol; computed by applying the enthalpy correction term $\delta E_{\text{H}} = -2.8$ kcal/mol). The good agreement between B97-D and M06-L in overall rate-limiting steps shows that this discrepancy is not systematic to B97-D and therefore comforts us in the choice of this functional to model this system. (b) Halpern, J.; Cai, L.; Desrosiers, P. J.; Lin, Z. *J. Chem. Soc., Dalton Trans.* **1991**, 717.
- (33) Grimme, S. *J. Comput. Chem.* **2004**, 25, 1463.
- (34) Piacenza, M.; Hyla-Kryspin, I.; Grimme, S. *J. Comput. Chem.* **2007**, 28, 2275.
- (35) Boys, S. F.; Bernardi, F. *Mol. Phys.* **1970**, 19, 553.

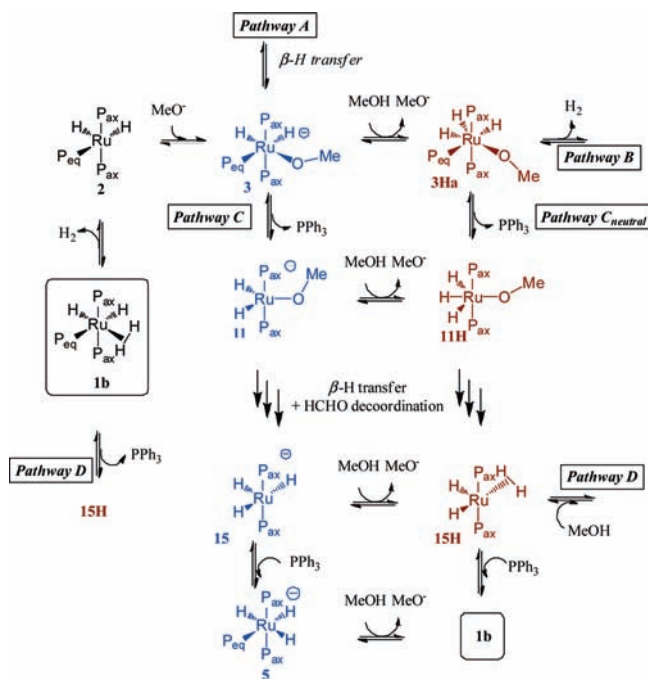


Figure 1. Overview of the investigated mechanisms A–D. P_{eq} and P_{ax} stand for equatorial and axial PPh_3 ligands, respectively.

5–10).³⁸ Structures of the complexes have been drawn with the VMD software.³⁹

Results

In this section we describe the four investigated pathways (labeled A–D). For each pathway, the description of the reaction free energy profiles is followed by a description of the relevant structural features of involved intermediates and transition states. Unless otherwise specified, all energy values stand for the Gibbs free energies of individual reactions (ΔG) computed at the ECP2 level of theory. The higher ECP3 level has been used to recompute selected steps only: namely, the initiation steps and the rate-limiting steps. All energy components are gathered in Table 1 (ECP2 level) and Table 2 (ECP3 level). A general schematic view of A–D is given in Figure 1, whereas individual full descriptions of each pathway are given separately, along with the corresponding free energy profiles (see Figures 2, 4, 6, and 8). Relevant structural information is provided in Figures 3, 5, 7, and 9, and characteristics of the initiation and rate-

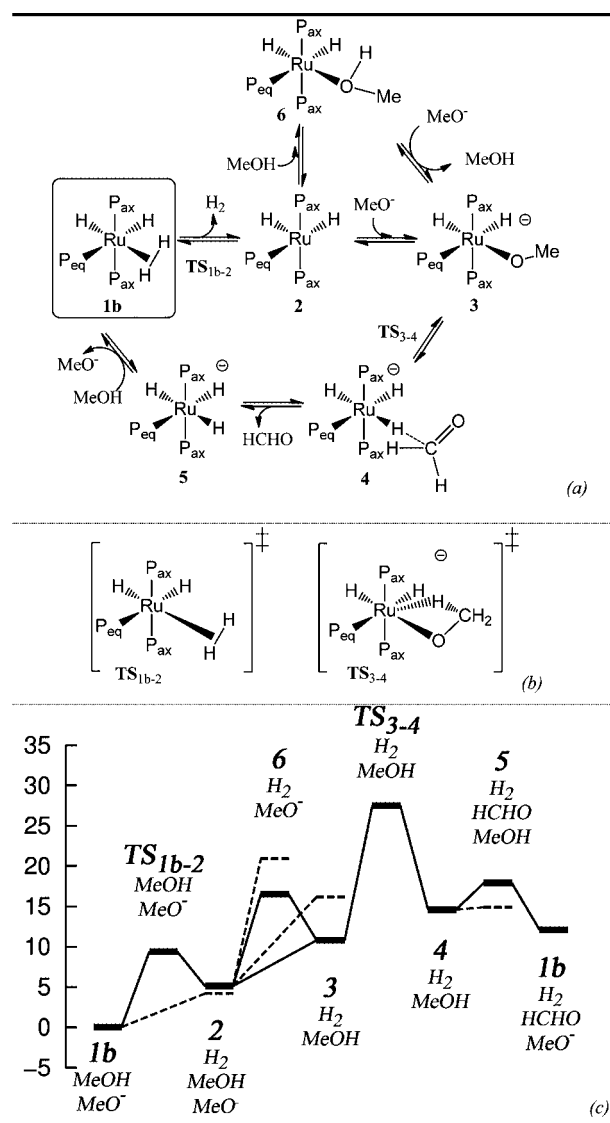


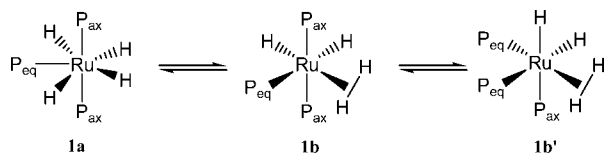
Figure 2. Reaction pathway A: (a) catalytic cycle; (b) schematic representation of the transition states; (c) free energy profile (kcal/mol), with calculations carried at the B97-D/ECP2 level of theory using MeOH as model solvent. The dashed lines indicate BSSE corrected energies. Reaction energies are given in Table 1.

limiting steps are summarized in Table 2 and Table S4 (Supporting Information).

1. Pathway A: β -Hydride Transfer Occurring via a Seven-Coordinated Transition State. (a). **Description of Reaction Pathway A.** We first consider the mechanism originally proposed by Morton and Cole-Hamilton,^{7a} where the catalyst precursor $[RuH_2(PPh_3)_3X]$ ($X = N_2, PPh_3$) affords the active catalyst **2** by decooordination of its X moiety (Figure 2). As the dehydrogenation reaction occurs under basic conditions, **2** can further coordinate either MeO^- (to afford **3**) or a solvent molecule (to afford **6**). Despite significantly attractive energies in the gas phase, both addition reactions are found to be unfavorable thermodynamically (by 11.1 and 15.8 kcal/mol for **3** and **6**, respectively) due to solvation effects (mainly stemming from the desolvation of the substrate) and entropic penalties. No transition state could be located for these two addition steps.⁴⁰ The intermediate **6** can be further deprotonated to afford **3**. The next step consists of the transfer of one β -hydrogen of the coordinated substrate to the metal, to afford intermediate **4**,

- (36) (a) Klamt, A.; Schüürmann, G. *J. Chem. Soc., Perkin Trans. 2* **1993**, 5, 799. The choice of this solvent model has been motivated by a recent study: (b) Takano, Y.; Houk, K. N. *J. Chem. Theor. Comput.* **2005**, *1*, 70–77. This study showed that COSMO-based models give satisfactory hydration free energies of small anions and neutral molecules. Following the comment of a reviewer, we validated our approach by the computation of the protonation reaction of **5'** by cyclohexanol in THF (to afford **1b**), for which an equilibrium constant has been measured.^{11d} We found a ΔG value of 4.7 kcal/mol (ΔE , δE_{BSSE} , δE_{Solv} , and δE_G contributions are 30.1, 0.0, –22.2, and –3.3 kcal/mol, respectively, at $T = 298.15$, $P = 1354$ atm, and $\epsilon = 7.4257$). This result is therefore in accord with the experiment ($K_{eq} = 0.13$, which corresponds to $\Delta G_{exp} \approx 1.7$ kcal/mol).
- (37) Pople, J. A. Gaussian 03, Revision E.01; Gaussian, Inc., Pittsburgh, PA, 2003. The full reference is given in the Supporting Information.
- (38) (a) Ahlrichs, R.; Baer, M.; Haeser, M.; Horn, H.; Koelmel, C. *Chem. Phys. Lett.* **1989**, *162*, 165. (b) Treutler, O.; Ahlrichs, R. *J. Chem. Phys.* **1995**, *102*, 346. (c) Arnim, M. v.; Ahlrichs, R. *J. Comput. Chem.* **1998**, *19*, 1746.
- (39) Humphrey, W.; Dalke, A.; Schulten, K. *J. Mol. Graphics* **1996**, *14*, 33.

Scheme 2. Labeling of the Different Isomers, using Complex 1 as Example



where the HCHO product is “hydrogen-bonded” to the $[\text{RuH}_3(\text{PPh}_3)_3]^-$ complex **5**.⁴¹ We note that this step is particularly difficult, since it is an uphill process (3.8 kcal/mol) and a significant energy barrier has to be overcome (16.6 kcal/mol). The subsequent release of the aldehyde product is favored by entropy and is easily achieved (+0.3 kcal/mol). As reported by Halpern et al.^{11c,d} and Cole-Hamilton et al.,^{7a} **5** is easily protonated (by -5.8 kcal/mol) to afford complex **1**.

This complex can exist in two tautomeric forms, the classical tetrahydride **1a** and the nonclassical dihydride **1b** with η^2 -coordinated molecular hydrogen (see Scheme 2). Both have been suggested to coexist in a dynamic equilibrium in solution.^{11b} Our calculations show that **1b** is slightly more stable than **1a** (by 3.8 kcal/mol), consistent with these observations. We also note that complex **5** (resulting from the hydrogen transfer in **3**) is formed as the *mer* isomer, whereas a *fac* isomer **5'** is found in the solid state⁴² and by ^1H NMR in THF (with K^+ counterions).^{11a} Our calculations show that **5'** is more stable than pristine **5** by 6.9 kcal/mol and are therefore consistent with experiment. We also investigated the *fac* isomers of **1b**, **3**, and **TS**₃₋₄ (labeled **1b'**, **3'**, and **TS**₃₋₄, respectively), and we found that the *mer* forms are more stable for these two complexes (by 5.4, 2.7, and 17.9 kcal/mol, respectively), whereas no *fac* isomer could be located for **2**. Thus, the steps on pathway **A** preceding the rate-limiting one only involve *mer* isomers, as shown in Figure 2.

The release of the H_2 product from **1b** is unfavorable, for both thermodynamic and kinetic reasons, since this process is 4.2 kcal/mol uphill with a 9.4 kcal/mol free energy barrier. Such a one-step reaction with a small activation barrier is consistent with the qualitative results of Linn and Halpern,^{11d} who investigated the dissociation of H_2 from **1b** by exchange with D_2 . They found that this process is fast and complete (at 85 °C) and that it does not involve PPh_3 dissociation. We find that **1b** is the resting state of the system, as characterized by ^1H and ^{31}P NMR under noncatalytic conditions.^{11b,d} On this path, the rate-limiting step is found to be the hydrogen transfer (**3** \rightarrow **5**), and not the H_2 dissociation (**1b** \rightarrow **2**) as initially suggested by

(40) No transition states could be located for the dissociation of the MeOH, HCHO, MeO^- , and PPh_3 ligands from tris(triphenylphosphine) complexes, presumably due to the shallow form of the underlying energy surface. On the basis of the experimental measurements of Sponsler et al. (Seetharaman, S. K.; Chung, M.-C.; English, U.; Ruhlandt-Senge, K.; Sponsler, M. B. *Inorg. Chem.* **2007**, *46*, 561) and on our computed energy profiles of dissociation of the ligands (in which small maxima are found at long metal-ligand distances; see Figure S7), we assume that the dissociation processes involve only late transition states with small extra activation barriers. The latter would be easily overcome under the reaction conditions and, because these steps are found between low-lying intermediates in the reaction profile, would affect neither the nature of the rate-limiting steps nor the overall activation barriers.

(41) Note that **4** is found as a result of the IRC calculations from **TS**₃₋₄ and effectively corresponds to a stationary point on the potential energy surface. However, this complex is not found on the BSSE corrected free energy surface and is therefore expected to be rather unstable.

(42) Chan, A. S. C.; Shieh, H.-S. *J. Chem. Soc., Chem. Commun.* **1985**, 1379.

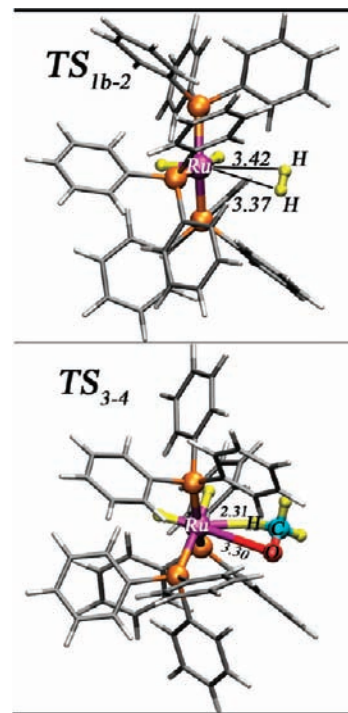


Figure 3. Transition states **TS**_{1b-2} and **TS**₃₋₄ involved in pathway **A** with selected interatomic distances (in Å).

Morton and Cole-Hamilton.^{7a} Computations at the higher ECP3 level show that the overall activation energy for this pathway is 29.4 kcal/mol (see Table 2). This barrier is significant but should be surmountable at the elevated temperatures of the experiments.⁴³

(b). Structural Features. Transition states **TS**_{1b-2} and **TS**₃₋₄ are depicted in Figure 3. In **TS**_{1b-2}, H_2 is fully decoordinated from the metal (the corresponding average $\text{Ru}-\text{H}_{\text{H}_2}$ distance being ca. 3.40 Å whereas the latter is ca. 1.75 Å in **1b**). As shown by the superimposed views of the structures of **1b** and **TS**_{1b-2} (see Figure S2; left picture), the conformation of the ligands are very similar in these two complexes. This feature is in contrast with the structure of **2**, where an important reorganization of the ligands is observed, mainly via rotations of the phenyl rings around the P–C bonds (see Figure S2; right picture). Interestingly, the deformation energies in **1b** and **TS**_{1b-2}, relative to that of **2**, are found to be 4.1 and 1.3 kcal/mol, respectively,⁴⁴ which is consistent with a gradual relaxation of the ligands as the H_2 dissociation occurs. This feature therefore suggests that the presence of a barrier for this step is due to the presence of the bulky PPh_3 ligands. This finding is confirmed by repeating the transition state search using PH_3 and PMe_3 instead of PPh_3 as ligands, where no transition states can be found for the H_2 elimination from both **1b/PH**₃ and **1b/PMe**₃ analogues.

(43) Using the simple Eyring equation, at 423 K such a barrier would correspond to a unimolecular rate constant on the order of 10^{-2} s^{-1} and, thus, to a half-life of a few minutes.

(44) These values are obtained by performing single points on the structures of **1b** and **TS**_{1b-2} in which the H_2 moieties have been removed by hand. The resulting energies are then compared to the optimized energy of **2**. The same procedure has been applied to compute the deformation energies involved in the H_2 decoordination in the other pathways, i.e. in **3Hb** and **TS**_{3Hb-7}, relative to **7** for pathway **B**, and in **16Hb** and **TS**_{16Hb-17} relative to **17** for pathway **D**. These values are computed in the gas phase at the B97-D/ECP2 level (ΔE).

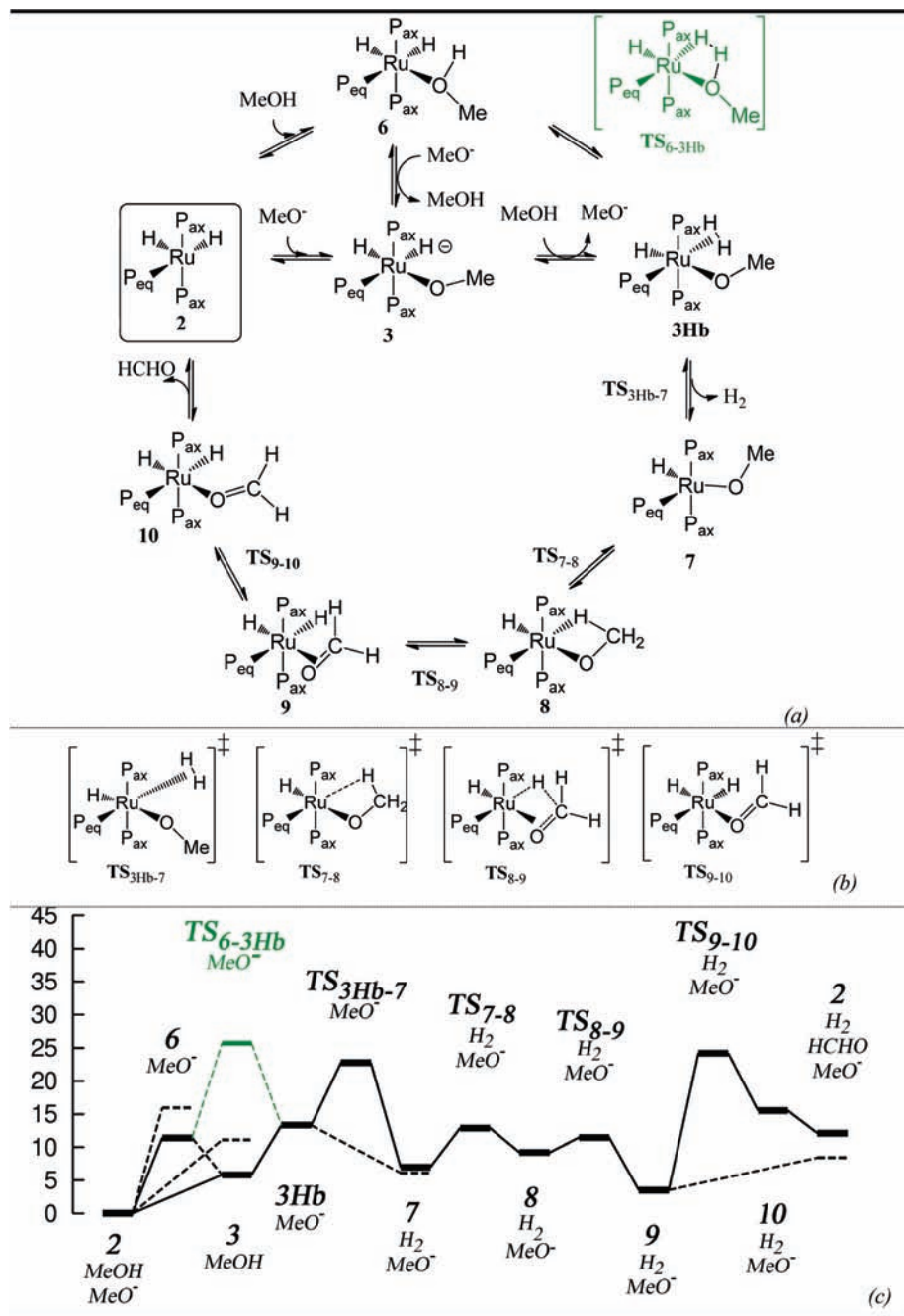


Figure 4. Reaction pathway B. See Figure 2 for a definition of labels (a), (b), and (c).

In TS₃₋₄, the Ru–O and the Ru–H distances are significantly elongated compared to those observed in the linking intermediates 3 and 4 (the Ru–O distances are 3.30 and 2.25 Å in TS₃₋₄ and in 3, respectively, and the Ru–H_{Me} distances are 2.31 and 1.83 Å in TS₃₋₄ and 4, respectively). Moreover, both O and H atoms are bent out of the equatorial plane, which is typical for such highly coordinated complexes. These structural characteristics are consistent with the corresponding high energy barrier, the β -hydride transfer being hindered by the lack of room in the equatorial plane. A concerted Ru–O bond breaking along with the formation of the Ru–H bond occurs at a single coordination site, therefore requiring a partial decoordination of MeO⁻ in TS₃₋₄ and the formation of a highly strained four-membered ring. All these features are particularly demanding energetically.

2. Pathway B: H₂ Elimination as a Prerequisite to the β -H Transfer. (a). **Description of Reaction Pathway B.** Searching for more favorable pathways, we first explored the possibility that a H₂ elimination occurs before the β -H transfer step. This leads to the competitive pathway B, derived from pathway A (see Figure 1), where 3 is protonated to afford 3H, from which an H₂ elimination can occur (see Figure 4). As for complex 1, the resulting 3H complex can exist as a heptacoordinated classical hydride isomer (3Ha) or as a hexacoordinated η^2 -H₂ isomer (3Hb). We found that 3Ha is more stable than 3Hb by 4.1 kcal/mol; however, the latter is more likely to further undergo a H₂ decoordination to afford 7, therefore following a least-motion pathway. The release of H₂ is thermodynamically favorable (–7.3 kcal/mol), but a 9.5 kcal/mol barrier has to be overcome. The resulting complex 7 possesses a vacant site,

where the subsequent β -H transfer can take place. The latter is achieved in two steps: (i) first, an agostic interaction is formed between the metal and one of the three methoxy hydrogens (intermediate **8**; +2.2 kcal/mol) and subsequently (ii) the latter hydrogen fully coordinates to Ru to form **9**, where the aldehyde product is π -coordinated to the metal (−5.6 kcal/mol). Both steps possess small activation barriers of 5.9 and 2.3 kcal/mol, respectively, therefore indicating that the hydrogen transfer is indeed significantly more facile than in pathway **A**. The HCHO product is only weakly bonded to Ru ($\Delta G_{9 \rightarrow 2} = 4.8$ kcal/mol), but its decoordination is found to be very demanding kinetically. A potential energy surface scan along the Ru–C_{HCHO} distance revealed that this process occurs in two steps, as the aldehyde is found to move from a η^2 to a η^1 coordination mode before full decoordination can occur. The first step (**9** → **10**) involves a high free energy barrier ($\Delta G^\ddagger = 20.6$ kcal/mol), whereas no transition states could be located for the subsequent full dissociation of the product (**10** → **2** + HCHO).⁴⁰ We note that the **TS**_{9–10} and **TS**_{3Hb–7} transition states are both very high in energy on the reaction profile and are almost isoenergetic. Computations at the higher B97-D/ECP3 level allowed us to identify the highest step and revealed that H₂ dissociation is rate-limiting, with a corresponding barrier of 32.1 kcal/mol (see Table 2). Because H₂ elimination occurs at a different stage compared to path **A**, complex **1b** is bypassed in path **B**, where **2** would be the resting state. This pathway therefore requires an initiation step, consisting of the decoordination of H₂ from **1b** to afford **2** ($\Delta G = 4.3$ kcal/mol, see Table 2).

We note that, in this pathway, the base is only required for the **2** → **3Hb** step and is not involved in any other steps. Interestingly, **3Hb** can alternatively be formed directly by intramolecular proton transfer from **6** ($\Delta G_{6 \rightarrow 3Hb} = 1.9$ kcal/mol). However, a significant activation barrier of 14.3 kcal/mol is associated with this process (see green line in Figure 4).

(b). Structural Features. A detailed analysis of the structures of the complexes involved in this pathway reveals some interesting features (Figure 5). As observed in pathway **A**, the PPh₃ ligands play an important role in the H₂ dissociation step, which is the rate-limiting step of this pathway. It is noteworthy that the deformation energies in **3Hb** and **TS**_{3Hb–7} are significantly higher here (18.8 and 7.8 kcal/mol, respectively)⁴⁴ and almost fully balance the loss of the H₂ binding energy. Superimposed structures of **3Hb** and **7** effectively reveal some reorganization of the PPh₃ ligands, via rotation of the phenyl rings, as observed above (see Figure S2). This can also be seen in the potential energy profile for the dissociation of H₂, where a quick drop in energy is observed when the Ru–H_{H2} distance reaches ca. 3 Å (see Figure S3). Looking at the structures of the involved complexes shows that, in **3Hb** and **TS**_{3Hb–7}, one PPh₃ ligand is somewhat distorted with one phenyl ring almost parallel to the equatorial plane. This is in contrast with **7**, in which all PPh₃ ligands adopt a regular propeller conformation. We note that repeating this calculation with PH₃ as ligand leads to a nonactivated process (see Figure S3). However, the rearrangement of the PPh₃ ligands is not the only origin of the important deformation energy involved in this process, since an important reorganization of the Ru coordination sphere itself is also observed: in **3Hb**, the Ru center possesses a quasi-octahedral environment, where the $\langle P_{eq}-Ru-O \rangle$ angle is 83.6° (see Figure S3) and where the O_{methoxy} and C_{methoxy} atoms are in the equatorial plane ($\langle P_{eq}-Ru-O-C \rangle = 163.2^\circ$). As the decoordination of H₂ occurs, the $\langle P_{eq}-Ru-O \rangle$ angle tends to increase, indicating that the Ru center moves toward a trigonal-

bipyramidal environment. Following the value of this angle along the IRC reveals that the latter is ca. 100° in **TS**_{3Hb–7}, 115° in **7**•••H₂ (i.e., a complex where H₂ is all but decoordinated) and ca. 132° in **7** (where H₂ is removed completely). At the same time, the methoxy ligand rotates from a fully equatorial orientation toward a perpendicular orientation ($\langle P_{eq}-Ru-O-C \rangle = 163^\circ$ in **3Hb** and 84° in **7**; see Figure S3). Interestingly, no stationary point could be located for a conformer of **3Hb** in which the methoxy ligand would be perpendicular to the equatorial plane, certainly due to steric repulsions with the bulky PPh₃ ligands within the complex.

The PPh₃ ligands also play an important role in the β -H transfer step. In **7**, the three hydrogens of the perpendicular methoxy ligand point away from the metal center (the closest hydrogen is found at 3.27 Å from Ru), and the vacant coordination site is somewhat “shielded” by the phenyl rings of the two axial phosphine ligands (Figure 5). Interestingly, the phenyl hydrogens do not form any agostic interactions with the metal but interact with the negatively charged H_{hydrid} and O_{methoxy} atoms. A conformational reorganization of the ligands is therefore mandatory in order to afford **8**, a feature which should increase the height of the corresponding activation barrier. In **TS**_{7–8}, one phenyl ring is indeed rotated in order to allow the approach of the methoxy hydrogen, which is found at 2.64 Å from Ru. The intermediate **8** is rather high in energy due to the formation of a strained four-membered ring (Ru–O–C–H), where the Ru–O–C, O–C–H, and Ru–H–C angles are respectively 79, 116, and 100° and the Ru–H distance is 1.83 Å. The transfer of H to the metal is achieved via transition state **TS**_{8–9}, which is similar to **8** but with an elongated C–H distance (1.47 Å) and a shorter Ru–H distance (1.70 Å). In **9**, the transferred hydrogen is fully coordinated to the metal (1.59 Å) and the C=O bond of the aldehyde product is strictly positioned in the equatorial plane. As observed for MeO[−] complexes, electrostatic interactions are formed between the oxygen atom and the phenyl hydrogens of the phosphine ligands, a feature which should slightly stabilize the bonding of the product. In **9**, HCHO is π -coordinated to Ru and the corresponding Ru–C and Ru–O distances are 2.17 Å and 2.23 Å, respectively. We note that the C=O distance is significantly longer (1.32 Å) in **9** than in the free formaldehyde molecule (1.22 Å), which suggests significant back-bonding interaction with the metal. As the decoordination occurs, the Ru–C distance gradually increases (2.91 Å in **TS**_{9–10} and 3.12 Å in **10**) and the HCHO moiety rotates from a “side-on” orientation in **9** to an equatorial “end-on” orientation in **10**, where one H_{HCHO} atom points toward an hydride ligand of the complex. We note that in **TS**_{9–10} and **10**, the C=O distance (ca. 1.25 Å) is close to the one of the free HCHO molecule, consistent with loss of metal–ligand back-bonding. After the full dissociation of the aldehyde, the resulting complex **2** retains its pseudo-octahedral geometry, the vacant site being shielded by PPh₃ phenyl rings.

3. Pathway C: Decoordination/Recoordination of One Phosphine Ligand. **(a). Description of Reaction Pathway C.** Keeping in mind that the presence of a vacant site can significantly facilitate the H-transfer step (see pathway **B**), one can imagine another possibility to form such a 16-electron complex by considering the decoordination of one phosphine ligand from **3** to afford **11** (Figure 6). Our calculations reveal that the PPh₃ ligands are indeed weakly bonded to the metal (by 2.8 kcal/mol for an axial phosphine and by 3.5 kcal/mol for the equatorial species), and therefore a non-negligible concentration of **11** should be present in the catalytic system.⁴⁰ As in pathway **B**, the subsequent

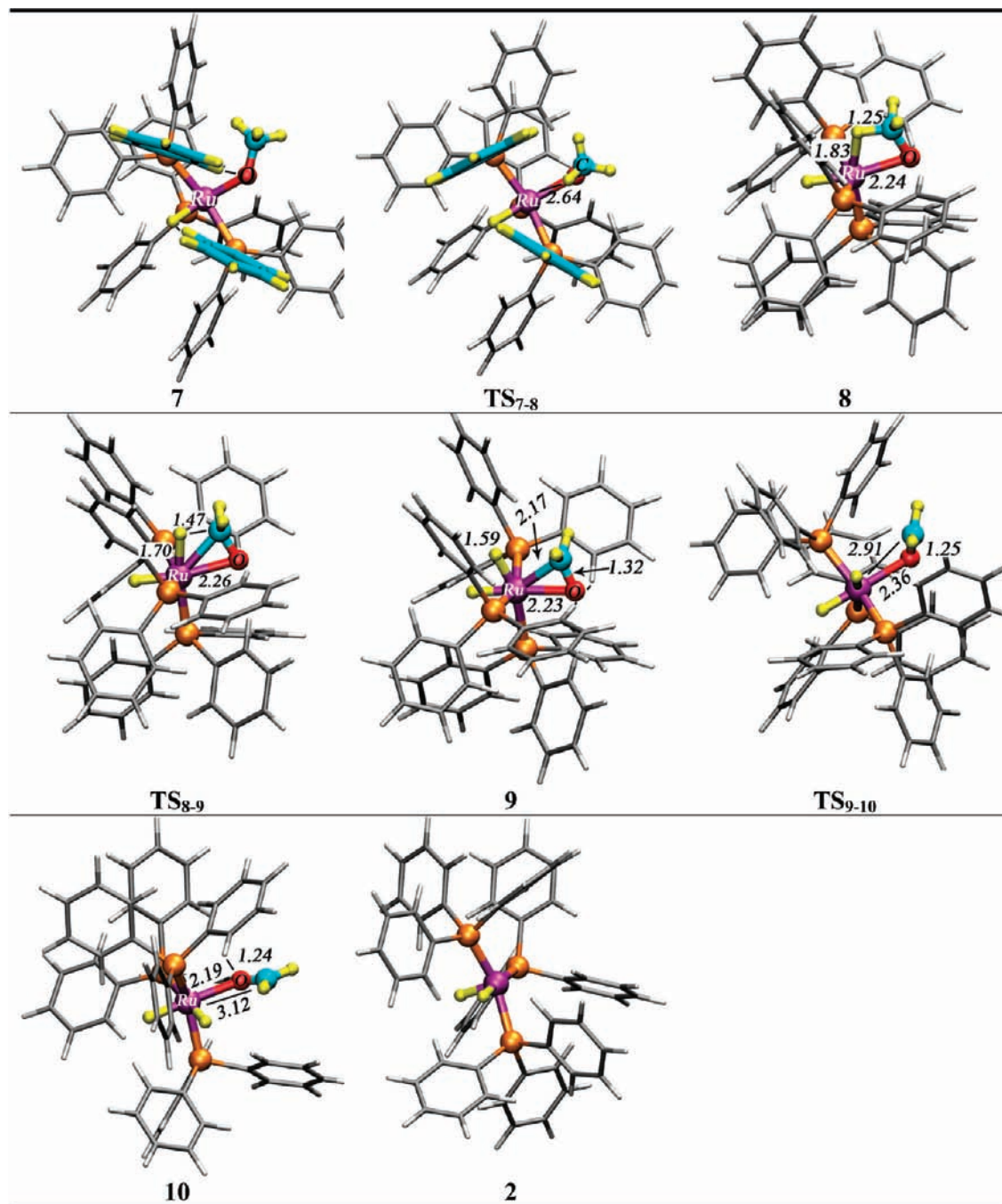


Figure 5. Structures of the intermediates and transition states involved during the proton transfer ($7 \rightarrow 9$) and the HCHO product decooordination ($9 \rightarrow 2$) occurring in pathway **B**. Selected interatomic distances are given in Å.

H-transfer is achieved in two steps: first, an agostic interaction is formed between one MeO[−] hydrogen and the metal (intermediate **12**; $\Delta G = 4.5$ kcal/mol and $\Delta G^\ddagger = 4.6$ kcal/mol), followed by the breaking of the C–H bond and the full coordination of the hydrogen to the metal (intermediate **13**; $\Delta G = -8.8$ kcal/mol and $\Delta G^\ddagger = 0.9$ kcal/mol), the HCHO product being π -coordinated to Ru. The resulting complex **13** is quite low in energy and the subsequent decooordination of the aldehyde ligand is very demanding kinetically and thermodynamically ($\Delta G_{13-15} = 12.5$ kcal/mol and $\Delta G_{13-TS13-14} = 22.7$ kcal/mol). As observed in pathway **B**, the decooordination of the product occurs via an intermediate where HCHO is η^1 -coordinated (**14**), and the latter is 20.6 kcal/mol higher in free energy than **13**. The last steps of the mechanism are downhill processes and

consist of the recoordination of the PPh₃ ligand to **15** (-8.8 kcal/mol) to afford **5**, which is further protonated to regenerate the active species **1b** ($\Delta G = -5.8$ kcal/mol).

The rate-limiting step is clearly the decooordination of HCHO and more specifically the η^2 – η^1 slippage involved in this process. The overall activation energy obtained at the higher ECP3 level is found to be 31.3 kcal/mol (see Table 2), therefore in the same order of magnitude as the two previously described pathways.

(b). Structural Features. Interestingly, the lowest minimum obtained for **11** exhibits a trigonal-bipyramidal geometry, where the terminal methyl group points away from the metal center, forming a 90° H_{hydrid}–Ru–O–C dihedral angle (i.e., Ru, P₁, P₂, O_{methoxy} and C_{methoxy} are in the same plane). The closest H_{CH3}

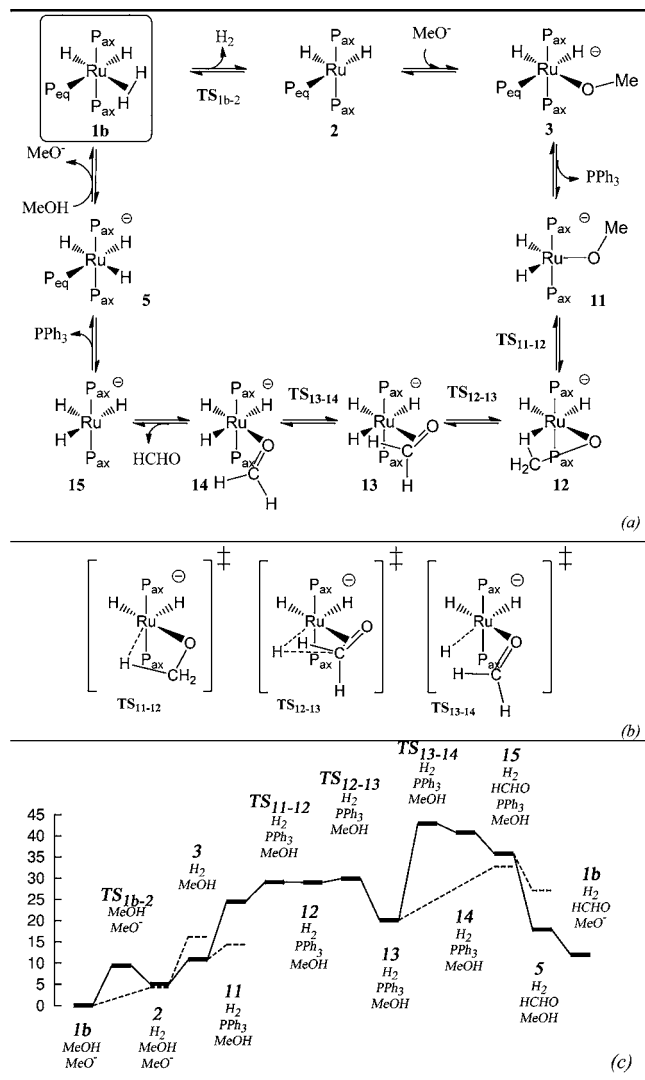


Figure 6. Reaction pathway C. See Figure 2 for a definition of labels (a), (b), (c).

atom is at a 3.31 Å distance from Ru (Figure 7). The proton transfer step therefore first requires the rotation of the methoxy ligand. A scan along the P–Ru–O–C dihedral angle reveals that such rotation is not activated and that the potential energy of the complex gradually increases as the ligand approaches a full equatorial orientation. In the transition state **TS₁₁₋₁₂**, corresponding to the transfer of one H proton to the metal, the H and O atoms of the methoxy ligand are in the equatorial plane and form a four-membered ring. In this complex, the Ru–H distance is significantly shorter than in **11** (3.01 vs 3.31 Å), and the Ru–O distance is elongated (2.22 vs 2.09 Å). In intermediate **12**, the H_{CH₃} atom forms an agostic interaction with the metal ($d_{\text{Ru-H}} = 1.91$ Å) and the corresponding C–H distance is slightly elongated by 0.10 Å. In **TS₁₂₋₁₃**, the Ru–H distance is shorter (1.72 Å) and the C–H distance is longer (1.48 Å), which is consistent with a transfer of the hydrogen atom from the carbon to the ruthenium. In **13**, HCHO is π -coordinated to Ru and exhibits an elongated C=O distance (1.34 Å). The structures involved during the dissociation of the aldehyde product are very similar to the ones obtained in pathway B. As the dissociation occurs, the Ru–C distance gradually increases from 2.22 (in **13**) to 3.10 Å (in **14**), and the HCHO moiety moves from a side-on orientation to a parallel end-on orientation

relative to the equatorial plane. As above, the C=O distances in **TS₁₃₋₁₄** and **14** are identical with that found in the free HCHO molecule, a feature revealing the diminished back-bonding interaction with the metal. We note that when the product is fully dissociated, the resulting trihydride complex **15** possesses a tetragonal bipyramid coordination sphere with a vacant site and does not rearrange to a trigonal bipyramid as observed in **7** and **11**.

Alternative Mechanisms Based on C. We note that the protonation reaction (i.e., **5** + MeOH \rightarrow **1b** + MeO[−]) can occur at any step on the pathway between complexes **11**–**15**, affording the protonated analogues **11H**–**15H** (see the two parallel pathways C in Figure 1). We therefore characterized another variant of pathway C, denoted pathway **C_{neutral}**, where the protonation occurs at the very first step and which therefore involves neutral intermediates during the proton-transfer process (instead of occurring at the last step; see Figure S4). The results show that the **11H**–**15H** intermediates are higher in energy than their anionic analogues (see Table S5), and that the overall activation barrier is slightly higher (see Table S4).

Another variant of pathway C has been investigated, where an axial PPh₃ ligand is dissociated from **3**, a feature which therefore leads to intermediates possessing two phosphine ligands in cis position (noted pathway **C_{cisP}**; see Figure S5). The full characterization of this pathway reveals that the latter has very similar initiation and activation free energies (see Table S4). The neutral variant of this pathway has not been fully characterized (noted **C_{cisP/neutral}**), since the energy of the *cisP*-**TS_{13H-14H}** transition state is found to be significantly higher (by 7.9 kcal/mol) than its trans phosphine analogue (see the relative energies in Table S1 and compare **C_{cisP/neutral}** and **C_{neutral}** pathways in Table S4).

4. Pathway D: Phosphine Dissociation as an Initiation Step.

(a). Description of Reaction Pathway D. Intermediate **15** possesses a vacant site and could alternatively react with a solvent molecule instead of undergoing a recoordination of a phosphine ligand as described in pathway C. We explored this possibility and found that the coordination of one methanol molecule is easily achieved if **15** is protonated first (to afford **15H**; $\Delta G_{15-15H} = -2.0$ kcal/mol and $\Delta G_{15H-16Hb} = 4.3$ kcal/mol),⁴⁵ whereas the direct MeOH coordination to **15** (to afford **16**) is more demanding thermodynamically ($\Delta G_{15-16} = +11.3$ kcal/mol; see Figure S6 and Table S6). The resulting complex **16Hb** therefore possesses both H₂ and MeOH ligands. The next steps consist of the decooordination of H₂ to afford **17** (+7.3 kcal/mol), followed by a deprotonation of the methanol ligand (−5.6 kcal/mol), therefore generating the previously considered intermediate **11** (Figure 8). The following steps are identical with those described for pathway C, i.e. the β -hydride transfer from **11** and the decooordination of the HCHO product lead to **15** and close the catalytic cycle.

The reaction profile indicates that intermediate **13** is the resting state of this pathway and that the rate-limiting steps are the aldehyde decooordination (occurring via **TS₁₃₋₁₄**) and the H₂ elimination (**TS_{16Hb-17}**). Computations at the ECP3 level show, however, that the latter is slightly higher in energy than the former, resulting to an overall activation free energy of 27.0 kcal/mol for this pathway (see Table 2). We also note that this mechanism also requires an initiation step, consisting of the

(45) The MeOH coordination is thermodynamically unfavorable by 2.3 kcal/mol; however, given the large excess of MeOH (solvent) compared to PPh₃, **16Hb** is expected to be accessible under reaction conditions.

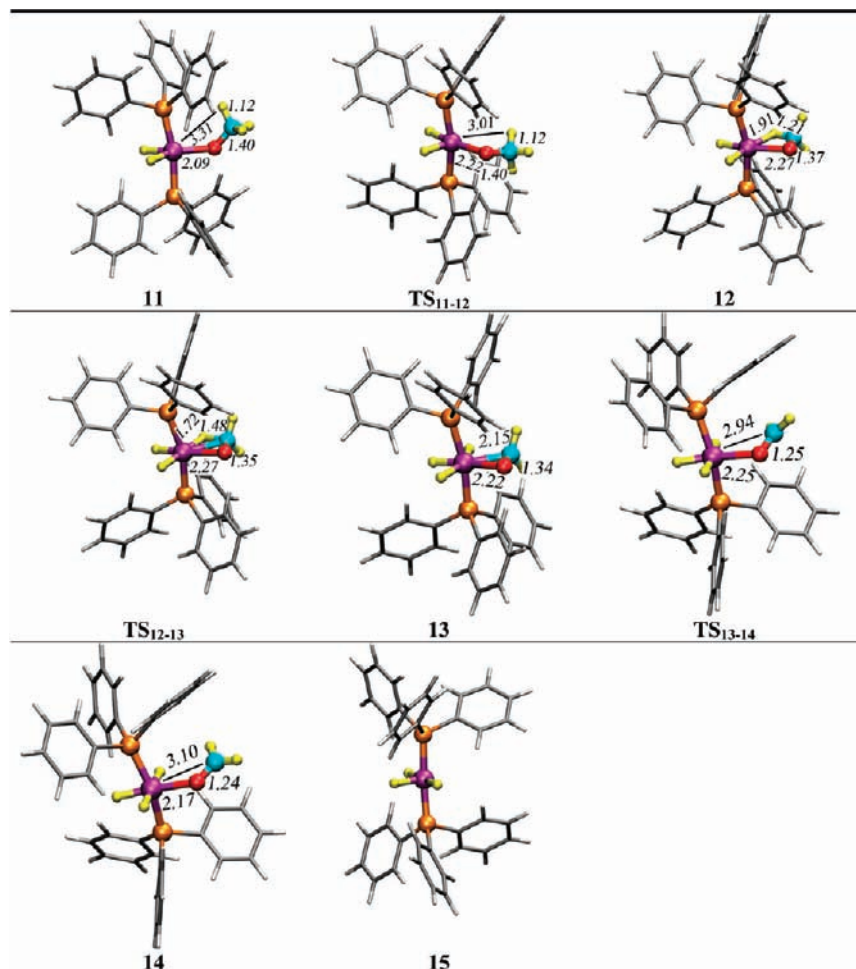


Figure 7. Structures of the intermediates and transition states involved during the proton transfer (**11** → **13**) and aldehyde decoordination (**13** → **15**) occurring in pathway C. Selected interatomic distances are given in Å.

decoordination of the equatorial PPh_3 ligand from **15H**. The latter is found to be reasonably demanding thermodynamically (10.9 kcal/mol at the ECP3 level, see Table 2).

(b). Structural Features. The tetrahydride complex **15H** possesses two hydride ligands, one H_2 ligand ($d_{\text{H-H}} = 0.91 \text{ \AA}$) and a vacant site in the equatorial plane (see Figure 9). No stationary point could be found for a “ D_{4h} -like” classical hydride analogue. We note that the structure of the $[\text{RuH}_2(\text{H}_2)(\text{PPh}_3)_2]$ moiety remains almost unaltered after coordination of one MeOH molecule (compare **15H** and **16Hb** in Figure 9), the latter being oriented in the equatorial plane pointing its alcohol hydrogen toward one PPh_3 ligand. As observed above, the transition state corresponding to the H_2 elimination (**TS**_{16Hb-17}) involves quite long Ru–H distances (ca. 3.7 Å), whereas the orientation and the Ru–O distances of the MeOH ligands remain unchanged (ca. 2.35 Å) even after full dissociation of the H_2 moiety. As observed above, the decoordination of H_2 occurs along with a relaxation of the $[\text{RuH}_2(\text{PPh}_3)_3]$ moiety (Figure S2), and the deformation energy is estimated to be 3.6 kcal/mol in **16Hb** and is almost zero in **TS**_{16Hb-17}.⁴⁴

Discussion

Substrate Coordination and Role of the Base. Two possibilities have been investigated for the insertion of the substrate in the catalytic cycle by considering the coordination of either the MeOH or the MeO^- moieties. In pathways A–C, the direct

coordination of MeOH is shown to be more thermodynamically demanding than the coordination of MeO^- (see Table 1). This step therefore involves a preliminary deprotonation of the substrate by the base, as suggested by Cole-Hamilton et al.⁷ However, this feature is not a general rule, since we found an opposite behavior in the case of pathway D, where the direct coordination of MeOH to **15H**, followed by the deprotonation of the coordinated alcohol, is found to be the easiest route (see Figure S6). The presence of a base is also beneficial for the formation of intermediate **3H** involved in pathways B (Figure 4) and $\text{C}_{\text{neutral}}$ (Figure S4). In absence of base, this intermediate would be afforded by addition of MeOH to **2**, followed by the intramolecular transfer of the alcohol hydrogen via **TS**₂₋₆. However, this step involves a high kinetic barrier (14.3 kcal/mol), whereas it is not activated when performed via **3**: i.e., by a sequence of proton exchanges with the base.⁴⁶ We note that such a high barrier is consistent with the studies of Delbecq et al.^{13b} and Joo et al.,^{13c} where this process has been described in the context of the hydrogenation of α,β -unsaturated aldehydes.⁴⁷ We note that the base can also react with the Ru center of catalyst complexes and therefore allows us to modulate the number of hydride and/or H_2 ligands at the metal. As a result, we found that anionic intermediates and transition states are generally lower in energy than their neutral conjugated acids (see Table S5), the former naturally leading to more kinetically favorable pathways. We note that the positive effect of the base

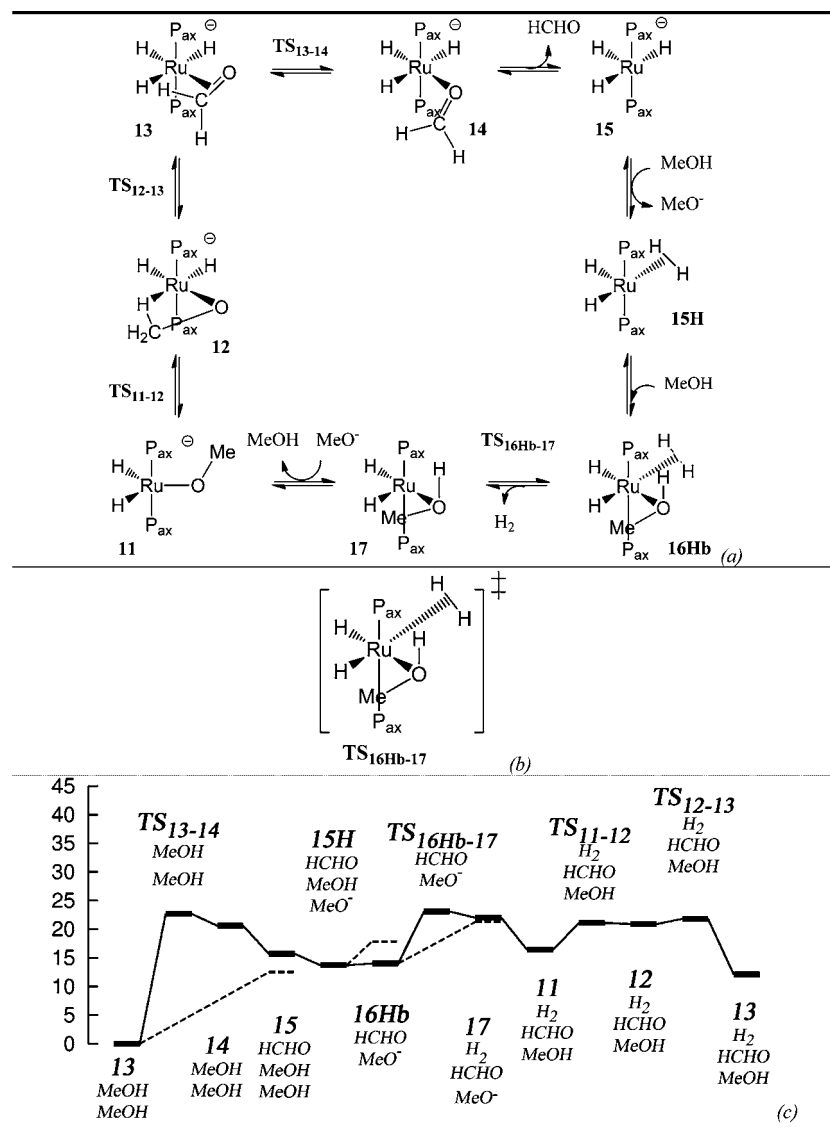


Figure 8. Reaction pathway D. See Figure 2 for a definition of labels (a), (b), (c).

is consistent with the early studies of Cole-Hamilton et al.⁷ who demonstrated an enhancement of the reaction rate upon an addition of small amounts of NaOH.^{7b} However, a full understanding of its role would require the consideration of the full catalytic system and, in particular, to take into account the decarbonylation and aldol condensation side reactions. However, our results point to the effect of the base on the dehydrogenation reaction itself, a feature which has not been reported in such details so far.

β -Hydride Transfer. In the four investigated pathways, the β -hydride transfer is found to occur via the formation of a four-membered ring (Ru–O–C–H). In pathway A, the latter is observed within a seven-coordinated complex and the resulting HCHO product is not coordinated to the metal at the end of the transfer step. This feature contrasts with other pathways, where prior dissociation of H₂ or PPh₃ facilitates the process due to the formation of a vacant site at the Ru center. This vacant site first allows the formation of an agostic interaction which initiates the transfer and next allows the coordination of the HCHO product to the metal. We note that the intermediacy of such a

four-membered ring is consistent with the early findings of Itagaki et al., who studied dehydrogenation at a Ru center in presence of acetate ligands,¹² and is also found in numerous studies of the reverse aldehyde hydrogenation reactions^{13b,c} and hydrogen-transfer^{14a,b} reactions.⁴⁸

(46) The different proton transfer processes involved in pathways A–D are considered to be non-activated. This assumption is based on the results of numerous computational studies on smaller systems, in which the corresponding free energy is found to evolve monotonically as proton transfer occurs. See e.g. the cases of the water self-hydrolysis reaction. (Sprik, M. *Chem. Phys.* **2000**, *258*, 139). the deprotonation of solvated formic acid. (Lee, J.-G.; Ascicchio, E.; Babin, V.; Sagui, C.; Darden, T.; Roland, C. *J. Phys. Chem. B* **2006**, *110*, 2325), or the deprotonation of an aqueous uranyl metal complex. (Bühl, M.; Kabrede, H. *ChemPhysChem* **2006**, *7*, 2290). However, the presence of such transition states in the particular case of the ruthenium hydride complexes can not be fully ruled out, but their characterization seems hardly feasible by a static/continuum approach. Ab initio molecular dynamics simulations involving explicit solvent molecules would be required for a meaningful investigation of proton transfers occurring between the solvent and Ru intermediates. Unfortunately, this approach is presently precluded by the size of the considered systems and the related large computational cost.

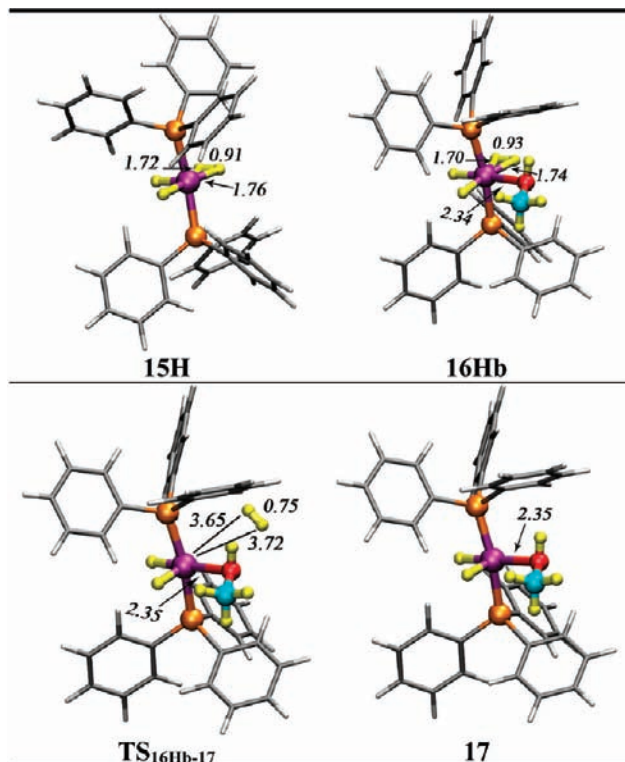


Figure 9. Structures of intermediates and transition states involved in pathway **D**, including selected interatomic distances (in Å).

Phosphine Dissociation. Pathways **C** and **D** involve the decooordination of one phosphine ligand occurring either from **3** (in **C**) or from **1b** (in **D**). We found that this process is thermodynamically facile (from ca. 3 kcal/mol in **3** to ca. 11 kcal/mol in **1b**), and this result is therefore consistent with the presence of a phosphine dissociation pre-equilibrium, as suggested by Shinoda et al.¹⁰ We both considered the possibility that the dissociated ligand recoordinates in each catalytic cycle (in **C**) or remains uncoordinated (in **D**), and these two paths are found to be feasible kinetically. The dissociation of a phosphine ligand is also consistent with the ¹H NMR characterization, under noncatalytic conditions, of the [RuH₃(PPh₃)₂][−] trihydride complex^{11a} which is involved in pathways **C** and **D** (intermediate **15**). This complex is obtained from its pentahydride [RuH₅(PPh₃)₂][−] analogue, which has also been characterized by ¹H and ³¹P NMR.⁴⁹ According to NMR, [RuH₅(PPh₃)₂][−] possesses its two phosphine ligands in a cis position, whereas the NMR spectrum of [RuH₅(PPh₃)₂][−] is found to be “consistent with a pentagonal bipyramidal structure or with a fluxional structure having a low activation barrier for interconversion”.^{11a} These observations are in accord with our calculations, since we found that, in the case of [RuH₃(PPh₃)₂][−], the cis isomer is

ca. 8 kcal/mol more stable than its trans analogue **15** (see Table S1). We also investigated cis forms of other intermediates and transition states involved in pathway **C** and found that the pairs of isomers are generally close in energy (within a range of ± 5 kcal/mol). Moreover, the full characterization of a variant of **C** involving cis complexes only (pathway **C**_{cis}; see Figure S5) revealed that they possess similar reaction profiles and almost identical activation energies (see Table S4). Our results therefore suggest that both forms are reactive and that they could be involved in competitive pathways.

Aldehyde Decoordination. In pathways **B–D**, the aldehyde decooordination step is particularly demanding kinetically, due to the presence of a high-energy transition state corresponding to a η^2 – η^1 slippage of the coordinated product preceding its full decooordination. In all investigated pathways, the η^2 form is preferred and both the height of the barrier and the energy difference between the two coordination modes are found to depend on the number of phosphine ligands attached to the metal, the global charge of complexes and the cis/trans position of PPh₃ ligands. These results are in agreement with the study of Delbecq et al.,⁵⁰ who investigated the binding of formaldehyde to several types of organometallic fragments. They found that HCHO can exhibit a high back-bonding interaction and that the latter can be strongly affected by the nature of the ligands. Studies of model Ru complexes at the low RI-BP86/ECPI level (see Table S7) suggest that back-bonding is especially important within Ru hydride complexes, since we found that a η^1 coordination is slightly preferred for [RuCl₂-(PPh₃)₃(HCHO)] (by 1.9 kcal/mol, in accord with Delbecq et al.⁵⁰ results) whereas a η^2 coordination mode is strongly favored in the case of its hydride analogue [RuH₂(PPh₃)₃(HCHO)] (by 15.7 kcal/mol). The cis/trans position of the hydride ligands has been found to have a small influence on the relative energies (3.0 kcal/mol), as has the replacement of PPh₃ by PPh₃ ligands (2.6 kcal/mol). The high energy barrier is therefore expected to stem from the breaking of such back-bonding interactions, and the further stabilization of the η^1 form would correspond to an optimal dative bond between HCHO and the Ru complexes. We note that the η^2/η^1 relative energies can be significantly affected by the nature of the carbonylated ligand (see below), since a preference for a η^1 coordination mode has been found for a series of α,β -unsaturated aldehydes.^{13a} For these substrates, transition states between the η^1 and η^2 forms have been characterized elsewhere^{13b,c} and their structures are reminiscent of those described herein (namely **TS9–10**, **TS13–14**, and **TS13H–14H**).

Other Alcohol Substrates and Consequences on the Reaction Efficiency. The interesting bonding behavior of substituted aldehydes with Ru complexes led us to investigate the coordination properties of ethanal and acetone, which would result from the dehydrogenation of EtOH and ⁱPrOH, respectively. These substrates have also been investigated in the original study of Morton and Cole-Hamilton, and they found that significantly higher turnover frequencies are obtained compared to those for MeOH.^{7a} We first focused on the decooordination process of the products in pathways **B**, **C**, and **C**_{neutral} (i.e., a pathway analogous to **C** involving protonated intermediates), which all involve a η^2 – η^1 slippage of the coordinated aldehyde (or ketone). Figure 10 gathers the results of these calculations and clearly shows that the nature of the product has a strong influence on the η^2/η^1 relative energies. The nature of the catalyst complex itself is also important, since

(47) We note that Delbecq et al.^{13b} and Joo et al.^{13c} investigated a reverse analogue of pathway **B** in which PPh₃ is used as model ligand and in which the presence of the base is not considered. The reaction profiles found in these studies are in qualitative agreement with our results; however, qualitative comparisons are hardly possible, since they considered different phosphine ligands and different substrates.

(48) For the less crowded complex **11**, we have also explored the possibility of a H transfer via a less strained six-membered ring involving the OH group of a second MeOH molecule. However, we could not find a feasible path for such a concerted, “outer sphere” mechanism (as had been suggested in the case of transfer hydrogenation¹⁹).

(49) We note that the carbonylated [RuH₃(CO)(PPh₃)₂][−] complex has also been characterized, which may be involved in the decarbonylation side reaction occurring in the system under scrutiny.

(50) Delbecq, F.; Sautet, P. *J. Am. Chem. Soc.* **1992**, *114*, 2446.

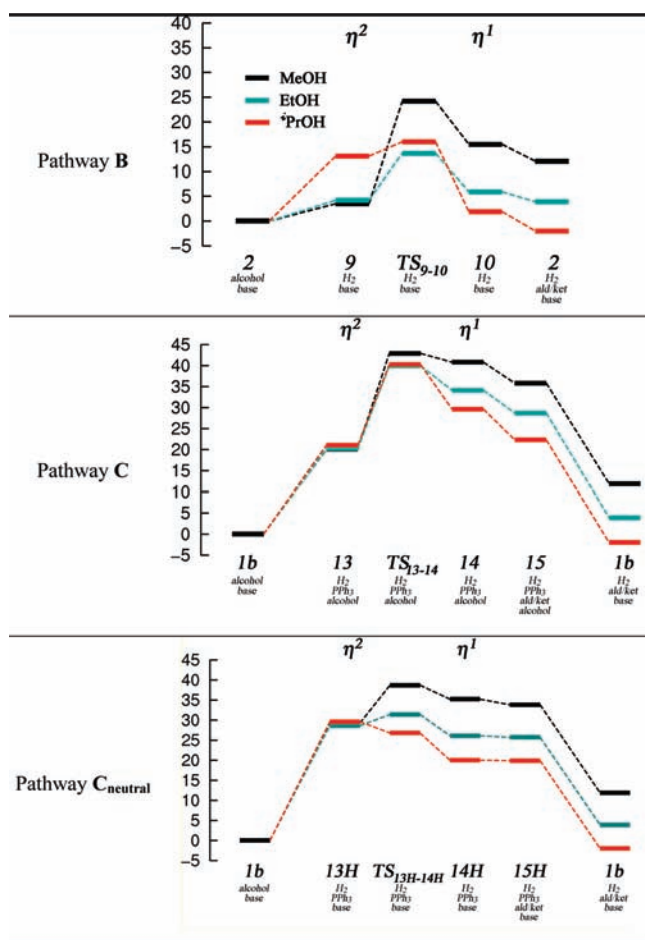


Figure 10. Free energy profiles (kcal/mol) for pathways B, C, and C_{neutral}, comparing MeOH (black), EtOH (blue), and ²PrOH (red) as starting substrates. Only steps corresponding to the η²–η¹ slippage and the subsequent aldehyde (or ketone) decoordination are represented. Free energies are computed in solution at the B97-D/ECP2 level and without BSSE correction (refined values for the rate-limiting barriers are given in Table 2).

a very different behavior is observed for each pathway. In pathway B, the preference for η² coordination observed in the case of HCHO moves toward quasi-isoenergetic η²/η¹ forms with MeCHO, whereas a η¹ coordination mode is clearly preferred for Me₂CO. This finding is consistent with observations in the solid state, where a η² coordination mode is observed in the related [Os(PPh₃)₂(CO)₂(HCHO)] complex⁵¹ and where acetone is mainly η¹-coordinated to transition metals.⁵²

The height of the barrier corresponding to the slippage decreases with increasing driving force: i.e. from HCHO to Me₂CO. In pathway C, involving anionic bis-phosphine complexes, the three substrates are equally well bonded to the metal when η²-coordinated (in 13), whereas the η¹ form is gradually stabilized when going from HCHO to Me₂CO. Interestingly, the corresponding activation energies are found to be very similar in this case. This behavior is in contrast with that

obtained for pathway C_{neutral}, in which both transition state and η¹ forms are stabilized with higher substrates. A common feature of the three studied pathways is that the nature of the substrate has little influence on the full decoordination energies.

Following this analysis of the bonding properties of the carbonylated products, we investigated the influence of the substrate on the kinetic of the reaction by recomputing the highest energies barriers for A–D with EtOH and ²PrOH as starting substrates (see Table 2). In most cases, the nature of the alcohol does not influence the nature of the rate-limiting steps, and the only exception is found for pathway D, where the highest barrier is found between 15H and TS_{13–14} with ²PrOH (instead of 13 and TS_{16Hb-17} with other alcohols). This is clearly shown in Figure S8, where we report the full corresponding reaction profile: with 2-propanol, the energy level of 16Hb is shifted down due to a more stable η¹-Me₂CO complex (intermediate 15), and the highest energy level therefore corresponds to TS_{13–14}, which is little affected by the nature of the substrate (vide supra). The overall activation barriers systematically decrease when going from MeOH to ²PrOH (Table 2), which is consistent with the trend of experimental reaction turnover frequencies reported by Morton and Cole-Hamilton.^{7a} Understanding this behavior is not straightforward, since it stems not only from the intrinsic (gas-phase) reaction energies but also from the contributions of solvation and thermochemical corrections. The reaction is also favored thermodynamically with higher alcohols, since the global reaction free energy gradually decreases from MeOH to ²PrOH (compare final vs initial energy levels in Figure 10).⁵³

Reaction Kinetics and Multiple Reaction Pathways. Pathways A–D involve rate-limiting steps of different nature: (i) in pathway A, the latter corresponds to the β-hydride transfer (occurring in TS_{3–4}); (ii) in pathways B and D, the reaction is rate-limited by the decoordination of the H₂ product (in TS_{3Hb-7} and TS_{16Hb-17}, respectively); (iii) in pathway C, the rate-limiting step is the partial decoordination of HCHO (TS_{13–14}). We also note that pathways B and D require an activation step: namely, the decoordination from 1b of H₂ (in B) and PPh₃ (in D). As shown in Table 2, we found that all these pathways possess very close activation energies, ranging from 27.0 kcal/mol for pathway D to 32.1 kcal/mol for pathway B. On the other hand, initiation free energies are found to be rather small (4.3 kcal/mol in B and 10.9 kcal/mol in D). These features therefore suggest that the four investigated pathways are competitive, since they are all accessible kinetically. Moreover, we note that A–D are strongly interlocked (see Figure 1), since intermediates 3, 5, and 15 and their protonated analogues (i.e., 3H, 1b, and 15H, respectively) are “at the crossing” of the different pathways, therefore providing links from one route to another, a feature which is expected to be beneficial to the overall kinetics of the system. As a matter of comparison, we found it interesting to estimate how this behavior depends on thermodynamic conditions and we recomputed the overall activation energies at the lower temperature of 64 °C (i.e., at the boiling point of methanol) and we found that, in this case, pathways A, B, and D still remain competitive and that pathway C (as well as its neutral and cis-phosphine analogues) is slightly penalized kinetically (see Table S4). Similarly, when varying the nature

(51) Brown, K. L.; Clark, G. R.; Headford, C. E. L.; Marsden, K.; Roper, W. R. *J. Am. Chem. Soc.* **1979**, *101*, 503.

(52) In a corresponding search in the Cambridge Structural Database considering the M(PC₃)₂(η²-HCHO) fragment (M being a group 8 metal), only one structure has been found, corresponding to [Os(PPh₃)₂(CO)₂(HCHO)]. Another search considering M(PC₃)₂(η²-Me₂CO) led to no hit, whereas searching the M(PC₃)₂(η¹-Me₂CO) fragment led to 30 hits.

(53) In comparison to high-level CCSD(T) or to experimental data, the absolute reaction enthalpies for dehydrogenation of the alcohols are notably underestimated at the B97-D level, but the relative sequence is very well captured at the DFT level (see Table S8).

of the substrate, we found that **A–C** remain competitive, whereas pathway **D** is favored with ethanol and 2-propanol (see Table 2).

Conclusion

To summarize, we applied modern DFT techniques to elucidate the mechanism of alcohol dehydrogenation of alcohols catalyzed by a ruthenium–triphenylphosphine catalyst. The modeling of “real” bulky PPh₃ ligands revealed the importance of steric effects and allowed us to model the key ligand dissociation steps. Comparison between model and real phosphines, i.e. PH₃ vs PPh₃, showed that the latter induces higher kinetic barriers. The initially proposed mechanism of Morton and Cole-Hamilton^{7a} is found to be kinetically accessible, as are three other mechanisms proposed in this study. The computations also furnish insights into the roles of the base, which are 3-fold: (i) it facilitates the coordination of the substrate (pathways **A–C**); (ii) it catalyzes intramolecular proton transfers; (iii) it allows regulation of the number of hydrogen atoms coordinated to the metal, a feature which can lead the system to more favorable pathways. The investigation of other alcohol substrates revealed that the reaction is kinetically favored with higher alcohols, a feature generally due to an easier aldehyde/

ketone decoordination step. The main result of our study is that the four investigated pathways are found to possess close overall activation free energies and should therefore be competitive. This feature may well be at the origin of the good efficiency of this reaction, in line with the emerging view⁵⁴ that providing several reaction channels is kinetically beneficial for catalytic reactions.

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Supporting Information Available: Text, tables, and figures giving relative energies of selected isomers, intramolecular BSSE correction terms, descriptions of other investigated pathways mentioned in the text, and Cartesian coordinates of selected complexes. This material is available free of charge via the Internet at <http://pubs.acs.org>.

JA101044C

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