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Highly Versatile Catalytic Hydrogenation of Carboxylic and Carbonic Acid Derivatives using a Ru-Triphos Complex: Molecular Control over Selectivity and Substrate Scope

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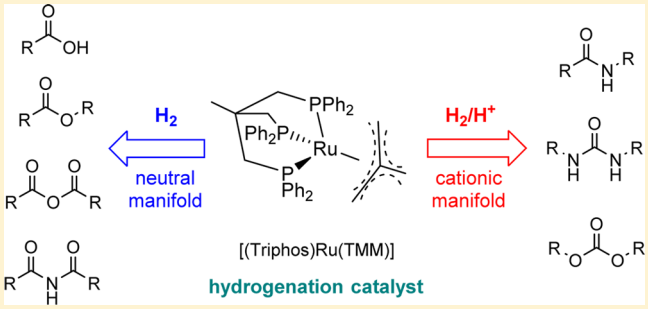
Supporting Information

ABSTRACT: The complex [Ru(Triphos)(TMM)] (Triphos = 1,1,1-tris(diphenylphosphinomethyl)ethane, TMM = trimethylene methane) provides an efficient catalytic system for the hydrogenation of a broad range of challenging functionalities encompassing carboxylic esters, amides, carboxylic acids, carbonates, and urea derivatives. The key control factor for this unique substrate scope results from selective activation to generate either the neutral species [Ru(Triphos)(Solvent)H_2] or the cationic intermediate [Ru(Triphos)(Solvent)(H)(H_2)]$^+$ in the presence of an acid additive. Multinuclear NMR spectroscopic studies demonstrated together with DFT investigations that the neutral species generally provides lower energy pathways for the multistep reduction cascades comprising hydrogen transfer to C=O groups and C−O bond cleavage. Carboxylic esters, lactones, anhydrides, secondary amides, and carboxylic acids were hydrogenated in good to excellent yields under these conditions. The formation of the catalytically inactive complexes [Ru(Triphos)(CO)H_2] and [Ru(Triphos)(μ-H)]$_2$ was identified as major deactivation pathways. The former complex results from substrate-dependent decarbonylation and constitutes a major limitation for the substrate scope under the neutral conditions. The deactivation via the carbonyl complex can be suppressed by addition of catalytic amounts of acids comprising non-coordinating anions such as $HNTf_2$ (bis(trifluoromethane)sulfonimide). Although the corresponding cationic cycle shows higher overall barriers of activation, it provides a powerful hydrogenation pathway at elevated temperatures, enabling the selective reduction of primary amides, carbonates, and ureas in high yields. Thus, the complex [Ru(Triphos)(TMM)] provides a unique platform for the rational selection of reaction conditions for the selective hydrogenation of challenging functional groups and opens novel synthetic pathways for the utilization of renewable carbon sources.



INTRODUCTION

Catalytic hydrogenation using organometallic complexes as catalysts is a key transformation in the toolbox of modern chemical synthesis on a laboratory and industrial scale.[1] Numerous catalysts and procedures have been developed for the addition of an H_2 molecule across C=C, C=O, and C=N bonds exhibiting high chemo- and stereoselectivities. In contrast, the selective and effective catalytic reduction of more complex functional groups such as carboxylic and carbonic acid derivatives remains a challenge for homogeneous catalysts (Scheme 1).[2] These transformations are of enormous potential in the synthesis of fine chemicals and pharmaceuticals[3] and in particular also for the valorization of alternative carbon feedstock such as biomass[4] or carbon dioxide.[5] The targeted conversions are, however, considerably more complex than standard hydrogenation reactions, requiring the activation and transfer of several H_2 molecules and the cleavage of C−O bonds to achieve the desired functional group transformation.[6]

Recent research efforts have illustrated that ruthenium complexes comprising multidentate ligand frameworks show a particular potential for the development of multifunctional catalytic systems enabling such complex de- and refunctionalization processes.[7] However, most of these catalytic systems are highly specialized for the hydrogenation of a specific substrate class and often require the usage of stoichiometric amounts of additives. Consequently, a highly versatile homogeneous catalyst for the reduction of a broad basis of carboxylic and carbonic acid derivatives would be desirable in order to enable a

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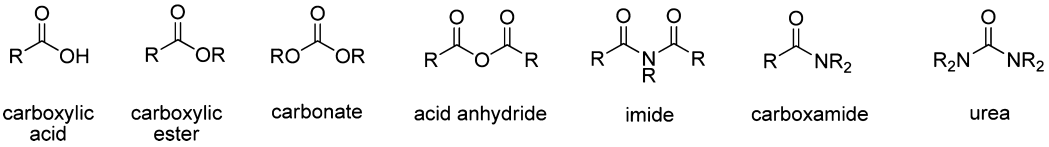
Scheme 1. Carboxylic and Carbonic Acid Derivatives Representing Highly Desirable, Yet Challenging, Substrates for the Selective Reduction with Molecular Hydrogen Applying Homogeneous Catalysts



flexible platform for the transformation of diverse functionalities.

RESULTS AND DISCUSSION

The hydrogenation of activated esters using *in situ* catalysts formed from ruthenium precursors such as [Ru(acac)$_3$] and the facially coordinating tridentate ligand Triphos (1,1,1-tris-(diphenylphosphinomethyl)ethane) was reported by Elsevier and co-workers in 1997.[8] Recently, it was shown that this system can be transformed to an highly effective and robust homogeneous catalyst in combination with acidic co-catalysts for the selective conversion of biogenic carboxylic acids such as levulinic and itaconic acid to the respective lactones, diols, or cyclic ethers.[4c,9] Hydrogenation of N-aryl substituted amides has also been achieved under similar conditions.[10] Most recently, the molecularly defined complex [Ru(Triphos)-(TMM)] **I-1** (TMM is trimethylenemethane) has been introduced, which is readily synthesized in one step from commercially available [Ru(cod)(methallyl)$_2$] and Triphos (Figure 1). This complex was found to enable C−O bond

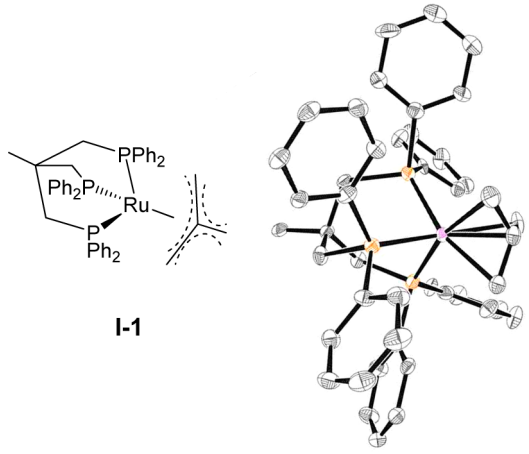


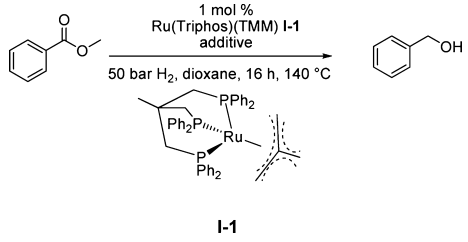
Figure 1. Molecular structure of the complex [Ru(Triphos)(TMM)] **I-1** used as catalyst precursor as derived from single crystal X-ray diffraction; hydrogen atoms are omitted for clarity.

cleavage in lignin model compounds[11] and the hydrogenation of formate esters and even CO_2 to methanol,[12] using protocols comprising again the use of acidic co-catalysts.

In the present study, we demonstrate that complex **I-1** can serve as catalyst precursor for the effective hydrogenation of essentially any of the various functional groups depicted in Scheme 1. The transformations exhibit unprecedented reactivity and selectivity in several cases. This unique reaction portfolio for a single catalyst precursor is based on the control of the activation procedure which can be rationalized on the basis of a molecular understanding of this system.

Exploring the substrate scope of complex **I-1**, the hydrogenation of methyl benzoate was investigated as benchmark substrate for nonactivated carboxylic esters (Table 1). Applying the established conditions for the reduction of formates (1.5

Table 1. Catalytic Hydrogenation of Methyl Benzoate with Ruthenium Catalyst I-1[a]



I-1

entry	acidic additive	benzyl alcohol [%]
1	MSA	4
2	*p*-TsOH	57
3	$HNTf_2$	10[b]
4	-	98

[a]Reaction conditions: methyl benzoate (1 mmol), [Ru(Triphos)-(TMM)] **I-1** (0.01 mmol), acid additive (0.015 mmol), dioxane (1 mL), T = 140 °C, $p(H_2)$ = 50 bar, t = 16 h. Yields determined by GC using dodecane as internal standard. [b]Full conversion of methyl benzoate. Main products methylbenzylether and dibenzylether.

equiv of methanesulfonic acid (MSA) as additive, T = 140 °C, $p(H_2)$ = 50 bar)[12] resulted in only 4% formation of benzyl alcohol (Table 1, entry 1). Using the weaker acid *p*-toluenesulfonic acid (*p*-TsOH) gave a moderate yield of 57% of the alcohol (Table 1, entry 2). Application of bis-(trifluoromethane)sulfonimide ($HNTf_2$) as acid additive gave full conversion, but reduced the selectivity to 10% due to pronounced etherification to dibenzyl- and methylbenzylether (Table 1, entry 3). An excess of $HNTf_2$ (3 equiv) resulted in low conversion and pronounced side-reactions. These results indicate that both the acid strength and the nature of the anion in the additive strongly influence the activation and reactivity of the catalyst precursor.

As acids are known to protonate the trimethylenemethane ligand in similar organometallic species,[13] we decided to first unravel the reactivity of complex **I-1** toward hydrogen under neutral conditions. Treating a solution of **I-1** in THF under 45 bar of hydrogen at 140 °C resulted in formation of the corresponding neutral dihydride complex **I-2** and the respective dimer **I-5** as evidenced by multinuclear high-pressure NMR (see Supporting Information for details). In a second reaction step, this species could be rapidly converted and fully characterized as the stable [Ru(Triphos)(CO)H$_2$][14] complex **I-3** in the presence of carbon monoxide (Scheme 2). This clean reactivity of the catalyst precursor prompted us to perform the catalytic hydrogenation reaction with complex **I-1** in the absence of any acid. Indeed, the catalytic hydrogenation of methyl benzoate was found to proceed smoothly under otherwise identical conditions, leading to full conversion and

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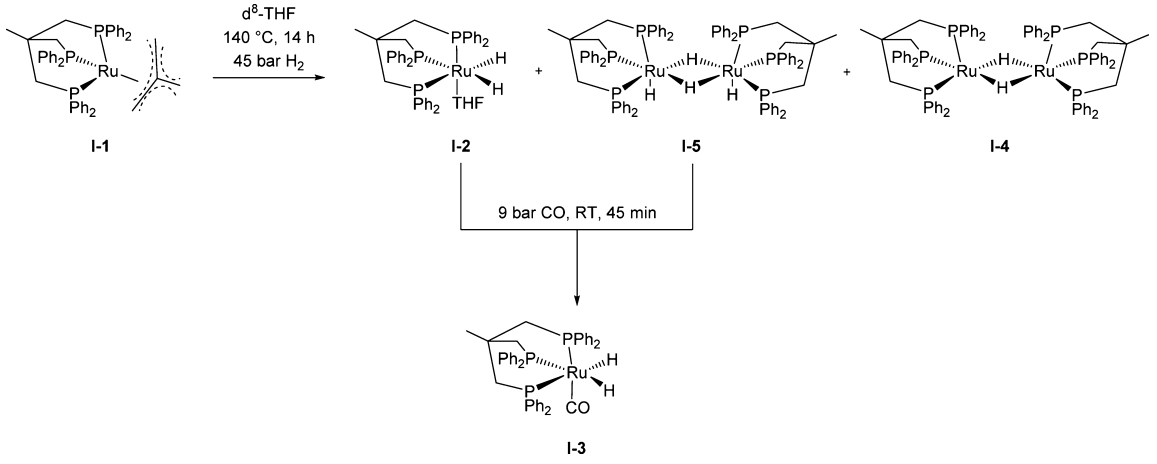
Scheme 2. Reactivity of the Ruthenium Catalyst I-1 in the Presence of Molecular Hydrogen at Elevated Temperatures and Interception of the Intermediates I-2/I-5 with CO



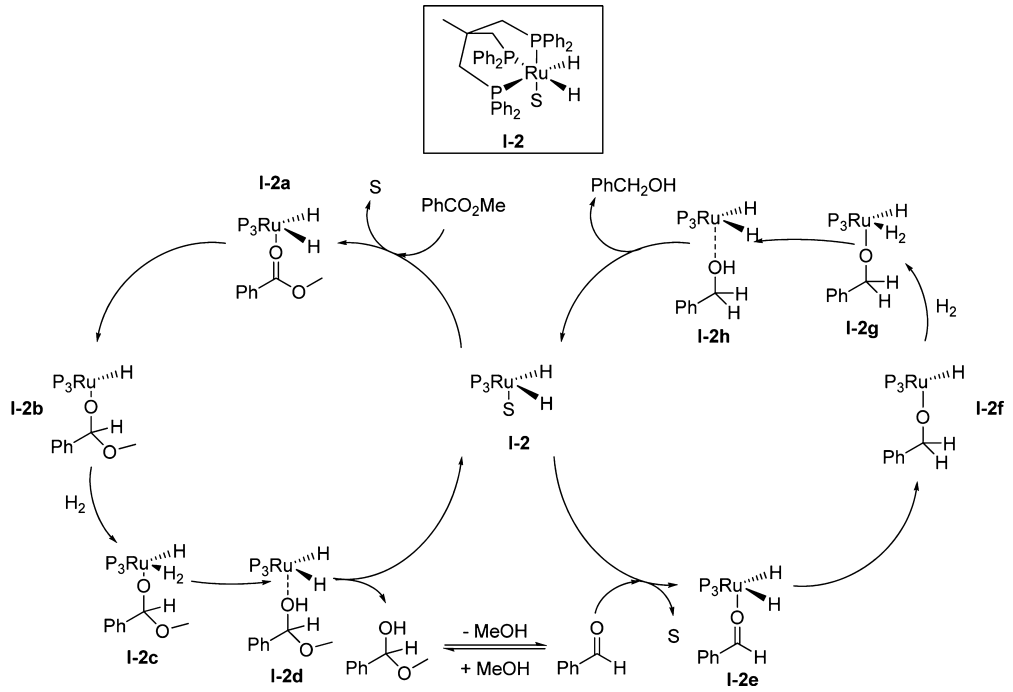


Figure 2. DFT-calculated catalytic cycle (S = tetrahydrofuran).

98% selectivity toward benzyl alcohol (Table 1, entry 4). The catalyst loading could be reduced even to 0.1 mol % yielding in a TON of 540.

In agreement with previous proposals,[7b,15] these findings indicate the neutral dihydride complex **I-2** as the active species in the hydrogenation of esters. In order to compare the resulting pathway directly to the complementary mechanism proposed for free acids based on cationic hydride intermediates,[9] the multistep sequence for the hydrogenation of methyl benzoate with the neutral ruthenium triphos complex **I-2** was studied with DFT calculations (Figure 2). The calculations were carried out on the M06-L/def2-TZVP(ECP)(IEFPCM) level (for details see the Supporting Information) and the resulting energy profile is depicted in Figure 3.

The dissociative replacement of THF by methyl benzoate yields the substrate complex **I-2a**, which reacts in a classical migratory insertion step via transition state **TS-I2a-I2b** to the monohydride complex **I-2b**. Reductive elimination at this stage is strongly disfavored to hydrogenolysis of the Ru−O bond: The transition state for elimination resides at 55.5. kcal/mol (not shown in Figure 3) which clearly indicates that such a pathway is not feasible. The hydrogenolysis of the Ru−O bond is initiated by coordination of a H_2 molecule yielding the neutral mixed classical/non-classical hydride complex **I-2c**. Proton transfer to the oxygen via the adjacent acidic H_2 ligand results in reformation of the classical dihydride structure, now containing the hemiacetal of benzyl alcohol as primary product (**I-2d**). The structure of the associated transition state **TS-I2c-I2d** is shown in Figure 4 highlighting the H−H bond cleavage. It represents the highest point on the hyper surface (25.4 kcal/mol).

The hemiacetal in **I-2d** can be readily replaced by a solvent molecule, regenerating **I-2**. The hemiacetal converts via low-energy pathway to the corresponding benzaldehyde and methanol outside the metal coordination sphere, resulting in the required C−O bond cleavage.[16] The reduction sequence

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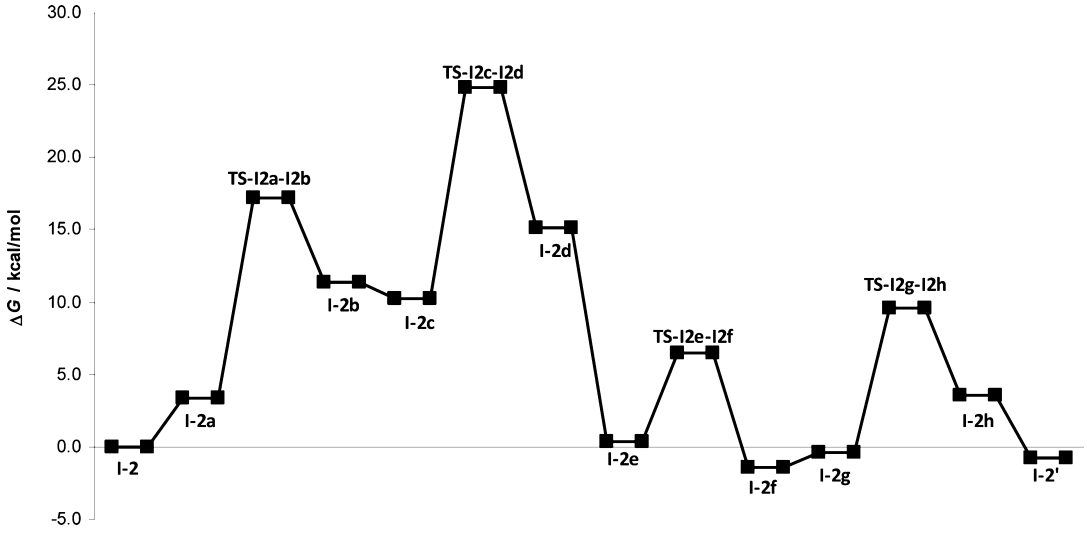


Figure 3. Gibbs free energy profile of the calculated mechanism as shown in Figure 2.

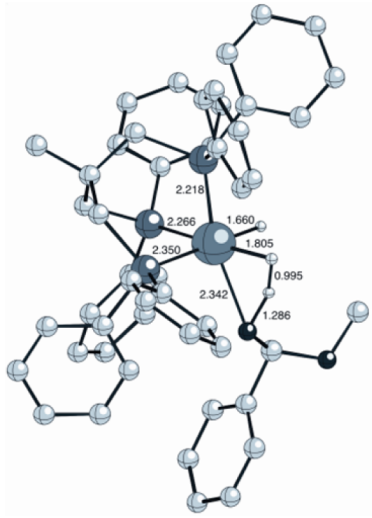


Figure 4. DFT-calculated structure with selected atom distances (Å) for the transition state **TS-I2c-I2d** of the hydrogenolysis. For clarity all hydrogen atoms were omitted except for the classical hydride and the nonclassical H_2 molecule.

then proceeds by recoordination of benzaldehyde at the metal center generating complex **I-2e**, initiating the subsequent hydrogen-transfer steps analogously to the mechanism described above passing through the intermediates and transition states **I-2f**, **TS-I-2f-I-2g**, **I-2g**, and **TS-I-2g-I-2h**, respectively. Dissociation of the product benzyl alcohol regenerates the active site which can be saturated with THF at any stage to yield the starting complex **I-2** as resting state.

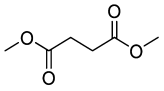
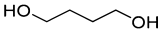
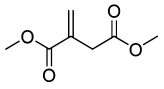
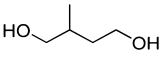
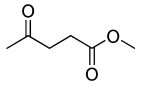
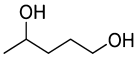
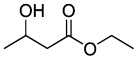
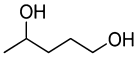
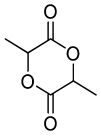
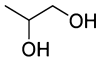
In this line, the reduction of the ester to the hemiacetal shows significantly higher energy barriers than the reduction of the benzaldehyde. The turnover-determining intermediate (TDI) and the turnover-determining transition-state (TDTS) were identified to be **I-2f** and **TS-I2c-I2d**, respectively, generating an effective activation barrier (energy span) of 25.4 kcal/mol. The experimentally determined TOF of 41 h^{-1} after 1.5 h reaction time at 140 °C in THF corresponds to activation energy of 28.1 kcal/mol, indicating a good agreement with the computationally determined value.

Consequently, the substrate scope of the neutral hydrogenation pathway based on ruthenium catalyst **I-1** was evaluated in the transformation of selected biogenic carboxylic esters. Dimethyl succinate could be efficiently converted to 1,4-butanediol in 99% yield at 140 °C and 50 bar hydrogen pressure in dioxane with a catalyst loading of 1 mol % (Table 2, entry 1). Comparable results were obtained with dimethyl itaconate, resulting in the respective branched diol in 99% yield (Table 2, entry 2). Methyl levulinate could be selectively transformed to 1,4-pentanediol without any concomitant formation of the cyclic ethers (Table 2, entry 3). Along the same line, ethyl-3-hydroxybutyrate was converted to 1,3-butanediol in 95% yield (Table 2, entry 4). The hydrogenation of γ-valerolactone also occurred under ring opening, affording again 1,4-pentanediol in 99% yield (Table 2, entry 5). Moreover, D,L-lactide could be selectively converted to 1,2-propanediol at low catalyst loading of 0.1 mol % (Table 2, entry 6).

The excellent selectivity toward the alcohol products prompted us to explore the possibility of sequential hydrogenation of diesters (Scheme 3). For dimethylsuccinate (DMS), the formation of methyl-4-hydroxybutyrate (M-4HB) could be observed in the initial phase of the reaction under standard conditions. Systematic parameter variation enabled to obtain a selectivity of 92% toward M-4HB at an optimized reaction temperature of 80 °C after 48 h, emphasizing the exceptional selectivity of the ruthenium catalyst **I-1**.[17] In the subsequent step, M-4HB is reduced to 1,4-butandiol (1,4-BDO) without any indication for the intermediate formation of the γ-butyrolactone at these low-reaction temperatures (see Supporting Information for details).

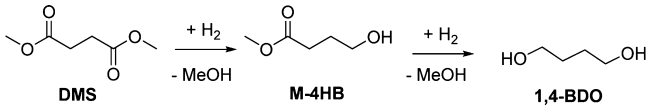
Notably, free carboxylic acids could also be hydrogenated to the corresponding alcohols with high selectivity using **I-1** under the additive-free protocol at slightly elevated temperatures (Table 3). Benzoic acid was hydrogenated to benzyl alcohol at 220 °C under otherwise identical conditions, without any concomitant hydrogenation of the aromatic ring (Table 3, entry 1).[18] The reduction of the aliphatic compound hexanoic acid resulted in a moderate yield of 50% (Table 3, entry 2). Levulinic and succinic acid could be converted to the respective diols in in 99 and 92% yield (Table 3, entries 3 and 4). Although the higher temperature may indicate that the reaction

Table 2. Selective Hydrogenation of Selected Carboxylic Ester and Lactone Derivatives with Catalyst I-1[a]

Entry	Substrate	Time [h]	Temperature [°C]	Product	Yield [%]
1		16	140		99
2[b]		24	140		99
3		16	140		99
4		16	140		95
5		16	140		99
6[c]		16	140		99

[a]Reaction conditions: substrate (1 mmol), [Ru(Triphos)(TMM)] **I-1** (0.01 mmol), dioxane (1 mL), $p(H_2)$ = 50 bar. Yields determined via ^{1}H NMR using mesitylene as internal standard. For all methyl esters methanol was observed in equal yield. [b]$p(H_2)$ = 75 bar. [c]**I-1** (0.001 mmol).

Scheme 3. Selective Hydrogenation of DMS at Low Reaction Temperatures



proceeds through the cationic mechanism for these substrates,[9] the absence of strong acids avoids the cyclization reactions typically encountered with the *in situ* system, thus providing again a complementary reactivity.[4c] Consequently, the stability of the developed catalysts systems toward acid substrates and the high reaction temperatures are important advantages in comparisons to other catalytic systems.[2] The additive-free protocol could also be extended to anhydrides, as shown for the hydrogenation of succinic anhydride that led at 195 °C to formation of 1,4-butanediol with a selectivity of 96% (Table 3, entry 5). Also imides are hydrogenated, as demonstrated for the reduction of 1H-pyrrole-2,5 dione to 1,4-butanediol in 86% yield after 24 h (Table 3, entry 6).[19] Along the same line, the secondary amide acetanilide was transformed to *N*-ethylaniline in 99% yield with 2 mol % catalyst loading at 160 °C in dioxane (Table 3, entry 7). A first limitation was encountered only when using the primary amide of benzoic acid as substrate, which resulted in a considerable lower conversion of 51% even after an extended reaction time of 72 h with benzyl alcohol as the main product (Table 3, entry 8).[7a] Future work will be directed to the mechanistic understanding of the factors controlling the selective C−N or C−O bond cleavage in the respective amide substrates.

In order to elucidate possible reasons for the substrate-dependent limitation, multinuclear NMR spectroscopic analyses of the reaction mixtures after typical catalytic experiments were carried out. The two major species observed in these mixtures were the dihydrido-carbonyl complex **I-3** and the hydrido(triphos)ruthenium(I) dimer ***I*-4**. In most cases, varying amounts of ***I*-4**, whose formation was already inferred as deactivation pathway in previous studies,[10b] could be detected by NMR in solution after catalysis. The formation of ***I*-4** under the conditions of hydrogen transfer could be studied in separate experiments: Starting from complex **I-1** the ruthenium-dihydride species **I-2** was generated in THF under H_2 pressure in a high-pressure NMR tube. Addition of benzaldehyde to this reaction solution at 80 °C resulted in reduction to benzyl alcohol and formation of the ruthenium(I) dimer ***I*-4**, disclosing a comproportionation reaction as possible basis for the formation of ***I*-4**.[20] The inactivity of ***I*-4** in catalytic reactions was confirmed in control experiments.

The formation of ***I*-4** appears to be a general deactivation mechanism for Ru-Triphos catalyst systems, but no correlation between the amount present at the end of reaction and the substrate dependence of the performance of **I-1** could be deduced from these investigations. In contrast, the amount of the dihydridocarbonyl(triphos)ruthenium(II) complex **I-3**,[14] the second major species detected in the deactivation mechanism, is correlated to the rate of decarbonylation of the respective reactive intermediates during the catalytic cycle,[21] providing a plausible explanation for the interdependence of the catalytic performance and the substrate structure. As previous studies had shown that complex **I-3** can be used to generate an active hydrogenation species under acidic

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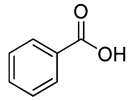
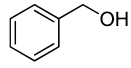
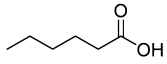
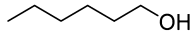
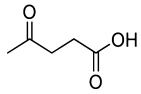
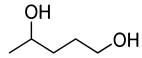
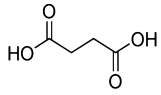
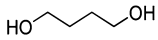
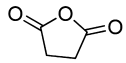
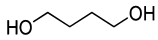
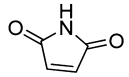
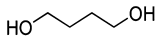
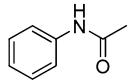
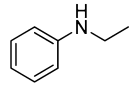
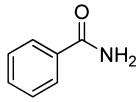
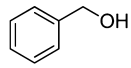
Table 3. Hydrogenation of Carboxylic Acids and Their Anhydride, Amide and Imide Derivatives Using Complex I-1 As Precursor under Additive-Free Conditions[a]

Entry	Substrate	Product	Time [h]	Temperature [°C]	Conversion [%]	Selectivity [%]
1[b]			24	220	93	95
2			16	195	50	98
3			16	140	99	99
4			24	195	92	92
5			24	195	99	96
6			24	160	99	86
7			16	160	99	99
8			16	160	51	99

[a]Reaction conditions: substrate (1 mmol), [Ru(Triphos)(TMM)] **I-1** (0.02 mmol), dioxane (1 mL), $p(H_2)$ = 50 bar. Conversion and selectivity determined by ^{1}H NMR using mesitylene as internal standard. [b]**I-1** (0.01 mmol).

conditions,[9] the controlled activation of **I-1** with stoichiometric amounts of acidic co-catalysts was assessed for benzamide and other substrates, where the neutral conditions proved unsuccessful. The results are summarized in Table 4. Using $HNTf_2$ as co-catalyst in a ratio of 2:3 relative to the precursor **I-1**, full conversion of benzamide to the product dibenzyl amine could be achieved after 16 h reaction time at 160 °C (Table 4, entry 1). Using the co-catalyst demonstrates that the acidic additive is required to avoid the formation or to reactivate the species **I-3**, resulting in the mechanism based on the cationic ruthenium complex. Consequently, with these reaction conditions the selective formation of dibenzyl amine is achieved, in contrast to the selective formation of benzyl alcohol in the absence of acid. Under identical reaction conditions, butyramide was also converted to dibutylamine with high selectivity, corroborating the effectiveness the ruthenium catalyst in the presence of acidic additives for the hydrogenation of primary amides (Table 4, entry 2).[10b] Similarly, dimethyl carbonate could not be hydrogenated using **I-1** without acid additive and reactions with the isolated complex **I-3** in a catalytic experiment confirmed again its inactivity under these conditions (Table 4, entries 3 and 4). However, complete transformation to methanol was enabled by the addition of 1.5 equiv of $HNTf_2$ relative to **I-3** (Table 4, entry 5). Consequently, the addition of $HNTf_2$ as co-catalyst to **I-1** resulted also in the transformation of dimethyl carbonate to methanol in 94% yield (Table 4, entry 6). Notably, carrying out the reaction in neat dimethylcarbonate afforded the formation of methanol with a TON of 6219 after 16 h.[22] The same behavior was observed for propylene carbonate, which could be converted to 1,2-propane diol and methanol only in the presence of acid additive (Table 4, entry 7 and 8).[23] These observations are in line with the catalytic activity of **I-1** in the hydrogenation of formates and carbon dioxide in the presence of $HNTf_2$.[12]

Finally, the influence of the acid co-catalyst to control the deactivation via decarbonylation was also found to be decisive in the hydrogenation of urea derivatives. Using *N,N*-

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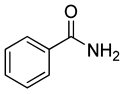
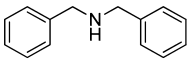
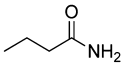
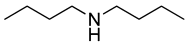
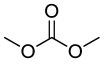
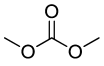
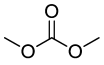
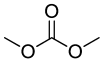
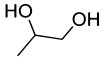
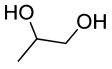
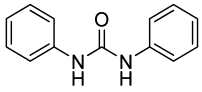
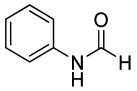
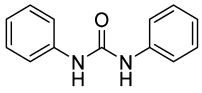
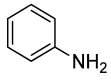
Table 4. Influence of Acidic Co-Catalysts on the Hydrogenation of Primary Amides and Carbonic Acid Derivatives[a]

Entry	Substrate	Product	Catalyst	$HNTf_2$ [eq]	Conversion [%]	Selectivity [%]
1[b]			**I-1** (2.0 mol%)	1.5	99	98
2[b]			**I-1** (2.0 mol%)	1.5	99	99
3		H_3C-OH	**I-1** (1.0 mol%)	-	1	99
4		H_3C-OH	**I-3** (1.0 mol%)	-	0	0
5		H_3C-OH	**I-3** (1.0 mol%)	1.5	99	60
6		H_3C-OH	**I-1** (1.0 mol%)	1.5	99	94
7			**I-1** (1.0 mol%)	-	0	0
8			**I-1** (1.0 mol%)	1.5	99	99
9[c]			**I-1** (1.5 mol%)	-	74	99[d]
10[e]			**I-1** (1.5 mol%)	1.5	98	66[f]

[a]Reaction conditions: substrate (1 mmol), [Ru(Triphos)(TMM)] **I-1** (0.01 mmol), acid additive (0.015 mmol), dioxane (1 mL), T = 140 °C, $p(H_2)$ = 50 bar, t = 16 h. Conversion and selectivity determined by ^{1}H NMR using mesitylene as internal standard. [b]160 °C. [c]72 h, 2 mL THF. [d]75% of aniline was observed as coupled product. [e]24 h, 2 mL THF. [f]Methyl aniline (24%), dimethyl aniline (8%), and methanol were observed as byproducts.

diphenylurea as substrate, the unprecedented hydrogenolysis of only one C−N bond to give aniline in 75%, and *N*-phenyl formamide in 74% yield was observed with **I-1** in absence of acid (Table 4, entry 9). At this stage, the carbonyl complex **I-3** was again the only complex observable by ^{31}P NMR in solution. This indicates that decarbonylation of *N*-phenylformamide prevents the further reduction of this primary product, providing a method for selective C−N cleavage in urea derivatives.[24] The respective hydrogenation of urea derivatives to the corresponding amines and methanol was achieved for the first time by Milstein and co-workers.[25] In line with our findings, the addition of 1.5 mol % $HNTf_2$ as co-catalyst afforded complete hydrogenation of *N*,*N*-diphenylurea to give aniline in 66% yield, together with methyl and dimethyl aniline as side products (Table 4, entry 10). The mechanism for the unexpected formation of dimethyl aniline is currently under investigation, but a construction of the methyl group involving methanol from the reduction of the urea derivative seems a likely possibility.

SUMMARY AND CONCLUSION

In summary, the molecularly defined [Ru(Triphos)(TMM)] complex **I-1** could be established as an efficient hydrogenation catalyst for a broad range of challenging functionalities encompassing carboxylic esters, amides, carboxylic acids, carbonates, and urea derivatives (Scheme 4). This unique substrate scope could be explored on the basis of a detailed understanding of the catalytic mechanism based on spectroscopic investigations and DFT calculations. The key control factor was found to result from the activation procedure, treating the catalyst precursor **I-1** with hydrogen either under neutral conditions or in the presence of catalytic amounts of acid as additive.

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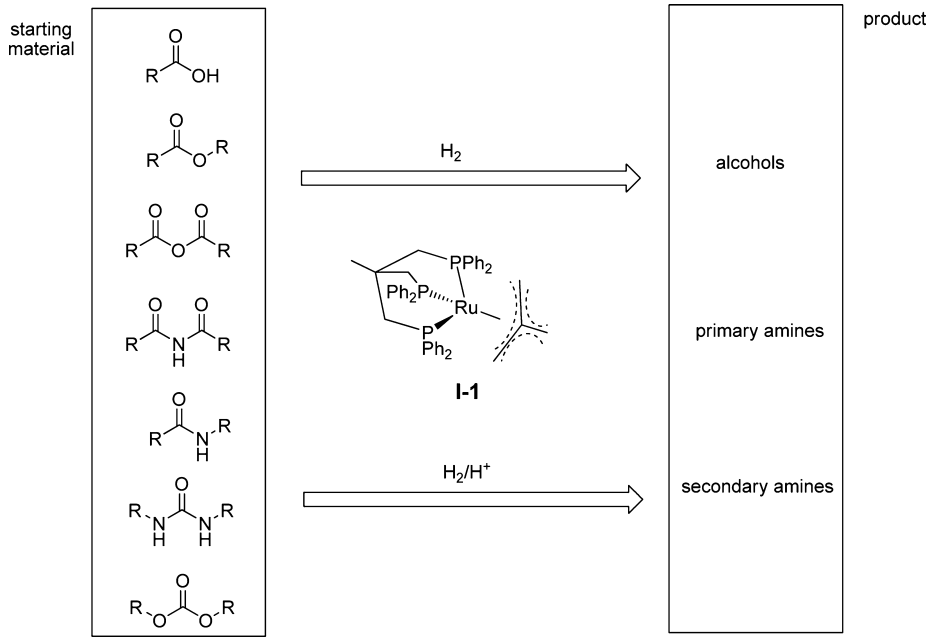
Scheme 4. [Ru(Triphos)(TMM)] As Catalyst Precursor for Challenging Hydrogenations: Molecular Control over Selectivity and Substrate Scope by Choosing the Neutral or Cationic Catalytic Cycle



Multinuclear NMR spectroscopic studies demonstrated clear access to the neutral species [Ru(Triphos)(Solvent)H_2] **I-2** upon activation of [Ru(Triphos)(TMM)] **I-1** with molecular hydrogen. DFT investigations confirmed low-energy pathways for hydrogen transfer to C═O groups in the coordination sphere of this active species, coupled with external C−O bond cleavage reactions. Consequently, using complex **I-1** as precatalyst without further additives enables the selective hydrogenation of carboxylic esters, acids, anhydrides, and selected amides.

However, complex **I-2** is also very active for decarbonylation, leading to the carbonyl complex [Ru(Triphos)(CO)H_2] **I-3**. As CO blocks the coordination site required for the neutral hydrogenation mechanism, this represents one deactivation pathway severely limiting the substrate scope under these conditions. However, the formation of **I-3** can be suppressed (or **I-3** can be reactivated) in the presence of catalytic amounts of acids comprising non-coordinating anions such as $HNTf_2$. Adding this acid during the activation with molecular hydrogen leads to the cationic species [Ru(Triphos)(Solvent)(H)-(H_2)]$^+$.[9] Although the corresponding cationic cycle shows higher overall barriers of activation, it provides a powerful hydrogenation pathway at higher temperatures, allowing reduction of primary amides, ureas, and carbonates with excellent yields.

In conclusion, these results demonstrate that the Triphos-Ru-fragment can be controlled to enter into a neutral or cationic catalytic cycle starting from readily available complex **I-3** as a single molecular precursor. This provides a unique platform for the rational selection of reaction conditions for the selective hydrogenation of challenging functional groups and opens novel synthetic pathways for the utilization of renewable carbon sources.

■ ASSOCIATED CONTENT

Supporting Information

Detailed experimental description and analytical data for the synthesis and characterization of metal precursors and intermediates as well as for catalytic procedures and also a detailed description of the computational studies including Cartesian coordinates of the stationary points. The information is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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