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Lewis Acid Promoted Ruthenium(II)-Catalyzed Etherifications by Selective Hydrogenation of Carboxylic Acids/Esters**

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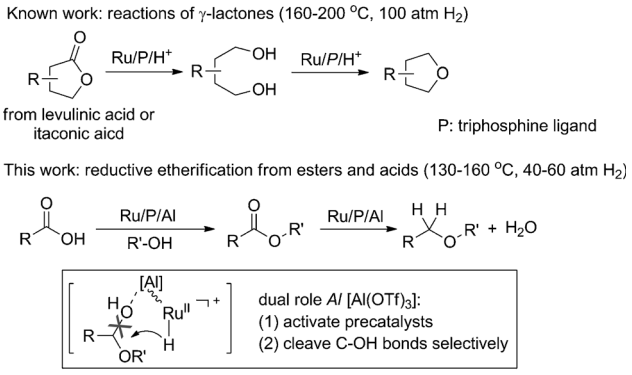
Abstract: *Ethers are of fundamental importance in organic chemistry and they are an integral part of valuable flavors, fragrances, and numerous bioactive compounds. In general, the reduction of esters constitutes the most straightforward preparation of ethers. Unfortunately, this transformation requires large amounts of metal hydrides. Presented herein is a bifunctional catalyst system, consisting of Ru/phosphine complex and aluminum triflate, which allows selective synthesis of ethers by hydrogenation of esters or carboxylic acids. Different lactones were reduced in good yields to the desired products. Even challenging aromatic and aliphatic esters were reduced to the desired products. Notably, the in situ formed catalyst can be reused several times without any significant loss of activity.*

Ethers represent an important class of compounds in nature and play a pivotal role in biochemistry. In addition, they are used as solvents, fuels, fragrances, pharmaceuticals, insecticides, and fumigants in the bulk and fine-chemical industries. To date, the general strategy for constructing ethers strongly relies on either the Williamson reaction, which was discovered in 1850, or the Ullmann ether synthesis.[1] Both methods suffer from drawbacks such as the use of a strong base and organohalide substrates. From an environmental and economic point of view, modern organic synthesis has to avoid the formation of stoichiometric amounts of problematic waste products.[2] However, for a benign preparation of ethers novel methodologies are rather underdeveloped despite the fast development of organic synthesis.[3] Catalytic hydrosilylation of esters to ethers is an important tool in this respect. The groups of Sakai[4a] and Beller,[4b] as well as Biermann et al.[4c] reported the direct reduction of esters to ethers using hydrosilanes. One exception is the catalytic preparation of ethers from alcohols promoted by Lewis acids. Recently, Corma and Renz reported a solid Lewis acid catalyzed (Sn- and Zr-containing silicate molecular sieves) preparation of a variety of ethers.[5a] Furthermore, Cuenca et al. made use of gold catalysis which displayed a relatively broad substrate scope.[5b]

An attractive alternative for the synthesis of ethers is the direct reduction of esters considering their easy access. So far, hydride reagents such as lithium aluminium hydride and hydrosilanes are known reductants for this purpose. As an instructive example, chemists at Pfizer developed the synthesis of an isochroman as the key fragment for a neurokinin-1 receptor antagonist CJ-17,493 through consecutive reductions of lactone→hemiacetal→ether using $NaBH_4$ and Et_3SiH.[6] Considering the (over)stoichiometric waste generation and complicated workup procedures accompanying such reductions, catalytic hydrogenation provides a much more benign and economic route.[7] Unfortunately, hydrogenation of carboxylic acid derivatives remains highly challenging. In fact, this area is considered as one of the grand challenges for organic synthesis.[8] Though several methods have been developed for the hydrogenation of carbonyl compounds to alcohols and/or alkanes, the deoxygenative hydrogenation of esters to ethers remains scarcely exploited.[9] In fact, only the hydrogenation of γ-lactones (derived from reductive condensation of levulinic acid or itaconic acid) was reported (Scheme 1).[9b] To develop a general reductive etherification methodology, efficient control of reactivity for reduction of the inert ester carbonyl group and fine control of the hydrogenolysis of the C–OH versus C–OR bond is crucial. Meanwhile, the active catalytic system has to be tolerant of water.



Scheme 1. Homogeneous catalytic hydrogenation of esters to ethers. Tf = trifluoromethanesulfonyl.

In the last decade enormous progress has been achieved for the reduction of esters to alcohols either using active reductants such as silanes,[10] or transition metal catalyzed hydrogenations.[11] In the latter area the pioneering work of Grey et al. and the group of Elsevier made use of an anionic ruthenium hydride complex or ruthenium complexes con-

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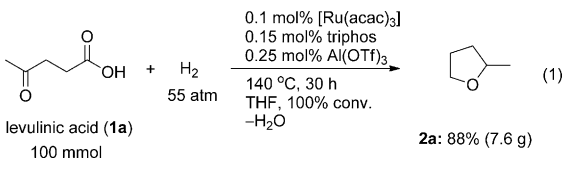
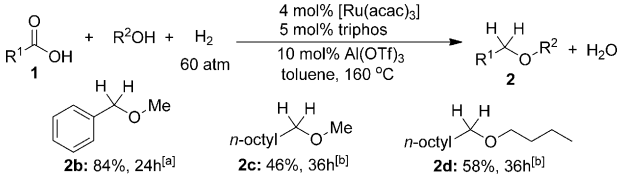
taining a tripodal phosphine ligand.[12] Later on, significant improvements regarding efficiency and functional-group tolerance of ester reduction have been achieved.[13] In 2006, a general catalytic hydrogenation of esters was developed by Milstein and co-workers by using a defined Ru/PNN-type pincer ligand complex.[14] In addition, Saudan and co-workers demonstrated that a Ru/bis(aminophosphine) complex allows efficient hydrogenation of a broad range of esters in the presence of alkali base additives.[15] More recently, new ruthenium catalysts with pincer ligands were used in this area by researchers in Takasago[16] and the group of Gusev.[17] In continuation of our previous efforts towards ester reduction,[18] our idea of converting esters into ethers was initially inspired by the successful application of Lewis acids for cleavage of C–O bonds to promote reactions such as S_N1-type amination of alcohols, oxygenolysis of alcohols, and tertiary ethers to alkenes etc.[19] Though oxophilic aluminum salts constitute an easy-to-envisage choice for selective cleavage of the C–OH bond during hydrogenations of esters to ethers, unfortunately all ester hydrogenation systems mentioned above have not been shown to be compatible with Lewis acids. Herein, we report the first catalytic deoxygenative hydrogenation of esters to the corresponding ethers by the combined use of a specific ruthenium-phosphine catalyst and Lewis acids such as $Al(OTf)_3$ or $Hf(OTf)_4$.

Based on our recent work on reductive amination of carbon dioxide,[20] we performed the hydrogenation of levulinic acid (**1a**) in the presence of $[Ru(acac)_3]$ (acac = acetylacetonate), $CH_3C(CH_2PPh_2)_3$ (triphos), and lithium halides. However, after extensive screening no desired reaction took place and in all the cases the hydrogenation reactivity was totally suppressed (see Table S1 in the Supporting Information).[21] Meanwhile, aluminium-based Lewis acids, which have been proven to control heterogeneous hydrogenations of phenol to cyclohexanone through specific Al-O interactions, were tested.[22] To our delight, $Al(OTf)_3$ was found as an active cocatalyst and improved the efficiency of the benchmark 2-MeTHF synthesis reaction from levulinic acid following sequential ketone reduction/intramolecular condensation/deoxygenative hydrogenation reactions [Eq. (1); acac = acetylacetonate, THF = tetrahydrofuran]. Compared to the reported method (160 °C, 100 atm of H_2), milder reaction conditions were used.[9b] The reaction on a 100 mmol scale provided 2-MeTHF (7.6 g) in 88 % yield when using 0.1 mol % of the ruthenium catalyst formed in situ from $[Ru(acac)_3]$ and triphos, without special precautions (use of commercial reagents in the absence of inert gas).



After intramolecular etherification of acid and ketone groups was achieved using the in situ formed Ru/triphos complex and $Al(OTf)_3$, we were interested in investigating the more challenging intermolecular version of this reaction. The direct synthesis of ethers by intermolecular reductive coupling of carboxylic acids and alcohols using H_2 as the reductant is a neglected challenge, although it constitutes an ideal alternative to the known reductive etherifications from ketones or aldehydes.[23] To the best of our knowledge such reactions have not been reported yet. Gratifyingly, efficient conversion of carboxylic acids and primary alcohols into the corresponding esters was achieved under similar reaction conditions using toluene as the solvent. In all cases, the desired reductive coupling reactions proceeded well with full conversion and good yields of the expected products (Scheme 2, 46–84 %). Aliphatic acids are more difficult

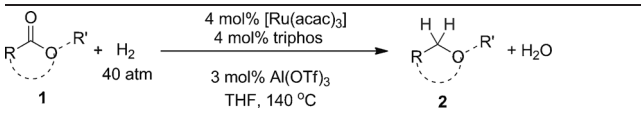


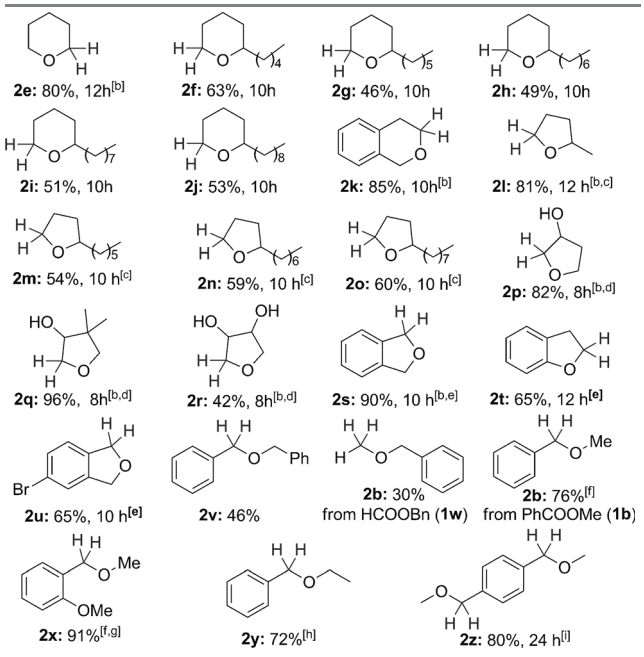
Scheme 2. Direct reductive coupling of carboxylic acids with primary alcohols. Reaction conditions: 0.5 mmol carboxylic acid, 10 mmol alcohol. Yields were determined by GC and ^{1}H NMR spectroscopy using *n*-hexadecane and anisole, respectively, as the internal standard. [a] 2 mL toluene as the solvent. [b] 10 mL toluene as the solvent.

substrates compared to the aromatic ones and longer reaction times are required to get moderate yields. Lower yields (< 20 %) of ether products were obtained when secondary alcohols were used, probably because of the difficulty of etherification step and/or the instability of the products in the presence of water.

Since the etherifications described above should occur via the corresponding ester intermediates, the general applicability of this methodology was investigated for the synthesis of ethers through hydrogenation of esters. Various aliphatic and aromatic lactones, linear esters, and one diester were hydrogenated in the presence of the dual Ru-Al catalyst system (Table 1). Notably, high conversions and good yields (GC) were obtained for all the reactions in Table 1. In general, the reactivity order was observed to be aliphatic γ-lactones > aliphatic δ-lactones > aromatic γ-lactones ⩾ linear esters. In some cases, because of the volatile character of the products the yields of the isolated compounds were lower than expected. The reduction of γ-lactones and δ-lactones occurred smoothly and gave **2e–o** in 46–85 % yield. Notably, the reduction of more sensitive α-hydroxy lactones to hydroxy tetrahydrofurans proceeded well at 130 °C with moderate to very good yields (**2p–r**). At higher temperature, also phthalides and coumaranone can be reduced to the desired products (**2s–u**). This novel methodology can also be employed with more challenging acyclic esters (**1v** and **1w**) and mediocre yields were obtained with high conversions (30–46 % yield). The main by-products (mainly different alcohols) were generated from side reactions with THF, and were caused by undesired nucleophiles generated by C–O bond cleavage of THF. It is worth noting that unsymmetrical acyclic methyl and ethyl ethers can be obtained with much higher yields by addition of extra methanol or ethanol to the

Table 1: Hydrogenation of esters to ethers.



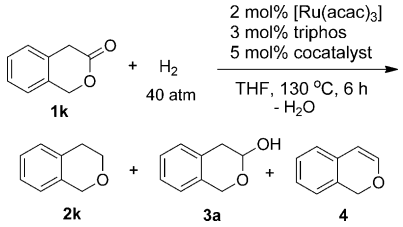


[a] Reaction conditions (**1e–u**): 0.5 mmol **1**, 4 mol% [Ru(acac)$_3$], 4 mol% triphos, 3 mol% Al(OTf)$_3$, 40 atm H_2, 2 mL THF, 140°C; (**1b,1v–z**): 0.5 mmol **1**, 2 mL THF, 4 mol% [Ru(acac)$_3$], 5 mol% triphos, 10 mol% Al(OTf)$_3$, 60 atm H_2, 160°C, 12 h. The yields are those of isolated products. [b] Yields determined by GC using *n*-hexadecane as the internal standard. [c] With 4 mol% [Ru(acac)$_3$], 4.3 mol% triphos and 5 mol% Al(OTf)$_3$. [d] With 2 mol% [Ru(acac)$_3$], 3 mol% triphos and 5 mol% Al(OTf)$_3$ at 130°C. [e] with 4 mol% [Ru(acac)$_3$], 6 mol% triphos, 10 mol% Al(OTf)$_3$ and 60 atm H_2 at 160°C. [f] 10 mmol methanol was added, toluene as the solvent. [g] 1 mol% [Ru(acac)$_3$], 2 mol% triphos, 2.5 mol% Al(OTf)$_3$, 40 atm H_2, 130°C. [h] 10 mmol ethanol was added, toluene as the solvent. [i] 20 mmol methanol was added.

hydrogenations of **1b** and **1x–z**, respectively. Hence, the desired products were achieved in yields ranging from 72 to 91% (Table 1).

To understand the reaction procedure and the role of Al(OTf)$_3$, we studied the mechanism using **1k** as the substrate for control experiments. Brønsted acids are known as important promoters in Ru/triphos-catalyzed reductions and were tested at first.[24–25] Notably, no reactivity was observed when MSA (methanesulfonic acid) or diphenylphosphate was used (Table 2, entries 2 and 3), even though after the reaction significant amounts of a major hydridic ruthenium species was detected by ^{1}H NMR spectroscopy given the signal at around $\delta = -6.50$ ppm. When using more acidic triflic acid, 87% conversion and 13% yield of **2k** were obtained with the major by-product as 1*H*-isochromene (**4**; entry 4). Meanwhile, the crucial influence of the Lewis acid cocatalyst was demonstrated and a reduced amount of Al(OTf)$_3$ drastically decreased the reactivity with hemiacetal compound **3a** as the main by-product (see Table S1). The triflate anion proved to be vital because the use of $AlCl_3$ or aluminum methanesulfonate resulted in no reactivity at all (entries 5 and 6). Nevertheless, some reactivity could be obtained when several other M(OTf)$_n$-type salt additives (M = La, Hf, Sc) were applied (see Table S1). When the reaction was reduced to 4 hours, **2k** was obtained in 55% yield with significant amounts of hemiacetal **3a**, an important intermediate to **2k** (entries 7 and 8).

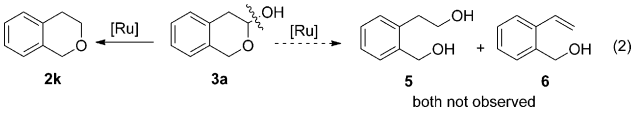
Table 2: Additive effect for hydrogenation of **1k**.[a]



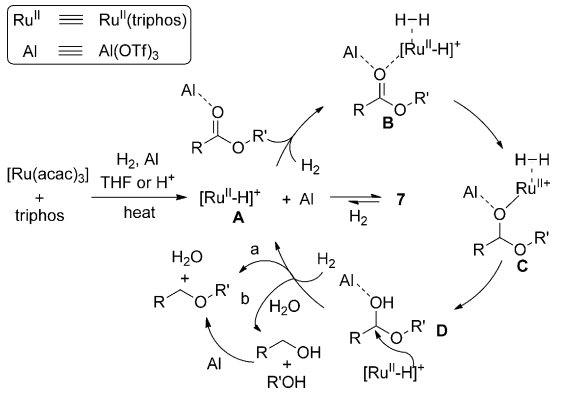
Entry	Additive	Conv. [%]	**2k** Yield [%]	**3a** Yield [%]	**4** Yield [%]
1	–	<1	0	0	0
2	MSA	<1	0	0	0
3	diphenylphosphate	<1	0	0	0
4	TfOH	87	13	0	45
5	$AlCl_3$	<1	0	0	0
6	Al(CH$_3$SO$_3$)$_3$	<1	0	0	0
7	Al(OTf)$_3$	99	83	0	1
8[b]	Al(OTf)$_3$	78	55	20	4

[a] Reaction conditions: 0.5 mmol **1k**, catalyst (2 mol%), ligand (3 mol%), 2 mL THF, 130°C, 6 h. Conversions and yields were determined by GC using *n*-hexadecane as an internal standard. [b] Reaction time is 4 h.

Formation of either the diol **5** or the related **6** was not observed in the reactions shown in entries 7 and 8 of Table 2, and it implies that ether products were generated through selective hydrogenolysis of hemiacetal intermediate **3a** [Eq. (2)]. However, the pathway proceeding through intramolecular condensation of diols to the corresponding ether cannot be excluded based on the results of control experiments (see Scheme S3 in the Supporting Information).[21]



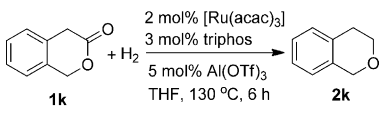
A preliminary mechanism for the etherifications by hydrogenation of esters is proposed in Scheme 3. Firstly, hydrogenative loss of the 2,4-pentanedionate (acac) ligand leads to the active cationic ruthenium(II) hydride species **A** in the presence of protons and aluminum triflate. The reduction of the ester to the hemiacetal intermediate **D** proceeds by migratory insertion of the coordinated carbonyl bond (in the transition-state **B**) into the Ru–H bond, and then protonation of the alkoxide anion with heterocleavage of the coordinated H_2 in **C**. The reduction of **D** follows two possible reaction pathways under the concerted catalysis of the Lewis acidic aluminum center and Ru–H of **A**: direct C–OH bond cleavage to form the ether product (a); C–OR′ bond cleavage



Scheme 3. Proposed reaction pathway.

by hydrolysis to form the alcohols being readily transformed to the same ether product (b).

During the reaction, there is a strong tendency to form the resting state species **7** (Scheme 3) which can be transformed back into the active species under heating conditions in the presence of H_2. The key role of the protons for activation of precatalyst was proven (Scheme 4). When water was added



Solvent	2k Yield [%]	solvent	2k Yield [%]
THF	83	toluene	n.r.
THF/H_2O[a]	82	toluene/H_2O[a]	67
THF/M.S.[b]	40	toluene/MeOH[a]	34

Scheme 4. Control experiments. Reaction conditions: 0.5 mmol **1k**, 2 mL THF. Yields determined by GC using *n*-hexadecane as the standard. [a] 5 mmol water or methanol was added. [b] 20 mg 3 A molecular sieves (M.S.) were added.

under otherwise standard conditions almost no negative influence was detected (full conv.; 82% yield of **2k**), and much lower conversion (40% yield of **2k**) was obtained when molecular sieves were added. By using nonpolar toluene as the solvent, the catalyst could not be activated. In contrast, good reactivity was achieved after the addition of water or methanol to toluene (full conv.; 34–67% yield). Apparently, the (relatively) acidic protons played an important role in the formation of the active species.

To understand the role of $Al(OTf)_3$, NMR experiments were carried out for the reduction of δ-valerolactone (**1e**). NMR spectra were obtained in [D]THF in the presence of 1 atm H_2 after the hydrogenation reaction of **1e** (see Figures S1–S3 in the Supporting Information). One major species (**7** in Scheme 3) was formed in high yield (95%), thus showing a sharp singlet peak at $\delta = 39.8$ ppm in the ^{31}P NMR. No ligand exchange with THF was observed with **7** and no change occurred to its signal after keeping the NMR sample at room temperature for two days. Thus, the C_{3v}-symmetric **7** probably has a $[Ru_2(triphos)_2X_3]^+$-type structure but not a $[Ru(triphos)Z]^+$ one.[25,26] Notably, X as hydride was excluded and the corresponding signals were basically not seen in the ^1H NMR spectra.[27] This observation was confirmed by IR, where no peak was found in the region 2200–1800 cm^{-1}, which is typical for Ru–H signals. In addition, in the ^{27}Al NMR spectrum a new peak for the Lewis acid at $\delta =$ 64.3 ppm was also observed. Nevertheless, this major species should represent the resting state in the catalytic cycle because when an extra portion of **1e** was added to this mixture, catalytic reduction continued smoothly. This assertion was further tested by catalyst recycling studies.

After the above reaction of **1e** was accomplished, the mixture was placed under vacuum to remove all the volatile components, such as solvent, water, and the product. Then, substrate and new solvent were added to the autoclave containing the residue followed by pressurized hydrogen and heating. The full reactivity was almost retained and only slightly lower yields were obtained through the third run under the same reaction conditions.[21] Considering the crucial role of the proton source for catalyst activation, we propose that $Al(OTf)_3$ reacts with water (R = H) or an alcohol (ROH) to form an aluminate counterion such as $[(RO)Al(OTf)_3]^-$ with concomitant formation of the crucial acidic protons, which are important for the synergistic generation of the active cationic $[Ru\text{-}H]^+$ species.[28,29] This assertion is in agreement with previous reports on Brønsted acid promoted formation of a cationic $[Ru\text{-}H]^+$ species[30] and the crucial formation of an aluminate counterion in $Al(OTf)_3$-promoted palladium-catalyzed methoxycarbonylation reaction.[31]

Finally, the anion effect was examined in the absence or presence of Cl^- to support the assumption on the cationic hydridic ruthenium complex as the active species in Scheme 3. The use of a preformed ruthenium hydride complex [Ru(triphos)(CO)H_2] (**8**) rendered a smooth reaction of **1k** with a yield of 78% (see Table S1, entry 14). When starting from [Ru(2-methylallyl)$_2$(cod)], similar reactivity was obtained (81%; see Table S1, entry 13). Instead, the reactivity was totally inhibited in the presence of chloride anion when using $[Ru_2(triphos)_2Cl_3]Cl$ (**9**) or $[\{Ru(cymene)Cl_2\}_2]$ as the precursor.

In summary, we have demonstrated a general and efficient deoxygenative hydrogenation of esters to ethers. In the presence of readily available ruthenium precatalysts, triphos (or the molecularly defined complex **8**), and $Al(OTf)_3$ as the cocatalyst, various aromatic and aliphatic lactones are transformed into the desired cyclic ethers with good to excellent yields. In addition, linear esters provide the corresponding ethers in the presence of this dual catalyst system. Preliminary mechanistic studies reveal the crucial role of the Lewis acid and water for activation of the catalyst in toluene and the novel selective C–OH bond cleavage of hemiacetal intermediates. Notably, for the first time the straightforward reductive coupling of carboxylic acids with alcohols to give ethers was also realized. The applicability of this new etherification methodology is demonstrated by recycling the robust in situ formed catalyst without significant loss of activity and in the synthesis of the industrially relevant 2-MeTHF from renewable levulinic acid in 88% yield.

Keywords: ethers · homogeneous catalysis · hydrogenation · Lewis acids · ruthenium

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