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Inexpensive Ruthenium NNS-Complexes as efficient ester hydrogenation catalyst with high C=O vs. C=C selectivities

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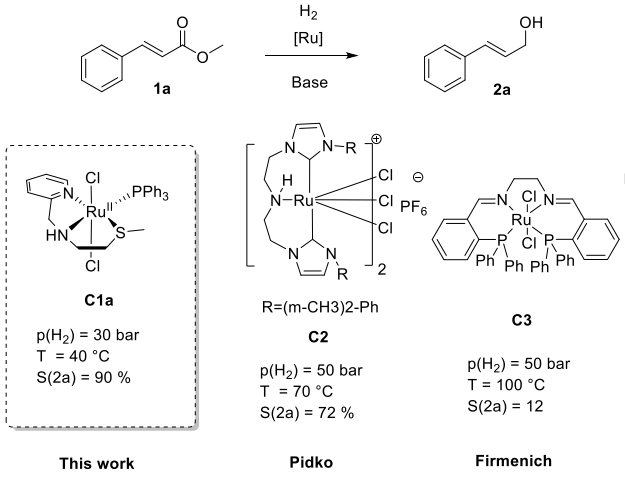
Abstract: Ru(NNS)(PPh_3)Cl_2 (NNS = 2-(methylthio)-N-(pyridin-2-yl-methyl)ethan-1-amine) was employed in the hydrogenation of α,β-unsaturated esters, reaching selectivities for the allylic alcohol up to 95% in the hydrogenation of iso-butylcinnamate. In addition, several ester substrates were hydrogenated with catalyst loadings as low as 0.05 mol%. Surprisingly, selectivity of the hydrogenation of the C=O *vs* the C=C bonds strongly depends on the solvent.

Keywords: ester hydrogenation; ruthenium; S-ligands; allylic compounds; chemoselectivity

Introduction

Interest in the homogeneous hydrogenation of carboxylic acid esters has grown vastly in the past decade[1]. Most of the reported catalysts are sophisticated complexes based on ruthenium[1a, 2], and more recently also based on iron[3], cobalt[4] or manganese[5]. These catalysts now reach rates which vastly exceed those obtained by heterogeneous catalysts at much lower temperatures. Although manganese and iron are more earth-abundant transition metals than ruthenium, these catalysts have the drawback that, most of the existing catalysts rely on non-symmetrical phosphine ligands, which can make the ligand more expensive than the metal employed [2a-c, 3, 5a, 6]. This cost aspect was recently addressed by the development of sulfur containing SNS-[7] and NNS-pincer[8] ligands although thus far these ligands have proven effective only with ruthenium and iridium, the resulting complexes are air stable and the ligands easily obtained by simple nucleophilic substitution or condensation reactions. However, despite the huge development of the field of homogenous hydrogenation, selective hydrogenation of the carbonyl group in α,β-unsaturated esters still represents a challenge[9].

To the best of our knowledge, only two complexes have been reported which enable this transformation, however, with only moderate selectivity towards the unsaturated alcohol, utilizing methyl cinnamate (1a) as substrate (Scheme 1)[10]

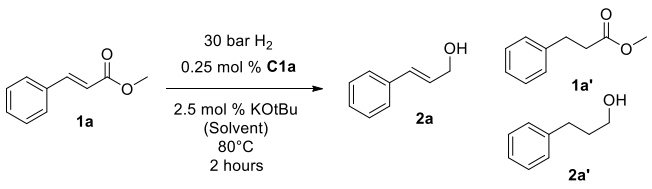


Scheme 1. Selectivities in the hydrogenation of methyl cinnamate (**1a**) towards cinnamyl alcohol (**2a**) with different ruthenium complexes.

Results and Discussion

Recently, we reported on the development of a class of ruthenium NNS-pincer complexes which showed high selectivity in the hydrogenation of unsaturated aldehydes and ketones to the corresponding unsaturated alcohols[11]. These findings encouraged us to employ complex **C1a** (Scheme 1) in the hydrogenation of methyl cinnamate (**1a**). As it is well known that the solvent polarity has a major effect on olefin hydrogenation,[12] we decided to perform a

careful solvent screening. In addition to the desired product **2a** we also monitored formation of the alkene hydrogenation product **1a'** as well as the saturated alcohol **2a'** using GC. The reaction conditions as well as the products monitored with GC are shown in scheme 2. The results of this screening are shown in figure 1.



Scheme 2: Reaction conditions in the solvent screening and the products monitored by GC. c(**1a**) = 0.5 mol L^{-1}.

Toluene, THF, MeOH and n-heptane were investigated first, as they represent typical π-polarizable, aprotic-polar protic, and apolar solvents. The reaction in THF resulted in only 11% conversion, mainly towards the undesired saturated ester 1a'. In methanol, 95% conversion with high selectivity to 1a' (92% yield) was observed. This is in line with studies about the solvent effect in homogenous hydrogenation of olefins, in which methanol or THF/methanol mixtures are considered the most effective solvents. Fortunately, the application of toluene or n-heptane shifted the selectivity towards the desired allyl alcohol 2a. In toluene, maximum conversion and yield were observed under the given reaction conditions (X=99%, Y(2a)=72%). The reproducibility in heptane was compromised by the low solubility of C1a in the solvent at room temperature. Since methanol had the effect of switching the selectivity from carbonyl to olefin hydrogenation, other alcohols other alcohols were investigated as solvents (Figure 1). Inevitably, trans-esterification of the starting material 1a with the alcoholic solvent occurred in all cases, and was most dominant in the presence of the linear alcohols EtOH and 1-hexanol. Transesterification of methyl cinnamate 1c with the product alcohol 2c was also observed. In the case of cyclohexanol and tBuOH, only poor conversion of the starting material 1a and no formation of the unsaturated alcohol 2a was observed. It was suspected that a different catalytic species formed in methanol, which exhibits a higher activity towards olefin hydrogenation. It is well known that ruthenium pincer complexes can dehydrogenate methanol to carbon monoxide under basic conditions[13]. The generated CO then binds to the ruthenium centre and can lower the activity of the complex for ester hydrogenation, as Gusev et. al. demonstrated by exchanging triphenyl phosphine ligands with CO in their SNS complexes[7a]. To test this hypothesis, C1a was dissolved in methanol together with 2.0 eq. KOtBu, which led to the formation of various ruthenium hydride species. (See ESI). Unfortunately, the number of different species and their labile nature made it impossible to further characterize them. Another reason for the altered reactivity in methanol could be the lability of the sulfur moiety which might be exchanged by small nucleophiles like methanolate. To get insight into this,

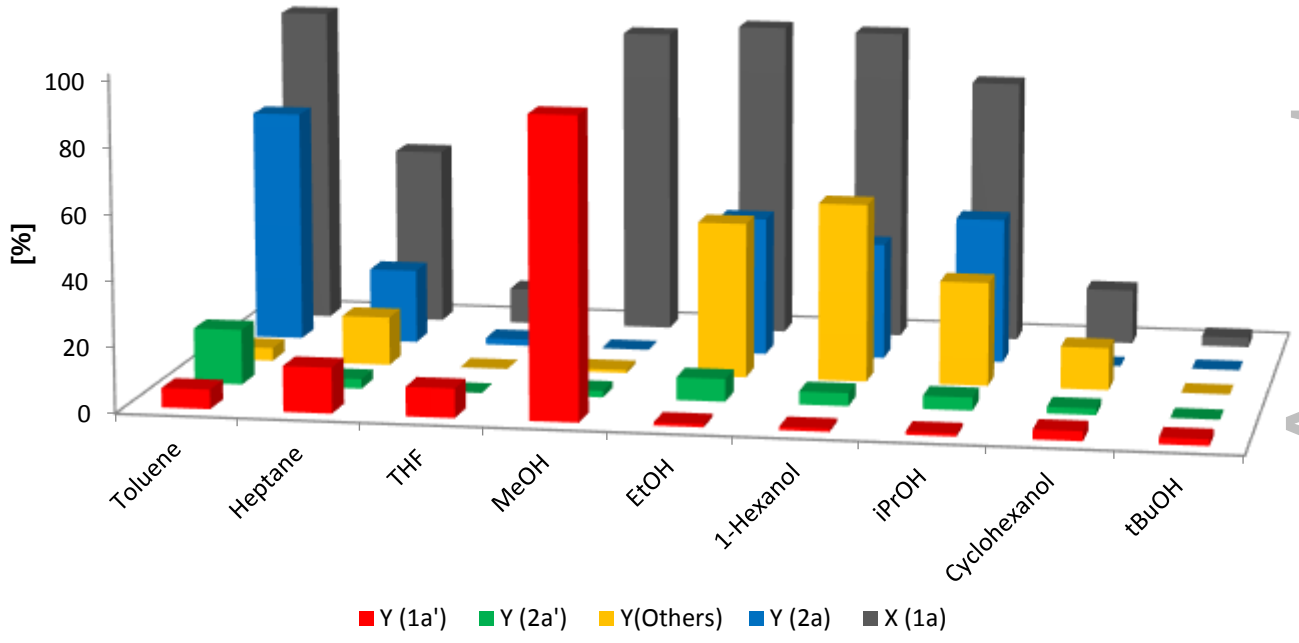


Figure 1: Effect of different solvents on product distribution in the hydrogenation of **1a**. Conversion (X) and Yields (Y) were determined by GC with *n*-dodecane as internal standard. Reaction conditions: 30 bar H_2, 0.25 mol % **C1a,** 2.5 mol % KO*t*Bu, T = 80°C, c(**1a**) = 0.5 mol L^{-1}, t = 2 h.

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complex **C1b** was synthesized, bearing a tert-butyl group on the sulfur atom. Single crystals of both **C1a** and **C1b** were grown, and their structures determined by single crystal X-ray diffraction analysis (Figure 2). In both complexes the coordination geometry at the Ru atom is distorted octahedral. In **C1b** the Ru-S distance is slightly elongated in comparison to **C1a** (C1a: 2.3333(9), 2.3369(10) C1b: 2.3648(5) Å.

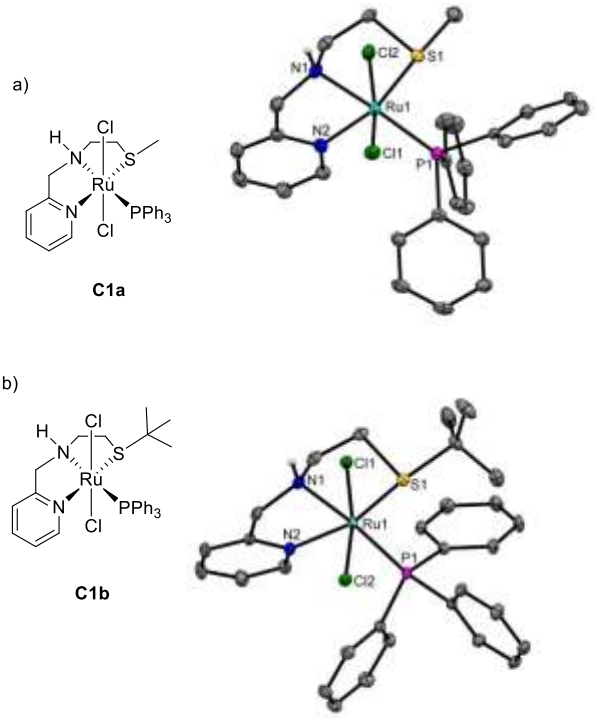
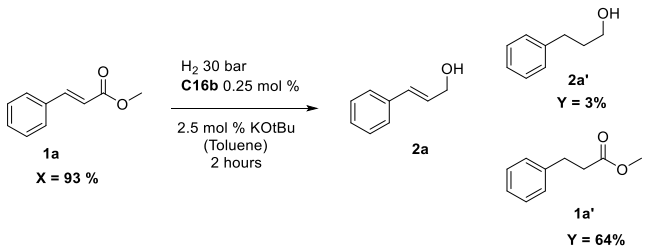


Figure 2: ORTEP diagrams of a) RuNNSMe (C1a), b) RuNNSt-Bu (C1b), with displacement ellipsoids drawn at 30% probability level, hydrogen atoms are omitted for clarity[14].

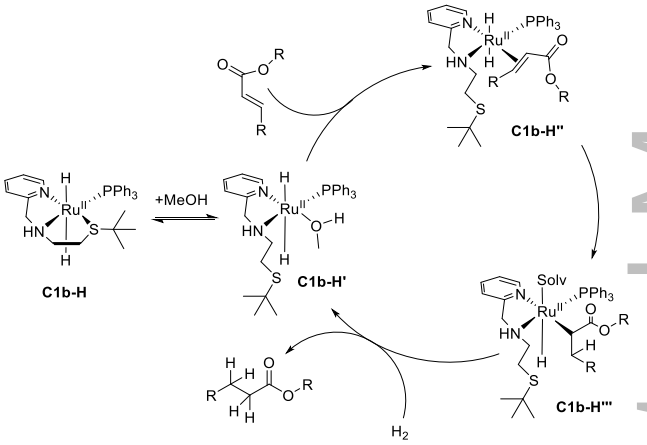
We then applied the two complexes **C1a** and **C1b** to the hydrogenation of methyl cinnamate (**1a**) in toluene under otherwise similar conditions.



Scheme 3: Results of the hydrogenation of **1a** with **C1b**

Indeed, in contrast to **C1a**, which delivered the unsaturated alcohol **2a** as main product (X=99%, Y(**2a**)=72%, see Figure 1), **C1b** showed a high selectivity towards the saturated ester **1a'** (X=93%, Y(**1a'**)=64%, scheme 3).

Presumably, complex **C1b** is activated through metal-ligand-cooperation, which is typical for pincer complexes bearing an amine functionality[1b, 15] and/or a benzylic position which can be deprotonated[2b]. This could lead to the ruthenium diyhdride species **C1b-H** (Scheme 4). Methanol, either formed by transesterification of KO*t*Bu with the substrate, or generated during hydrogenation of methyl esters, might then replace the sulfur moiety yielding species **C1b-H'**. This behaviour is also known in other pincer complexes[16]. Now, the methanol ligand can be replaced by the substrate coordinating to the metal centre in an η^2-binding mode (**C1b-H''**). This allows migratory insertion into the Ru-H bond (**C1b-H'''**). Reductive elimination of the product and subsequent oxidative addition of H_2 can form **C1b-H'**, closing the catalytic cycle. This resembles the mechanism reported for olefin hydrogenation with Wilkinson's catalyst.[17]



Scheme 4: Proposed mechanism for the hydrogenation of methyl cinnamate (**1a**) with complex **C1b** and the role of methanol in the catalytic cycle.

Since it is clear that the presence of methanol leads to poor selectivity we decided to perform further optimization experiments, with the homologuous isobutyl cinnamate (**1b**) at 100°C, 80°C and 40°C (See ESI). It should be noted that, especially at 100°C formation of the saturated ester **1b**' was observed as a side product (up to 12% area percentage,). At this temperature, a decrease in selectivity was observed. Still, this experiment underlines the remarkable activity of RuNNS^{Me} (**C1a**) in ester hydrogenation reactions, since 94% of the starting material had been converted in 10 minutes to a total yield of alcohols of 68%. Further, by lowering the temperature to 40°C, formation of product **2a** was delayed which might be

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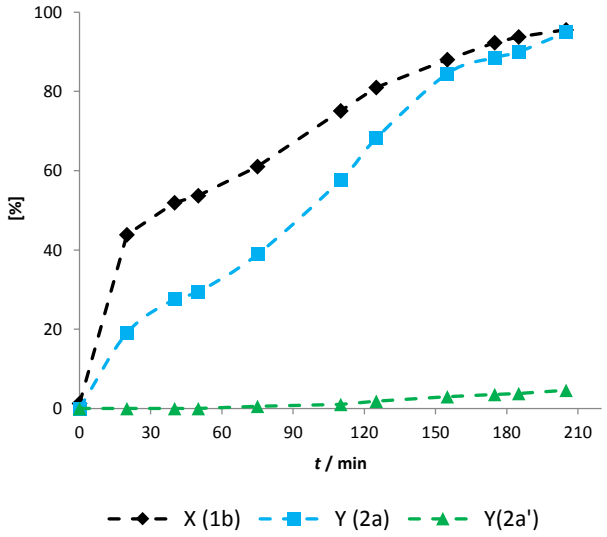
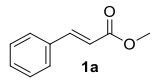
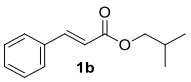
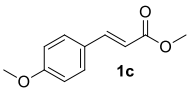
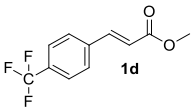
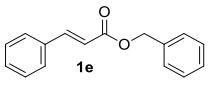
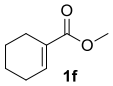


Figure 3: Reaction profile of the hydrogenation of isobutyl cinnamate (**1b**). Conditions: *c*(**1b**)= 0.5 mol l^{-1}; initial pressure 30 bar Hydrogen, 0.25 mol% **C1a**, 2.5 mol% KO*t*Bu in Toluene at 40 °C. Dashed lines serve only as guide for the eye and do not represent actual data points

Table 1: Hydrogenation of various α,β-unsaturated esters

Entry	Substrate	X [%]	Y [%]	(UA/SA)[e]
1		99%[a]	99%[a] 83%[b]	90:10[a] 90:10[c]
2		99%[a]	96%[a] 69%[b]	95:5[a] 93:7[c]
3		n.d.	63%[b]	87:13[c]
4		n.d.	60%[b,f]	85:15[c]
5		92%[a]	61%[a]	95:5[a]
6		77%[d]	63%[b]	100[c]

Reaction conditions: 40°C, 30 bar H_2. 15 mmol substrate in 30 ml toluene, 0.25 mol % **C1a,** 2.5 mol % KOtBu, reaction time 4h, despite entry 1 (16h) , [a] determined by GC, [b] Isolated yield of the combined product alcohols, [c] determined with NMR spectroscopy, [d] based on recovered starting material, [e] Ratio unsaturated (UA) saturated alcohol (SA), [f] 10 mmol in 10 ml toluene

due to a higher accumulation of transesterification products, which then lowers the TOF of the substrate **1b** via competition for the active catalytic species (Figure 3). After 205 minutes, the saturated alcohol **2a'** had formed in only 5% yield, whereas a yield of 95% of cinnamyl alcohol (**2a**) was measured via GC. Unfortunately, we were not able to further suppress the formation of the byproduct **2a'** by further lowering the temperature as the catalyst was not activated, and thus no conversion was observed at all. Lowering the catalyst concentration only increases reaction time but does not increase selectivity (see ESI for details). At 40°C, it was also possible to convert substrate **1a** to the alcohol **2a** (Table 1).The ratio between the unsaturated alcohol and the saturated by-product was 90:10. The best selectivity so far was achieved with the aforementioned isobutyl cinnamate **1b**. The mixture of alcohols was isolated in 70% yield. Unfortunately, we were not able to separate the unsaturated product **2a** due to its similar properties with **2a'**. The hydrogenation of linear aliphatic α,β-unsaturated esters unfortunately led to the formation of the saturated alcohol, which might indicate an electronic effect on product selectivity. Varying the substituents of the aromatic ring however, had only a minor effect on the selectivity, as 4-methoxy-methyl-cinnamate (**1c**) showed similar reactivity to **1a**. Exchanging the methoxy group with trifluoromethyl led to a slightly higher formation of the saturated alcohol. When the double bond was located in a ring, as in substrate **1f**, it was possible to isolate 63% of the pure allylic alcohol, although conversion was only 77%. In practice, it is quite easy to separate the allyl alcohol in good yield by distillation from the unsaturated ester if conversion is kept below 100%. The unconverted unsaturated ester could be returned to the hydrogenation reaction in a continuous process**.**

Since one of the major research areas in our group is the formation of platform chemicals from renewable resources[18], we were also in interested in the applicability of this catalyst to the hydrogenation of γ-valerolactone (**3a**) to 1,4-pentanediol (**4a**, Table 2, entry 1). 1,4-Pentanediol (**4a**) is a potential renewable building block in polymer chemistry, replacing petro-chemical derived diols[18b, 19]. Initially, we utilized a catalyst loading of 0.25mol% and isolated **4a** in 92% yield after 2 hours reaction time. It was also possible to perform the reaction at a 500 mmol scale in only 2 mL solvent at a catalyst loading as low as 0.05 mol%, yielding 91% of **4a**.

The acetate group is commonly used as protecting group in organic synthesis[20]. Entries 5 and 6 show that this hydrogenation is an efficient method for the deprotection of acetylated alcohols. This can be useful in cases where conventional hydrolysis is not feasible. We previously reported that the RuNNS catalyst selectively hydrogenates the aldehyde functionality in methyl 4-formylbenzoate in methanol[11]. Indeed, when this reaction was performed in toluene, both aldehyde and ester were reduced (entry 7). Interestingly, when the solvent was

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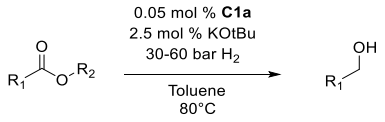
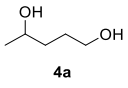
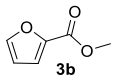
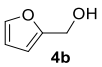
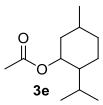
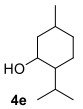
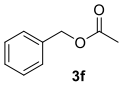
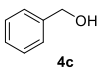
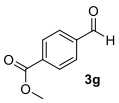
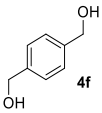
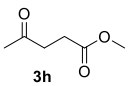
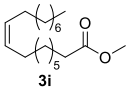
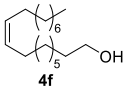
changed to methanol, the ketone functionality in methyl levulinate (**3h**, Entry 8) was hydrogenated selectively; subsequent ring-closing delivered γ-valerolactone (**3a**). Demonstrating once more the control of selectivity via simple exchange of the solvent. Although already represent in literature for other catalyst systems, it is notworthy that it is also possible to hydrogenate unsaturated fatty acid esters such as mehtly oleate (**3if)** (table 2, entry 9) without affecting the olefinic bond.

Table 2. Hydrogenation of various esters using **C1a**. Reaction conditions: 15 mmol ester substrate 30 ml of Toluene; [a] Isolated yields. [b] 0.25 mol% of **C1a**. [c] 500 mmol substrate, 2 mL toluene. [d] Reaction was run in methanol with 0.25 mol% **C1a**



Entry	Substrate	Product	Yield [%][a]	Time [h]	$p(H_2)$ [bar]
1			92[b] 91[c]	2	60
2			80	10	50
3			97	24	40
4			65	3	30
5			99	3	40
6			98	3	40
7			99	3	40
8			77[d]	2	50
9			95	3	30

Conclusion

In summary, we have shown that RuNNS-complex **C1a** is a highly active ester hydrogenation catalyst. We observed high selectivities towards allylic alcohols in the hydrogenation of α,β-unsaturated esters, which demonstrates that the NNS ligand class is an efficient and in expensive alternative to the established phosphorous based ligands. Further there is a remarkable influence of both alkyl rest as well as of the solvent on this selectivity It was possible to change the selectivity from ester hydrogenation towards olefin or ketone hydrogenation by simply modifying the ligand or by solvent exchange. Which thoughtfully applied might be a usefull tool in organic synthesis or fine chemical industry. However further experiments are needed and will be conducted in our laboratory to increase the catalysts selectivity and to understand the effect of methanol on the system are continued in our laboratory.

Experimental Section

Preparation of NNS-Ru-Complexes

C1a has been prepared according to previously published work of our group[11]; the preparation of **C1b** is given below.

2-(methylthio)-N-(pyridin-2-ylmethyl)ethanamine (NNS^{Me})(Standard procedure SP1):
A dry 50 ml Schlenk round bottom flask equipped with a magnetic stirring bar was charged with 20 ml dichloromethane, followed by 1.07 g (10 mmol, 1.0 eq.) of pyridinecarboxaldehyde, 0.91 g (10 mmol, 1.0 eq.) of 2-(methylthio)ethanamine and 3.0 g (20 mmol, 2.0 eq) of anhydrous sodium sulfate. The resulting suspension was then stirred over night at ambient temperature. Afterwards the inorganic salts were filtered of and washed with dichloromethane (2 x 10 ml) and the solvent was removed in vacuo. The resulting red oil was then dissolved in 20 ml methanol in a 50 ml round bottom flask and subsequently 0.8 g (20 mmol, 2.0 eq.) of sodium borohydride were added portion wise at 0 °C. Afterwards, the reaction mixture was allowed to warm up to room temperature and stirred for 2 hours. Then the reaction was quenched by adding 20 ml of dichloromethane and 20 ml of a saturated $NaHCO_3$ solution. When gas evolution ceased, the mixture was poured in a seperatory funnel, and the organic layer was separated. The aqueous layer was extracted with DCM (3 x 10 ml). The combined organic layers were dried over sodium sulfate. Evaporation of the solvent yielded a dark yellow oil from which 0.96 g (52 % of theory) of the title compound was isolated via kugelrohr distillation (200 °C, 0.5 mbar) as a clear slightly yellowish oil

^{1}H NMR (300 MHz,$CDCl_3$) δ 8.53 (d, J = 4.0 Hz, 1H, Pyr*H*), 7.62 (td, J = 7.6, 1.8 Hz, 1H, Pyr*H*), 7.30 (d, J = 7.8 Hz, 1H, Pyr*H*) 7.13 (dd, J = 7.3, 5.0 Hz, 1H, Pyr*H*), 3.91 (s, 2H, PyrCH_2N), 2.85 (d, J = 6.5 Hz,

2H, NC*H*$_2$CH$_2$S), 2.67 (t, J = 6.4 Hz, 2H, NCH$_2$C*H*$_2$S), 2.15 (s, br, 1H, N*H*), 2.06 (s, 3H, SCH3); ^{13}C NMR (75 MHz, CDCl3) δ 159.70, 149.35, 136.49, 122.21, 121.98 , 54.93 , 47.61 , 34.44 , 15.31; HRMS (EI) calculated for $C_9H_{14}N_2S$: 182.08722 (M+); found 182.08617 (M+)

2-(tert-butylthio)-N-(pyridin-2-ylmethyl)ethan-1-amine(NNS^{tBu}):

This ligand was prepared like NNS^{Me} reacting 0.51 g (5 mmol, 1.0 eq.) of pyridine carboxaldehyde (17), 0.72 g (5 mmol, 1.0 eq.) of 2-(tert-butylthio)ethanamine and 1.5 g (10 mmol, 2.0 eq) of anhydrous sodium sulfate. Kugelrohr distillation was performed at 230 °C and 0.5 mbar, yielding 0.88 g (80%) of 20b.

^{1}H NMR (300 MHz, CD_2Cl_2) δ 8.54 (d, J = 4.9 Hz, 1H, Pyr*H*), 7.64 (td, J = 7.6, 1.8 Hz, 1H, Pyr*H*), 7.34 (d, J = 7.7 Hz, 1H, Pyr*H*), 7.17 (dd, J = 7.1, 5.2 Hz, 1H, Pyr*H*), 3.90 (s, 2H, PyrC*H*$_2$N), 2.85 (t, J = 6.5 Hz, 2H, NC*H*$_2$CH$_2$S), 2.73 (t, J = 6.9 Hz, 2H, NCH$_2$C*H*$_2$S), 2.02 (s, br, 1H, N*H*), 1.31 (s, 9H, C(C*H*$_3$)$_3$); ^{13}C NMR (75 MHz, CD_2Cl_2) δ 163.18 , 152.07 , 139.13 , 124.85 , 124.65 , 57.83 , 52.22 , 44.75 , 33.80 , 31.84; HRMS (ESI+) calculated for $C_{12}H_{20}N_2S$: 225.1420 (M+H) found: 225.14239

[Ru(NNS^{Me})(PPh$_3$)Cl$_2$] (**C1a**)

In a dry 25 ml Schlenk tube equipped with a magnetic stir bar, 962 mg (1 mmol, 1.0 eq.) of tris(triphenylphosphine)ruthenium(II)dichloride were dissolved in 2 ml of anhydrous diglyme. To this solution 219 mg (1.2 mmol, 1.2 eq) of 2-(methylthio)-N-(pyridin-2-ylmethyl)ethan-1-amine were added. The resulting reaction mixture was refluxed for 2 hours. Afterwards, the mixture was stored overnight at -20°C. The next day an orange-yellow precipitate could be filtered off. This was washed with diethylether (5x2 ml). The remaining solid was then dissolved in dichloromethane and subsequently transferred to another Schlenk tube where the solvent was evaporated, yielding 515 mg (84 % of theory) of an orange crystalline solid. The obtained complex consisted of two coordination isomers.

Major isomer:

^{1}H-NMR (300 MHz, CD_2Cl_2) δ 8.47 (d, *J* = 5.0 Hz, 1 H, Pyr*H*), 7,72 (m, 1 H, Pyr*H*), 7.64 – 7.49 (m, 6 H, 6 x Ar*H*), 7.40 – 7.24 (m, 10 H, Ar*H*), 6.87 (t, *J* = 6.7 Hz, 1H, Pyr*H*), 5.47 (s, br, 1 H, N*H*), 5.24 (t, J_{H-H} = 6.3 Hz, 1 H, PyrC*H*$_2$N), 4.38 (m, 1 H, Pyr-CH2-N), 3.43 (m, 2H), 3.29 (d, *J*(H-H) = 11.0, 1H), 2.57 (m, 1H), 1.50 (s, 3 H, SC*H*$_3$); ^{31}P-NMR (122 MHz, CD_2Cl_2) δ 51.75 (s, 1 P, *P*Ph$_3$);Minor isomer: ^{1}H-NMR (300 MHz, CD_2Cl_2) δ 8.69 (d, 3J = 5.0 Hz, 1 H, Pyr*H*), 7,72 (m, 1H, Pyr*H*), 7.64 – 7.49 (m, 6 H, 6 x Ar*H*), 7.40 – 7.24 (m, 10 H, 10 x Ar*H*), 6.87 (t, J = 6.7 Hz, 1H, Pyr*H*), 5.47 (s, br, 1 H, N*H*), 5.24 (t, J(H-H) = 6.3 Hz, 1H, PyrC*H*$_2$N), 4.38 (m, 1H, PyrC*H*$_2$N), 3.43 (m, 2H), 3.29 (d, *J*(H-H) = 11.0, 1H), 2.57 (m, 1H), 1.53 (s, 3 H, SCH$_3$); ^{31}P-NMR (122 MHz, CD_2Cl_2) δ 50.70 (s, 1 P, *P*Ph$_3$); HRMS (ESI+) calculated for $C_{27}H_{29}Cl_2N_2PRuS$: 616.0210 (M+) found: 616.0202 (M+)

[Ru(NNS^{t-Bu})(PPh$_3$)Cl$_2$] (**C1b**)

In a dry 25 ml Schlenk tube equipped with a magnetic stir bar, 962 mg (1 mmol, 1.0 eq.) of tris(triphenylphosphine)ruthenium(II)dichloride were dissolved in 2 ml of anhydrous diglyme. To this solution 270 mg (1.2 mmol, 1.2 eq) of 2-(tert-butylthio)-N-(pyridin-2-ylmethyl)ethanamine was added. The resulting reaction mixture was refluxed for 4 hours. Afterwards, the mixture was stored overnight at -20°C. The next day a yellow precipitate could be filtered off. This was washed with diethylether (5x2 ml). The remaining solid was then dissolved in toluene and subsequently transferred to another Schlenk tube where the solvent was evaporated, yielding 200 mg (30% of theory) of a yellow crystalline solid.

Major isomer:

^{1}H-NMR (300 MHz, CD_2Cl_2) δ 8.11 (d, J = 5.8 Hz, 1 H, Pyr*H*), 7.70 – 7.49 (m, 5 H, 5 x Ar*H*), 7.40 – 7.24 (m, 11 H, Ar*H*), 6.57 (t, *J* = 6.7 Hz, 1H, Pyr*H*), 5.75 (s, br, 1 H, N*H*), 5.26 (t, J_{H-H} = 6.3 Hz, 1H, PyrC*H*$_2$N), 4.40 (m, 1H, Pyr-C*H*$_2$-N), 3.53 (m, 2H), 3.21 (d, *J*(H-H) = 11.0 1H), 3.08 (m, 1H), 1.0 (s, 9 H, SC(C*H*$_3$)$_3$). ^{31}P NMR (122 MHz, CD_2Cl_2) δ 49.3 (s, 1 P, *P*Ph$_3$); Minor isomer: ^{31}P NMR (122 MHz,CD_2Cl_2) δ 38.6 (s, 1 P, *P*Ph$_3$);

HRMS (ESI+) calculated for $C_{30}H_{35}ClN_2PRuS$: 623.09906 (M-Cl), $C_{30}H_{35}Cl_2N_2PRuS$: 658.06791 (M+), $C_{30}H_{35}ClN_2PRuS$: 664.12561 (M-Cl+MeCN); found: 623.09034(M-Cl), 658.07430 (M+), 664.12426 (M-Cl+MeCN).

Hydrogenation reactions

Screening reactions:

In a typical screening reaction, oven dried 4 ml glass vials equipped with magnetic stirring bars were used. To each vial 1.5 mg (2 µmol; 0.25 mol%) of **C1a** or **C1b** and 1 mmol of methyl cinnamate **1a** were added, and the exact weight of the substrate noted. The vials were placed in an aluminum inlet suitable for high pressure reactions and closed with PTFE/rubber septa pierced with a needle. Afterwards, 2 ml of the desired solvent, 50 µl (2.5 mol%) of a freshly prepared solution of potassium *tert*-butoxide in THF (c= 1.0 mol/l) and 50 µl of *n*-dodecane were added via syringe. Then the vessels were put in an argon flushed 300 ml stainless steel autoclave which was pressured two times with 10 bars of N_2, followed by two times 10 bars with H_2 and finally pressurized with 30 bars of H_2. The autoclave was then put in an aluminum block which was preheated to 80°C. After 2 hours the reactor was carefully depressurized and 100 µl samples of each vial where taken. Subsequently the samples were filtered through celite, diluted with 1 ml of acetone, and analyzed by gas chromatography.

Reaction monitoring

A 100 ml hastelloy autoclave with mechanical stirrer and a high pressure sample outlet was charged with [Ru(NNS^{Me})(PPh$_3$)Cl$_2$] **C1a** (23 mg, 0.038 mmol, 0.25 mol%), ester substrate **1b** (15 mmol), 30 ml of toluene, KOtBu (41 mg, 0.38 mmol, 2.5 mol%), and 1000 µl of anhydrous n-dodecane under an argon atmosphere. The autoclave vessel was flushed with 20 bar of N_2 three times, with 10 bar of H_2 two times, then pressurized to 30 bar H_2 and heated to the desired temperature and stirred. During the reaction, samples in the size of approximately 100 µl were taken, filtered over celite and diluted with 1 ml of acetone. Results for 40°C are shown in figure 3. For exoperiments at 80°C and 100°C please refer to the supporting information.

Hydrogenations:

A 100 ml hastelloy autoclave with mechanical stirrer was charged with the desired amount of Ru(NNS^{Me})(PPh$_3$)Cl$_2$, KO*t*Bu (41 mg, 0.38 mmol, 2.5 mol%), ester substrate (15 mmol) and 30 ml of toluene under an argon atmosphere. If lower amounts of substrates were used solvent and catalyst/base were adjusted accordingly. The autoclave vessel was flushed with 20 bar of N_2 three times, with 10 bar of H_2 two times, then filled with H_2 to a desired pressure, heated to the desired temperature and stirred for the indicated time. During the reaction time the vessel was repressurized to keep the pressure over 20 bars. The pressure vessel was cooled down to room temperature and then carefully depressurized. Then 0.1 ml of the reaction mixture was filtered through celite and rinsed with acetone (1 ml), and analyzed by gas chromatography and/or the alcohol fraction isolated.

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Conflict of interest

The authors declare no conflict of interest.

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FULL PAPER

Inexpensive Ruthenium NNS-Complexes as efficient ester hydrogenation catalyst with high C=O vs. C=C selectivities

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