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Non-bifunctional Mn catalysts based on phosphine-phosphites for the hydrogenation of carbonyl substrates

A series of Mn(i) complexes bearing phosphine–phosphite ligands (P-OP) of formula [Mn(Br)(P-OP)(CO)₃] (1) have been prepared and characterised. These compounds exist in solution as a mixture of *fac* and *mer* isomers with *fac/mer* ratios from 18:1 to 2:1. The relatively low donor ability of P-OP compared to bis(trialkylphosphines) or bis–NHC ligands, typically found in non-bifunctional Mn catalysts reported to date, is evinced in IR spectra. Compounds 1 provide efficient catalysts for the hydrogenation of carbonyl substrates using KOtBu as a base. Notably, these complexes constitute a set of modularly designed precatalysts and optimisation of the P-OP ligand provided appropriate catalysts for the reduction of a wide variety of aldehydes and ketones under mild reaction conditions (S/C = 250–500, 20 bar H_2 , RT to 40 °C). A mechanistic study combining spectroscopic and computational results provides support for a catalyst activation process based on the nucleophilic attack of the alkoxide on a coordinated CO in [Mn(OtBu)(P-OP)(CO)₃], as well as a non-bifunctional inner-sphere hydrogenation pathway in the representative hydrogenation of benzophenone. The catalytic cycle is also characterised by a rather stable pentacoordinated alkoxide [Mn(k^1 -O-OCHPh₂)(P-OP) (CO)₂] which determines the energetic span of the reaction.

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Introduction

The search for cost-effective alternatives to well-established noble metal catalysts is one of the more important research topics in homogeneous hydrogenation.1 In this regard, Mn catalysts have already shown particularly promising results in terms of broad substrate scope and catalyst activity.2 This field emerged a decade ago with prominent examples of bifunctional catalysts,3 which boosted the research on this type of systems. 4,5 Alternatively, non-bifunctional ones have remained much less explored and are notably restricted to derivatives of highly donating bidentate ligands. The corresponding catalyst precursors have the formula Mn(X)(L-L)(CO)3 where X denotes an anionic ligand such as Br, alkyl or triflate, while L-L corresponds to bis(trialkylphosphine) or to NHC based ligands. For instance, complex A (X = Br, R = nPr; Fig. 1) 6a provides an active catalyst for the hydrogenation of ketones and nitriles, while for the latter a triflate derivative (R = iPr) reported by the group of García operated under milder conditions.⁷ Moreover, Kirchner and coworkers have

demonstrated that alkyl compound **B** has a remarkable reactivity in hydrogenation and is capable to reduce without the need of base ketones, alkenes, alkynes and CO_2 . The other hand, bis–NHC derivatives **C** (ref. 8) provide outstanding results in the challenging hydrogenation of esters. An example of this type developed by Beller and coworkers (R = R' = Me) exhibits a broad scope and also hydrogenates a wide variety of ketones, nitriles and olefins. Finally, the group of Sortais has reported an interesting case of a complex based on a NHC–thioether ligand (**D**) which leads to an active catalyst for the hydrogenation of olefins and ketones. These precedents raise the question of whether it is possible to expand catalyst activity in hydrogenation reactions to less donating ligands (*e.g.* arylphosphines, phosphoramidites, phosphites). This is an

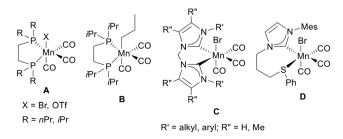


Fig. 1 Structure of compounds A-D.

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area with a high potential due to the vast structural diversity of these P-ligands, which span a wide range of electronic and steric properties, features that are most useful for comprehensive catalyst optimisation.¹³

In our laboratory we have been interested in the study of phosphine-phosphite ligands (P-OP) in Rh, Ir and Ru catalytic hydrogenation, 14 while applications in other catalytic processes such as hydroformylation (Rh), 15 conjugate addition or alkylation (Cu)¹⁶ cycloaddition (Au)¹⁷ or hydrocyanation reactions (Ni), 18 have also been described. These ligands are characterized by an easily tuneable structure and a π -acceptor phosphite fragment which makes them less donor than ubiquitous diphosphines, 19 while the different electronic properties of their P fragments cause important directing effects in catalysis.²⁰ In this contribution we report the first application of P-OP ligands in Mn catalysed hydrogenation. Complexes prepared show good activity in the hydrogenation of a wide variety of ketones and aldehydes under mild reaction while complementary spectroscopic computational results provide support for a low-barrier catalyst activation pathway and a non-bifunctional inner-sphere hydrogenation mechanism.

Results and discussion

Synthesis and characterization of Mn phosphine-phosphite complexes

Compounds $[Mn(Br)(P-OP)(CO)_3]$ (1a–1d) were obtained in high yields from $[Mn(Br)(CO)_5]$ and a stoichiometric amount of P-OP ligand (L1–L4, respectively; Scheme 1). Moreover, 1a reacts with AgOTf to give $[Mn(OTf)(L1)(CO)_3]$ (2a), while the latter reacts with KBH₄ to give the corresponding hydride $[Mn(H)(L1)(CO)_3]$ (3a). For these complexes, four isomers can be distinguished: two chiral facial isomers, *fac1* and *fac2* (Fig. 2), which differ in metal configuration, and two meridional isomers *mer1* and *mer2*, which can be differentiated by the relative positions of

Scheme 1 Synthesis of complexes 1-3.

X = Br, OTf, H; P-OP = L1-L4

Fig. 2 Structure of isomers of complexes 1–3.

the X and P atoms. The fac isomers can be notated as OC-6-44-C and OC-6-44-A, respectively, 21 although for simplicity, C (fac1) and A (fac2) will be used to refer to metal configuration. It is important to note that a stereogenic axis in the biaryl is generated upon phosphite coordination. However, a fast atropisomerization of the biaryl fragment at room temperature is expected, as observed before in Rh (ref. 22) and Ru (ref. 20b) complexes containing these P-OP ligands.

Characterisation in solution of compounds **1** show a mixture of two isomers, with the *fac* isomer being predominant, and *fac/mer* ratios from 18:1 (**1c**) to 2:1 (**1d**). This is an interesting difference with diphosphine derivatives [Mn(Br)(P-P)(CO)₃] which solely exist in solution as *fac* isomers. ^{6a,23} For compounds **1** comparison of ³¹P{¹H} NMR spectra show distinct data for the two isomers, thus J_{PP} coupling constants are between 12 and 17 Hz higher in the *fac* isomer. In addition, there is a marked low field shift ($\Delta\delta$ = 27–30 ppm) of the phosphite signal of the *mer* isomer compared to the *fac* one (Fig. 3a). Due to the relatively high concentration of *mer*-**1d**, full characterization in solution from ¹H and ¹³C{¹H} NMR (Fig. 3b) has been possible for this isomer. In contrast, for the triflate derivative **2a**, the isomer ratio is 24:1, while for hydride **3a** only the *fac* isomer was

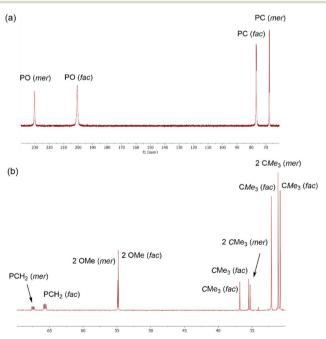


Fig. 3 (a) $^{31}P\{^1H\}$ NMR (C₆D₆, 202 MHz) spectrum of 1d and (b) aliphatic region of $^{13}C\{^1H\}$ NMR (C₆D₆, 125 MHz) spectrum of 1d.

observed. Moreover, the observation of three strong bands in the carbonyl region of IR spectra of complexes 1-3 is also consistent with the fac isomer (e.g. 2030, 1969 and 1943 cm⁻¹ for 1a). Nevertheless, less intense bands attributable to minor mer isomers have also been detected (e.g. 1987 and 1960 cm⁻¹ for 1a). With the available spectroscopic data, it is not possible to ascertain the stereochemistry of the mer isomer, although it is reasonable to propose a mer1 structure in which CO and phosphite avoid mutually trans positions. These assumptions will be further supported by DFT calculations (see below). Compound 1a has been studied by ¹H and ³¹P(¹H) NMR at low temperature with the aim of freezing phosphite atropisomerization. However, down to -80 °C, no significant lineshape changes in these spectra were observed, indicating that atropisomerization is still fast at this temperature. This compound has also characterized by single crystal X-ray crystallography (Fig. 4). In the crystal lattice a racemic mixture composed by C,Sax and A,Rax isomers was observed. Thus, stereoisomers differing in the relative metal and biaryl configuration (i.e. C, $R_{\rm ax}$ and $A_{\rm s}S_{\rm ax}$) should be less stable.

An interesting difference between compounds **1** and non-bifunctional catalyst precursors found in literature concerns the lower electron density at the metal centre in the former. This is evidenced by the position of v(CO) bands in IR spectra. Thus, the bands of **1a** appear at higher frequencies than those of **A** (X = Br, R = nPr; 2003, 1935 and 1903 cm⁻¹), ^{6a} C (R' = R" = Me; 1995, 1908 and 1868 cm⁻¹)¹⁰ and **D** (2010, 1925 and 1894 cm⁻¹). ¹¹ A similar trend is observed when by comparing **2a** or **3a** with their 1,2-bis(diphenylphosphino) ethane analogues. ²⁴

To complete the study, we have investigated the relative stability of the isomers of representative complexes 1a (Fig. 5) and 1c by DFT methods. For the sake of clarity, the $S_{\rm ax}$ configuration at the biaryl was selected throughout the study. In the case of 1a, the most stable structure corresponds to fac1-1a, matching the structure observed by X-ray crystallography, while diastereomeric fac2-1a is 2.8 kcal mol⁻¹ higher in free energy. In addition, mer1-1a is 3.7 kcal mol⁻¹ less stable than fac1-1a, while mer2-1a is the least stable isomer (6.4 kcal mol⁻¹). For 1c, the preferred structure is fac2-1c, while the fac1, mer1 and mer2

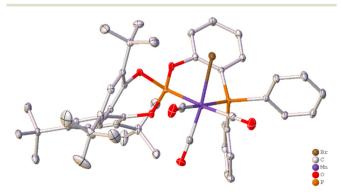


Fig. 4 ORTEP view of C,S_{ax} isomer of complex $\mathbf{1a}$ (H atoms have been omitted for clarity).

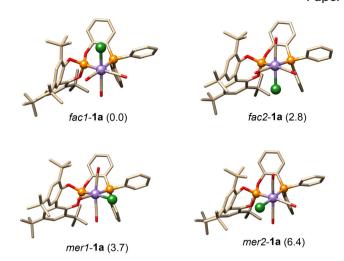


Fig. 5 Optimized geometries of isomers of **1a**. Numerical values correspond to free energies relative to *fac1* isomer (kcal mol⁻¹, hydrogens have been omitted for clarity).

isomers lie 3.2, 2.9 and 7.0 kcal mol^{-1} higher in free energy, respectively. Likewise, analysis of the isomers of 3a showed that the fac1 isomer is the more stable, with the fac2, mer1 and mer2 structures lying 2.1, 3.8 and 5.2 kcal mol^{-1} above fac1-3a, respectively. These results are consistent with the experimental preference for the fac isomer, while the small energy differences observed between fac1 and fac2, besides a fast atropisomerization, suggest a mixture of these facial isomers in solution, along with minor amounts of mer1. In contrast, mer2 isomers can be disregarded due to their significantly higher energies. Similarly, a difference of 7.9 kcal mol^{-1} between A(X = Br, R = nPr) and the corresponding mer isomer has been reported. 6a

Catalytic hydrogenation of carbonyl compounds

To examine the potential of compounds 1 in catalytic hydrogenation, we first carried out a series of hydrogenations of acetophenone with these complexes under relatively mild reaction conditions in iPrOH using KOtBu as a base (20 bar H₂, RT, S/C/B = 500/1/10). We were pleased to observe that complex 1a provided nearly full conversion under these conditions (entry 1; Table 1), while the remaining complexes gave moderate values (65, 53 and 61 %, for 1b-1d, entries 2-4 respectively). From these results, we selected 1a for further optimisation. First, the use of alternative solvents was examined, with satisfactory results obtained in toluene (entries 5, 7), while lower activity was observed in CH₂Cl₂ (entry 6). We then attempted to lower the catalyst loading. In this regard, it was observed that increasing the base concentration led to a decrease in conversion (entries 9-12). Notably, increasing the reaction temperature proved detrimental in both toluene (entries 13, 14) and iPrOH (entry 15). Finally, a mercury drop test indicated that the reaction is homogeneous (entry 16). In contrast to 1a, the triflate complex 2a showed reduced activity (entries 17, 18), while a reaction with hydride 3a in the absence of base lead to

Table 1 Hydrogenation of acetophenone with catalyst precursors 1–3^a

Entry	Complex	Solvent	S/C/B	Temp. (°C)	Conv. (%)
1	1a	<i>i</i> PrOH	500/1/10	RT	99
2	1b	iPrOH	500/1/10	RT	65
3	1c	<i>i</i> PrOH	500/1/10	RT	53
4	1d	iPrOH	500/1/10	RT	61
5	1a	Toluene	100/1/10	RT	100
6	1a	CH_2Cl_2	100/1/10	RT	52
7	1a	Toluene	500/1/10	RT	100
8	1a	Toluene	500/1/5	RT	100
9	1a	Toluene	1000/1/5	RT	77
10	1a	Toluene	1000/1/10	RT	61
11	1a	Toluene	1000/1/20	RT	49
12	1a	Toluene	1000/1/50	RT	34
13	1a	Toluene	500/1/10	40	82
14	1a	Toluene	1000/1/10	40	28
15	1a	<i>i</i> PrOH	500/1/10	60	19
16^b	1a	Toluene	500/1/10	RT	100
17	2a	Toluene	500/1/10	RT	17
18	2a	Toluene	500/1/0	RT	0
19	3a	Toluene	500/1/0	RT	0

 $[^]a$ Reactions performed under 20 bar $\rm H_2$ with solvent and temperature specified with KOtBu as a base, conversion was determined by $^1\rm H$ NMR. b Mercury test.

no conversion (entry 19). We next examined the substrate scope for ketone hydrogenations using **1a** (Scheme 2). Notably, this compound displayed a broad substrate scope, reducing a variety of alkyl/aryl, dialkyl and diaryl ketones with conversion values exceeding 95 %. Worth to note, these results have been obtained with a lower catalyst loading and milder reaction conditions than those reported for other Mn(Br)(L–L)(CO)₃ precursors of non-bifunctional catalysts in these reactions (1–3 mol %, 30–50 °C, 50 bar H₂). ^{6a,11}

Due to the limited applications of non-bifunctional catalysts in the hydrogenation of aldehydes,26 we also investigated the performance of compounds 1 in these reactions (Scheme 3). Hydrogenation of benzaldehyde under mild conditions (20 bar H2, RT, toluene) using 1a showed full conversion after 24 h. Product analysis indicated the preferential formation of benzyl alcohol, along with benzyl benzoate, resulting from a Tishchenko-type condensation,²⁷ with an alcohol/ester ratio (A/E) of 4.1 (entry 1, Table 2). Using 1b led to a slightly lower conversion but a significant increase in the A/E ratio (entry 2). Increasing the temperature to 40 °C resulted in slightly higher selectivity (entry 3). We reasoned that the formation of the ester could be disfavoured by lowering the substrate concentration. Thus, the A/E ratio improved up to 23.0 (entry 4). The superior performance of 1b was further confirmed by repeating the reaction with 1a under the same conditions (entry 5). A blank reaction under these conditions showed nearly full conversion, but the ester as the main product (entry 6). Comparison of reactions of entries 4 and 6 clearly illustrates the significant impact of the catalyst on product selectivity. To further explore the utility of this catalytic system, we examined the hydrogenation of various aldehydes. Hydrogenation of several aryl aldehydes showed full conversion within 24 h and a good selectivity

Scheme 2 Conversion (isolated yield in parentheses) values obtained in ketone hydrogenation reactions with 1a.

100 (89)

99 (58)

towards the desired alcohol, with A/E ratios up to 50.0. A couple of α , β -unsaturated aldehydes were also tested. In

Scheme 3 Hydrogenation of aldehydes using complex 1b. All reactions proceeded with full conversion. For aryl aldehydes the numerical values correspond to the alcohol/ester ratio. In the case of cinnamaldehyde and geranial, the values indicate the ratio between the allyl alcohol and the fully hydrogenated product.

Table 2 Hydrogenation of benzaldehyde with catalyst precursors 1a and 1b^a

Entry	Complex	S/C/B	$[S]^b$	Temp. (°C)	Conv. (%)	Select (A/E) ^c
1	1a	500/1/10	1.1	RT	100	4.1
2	1b	500/1/10	1.2	RT	96	9.3
3	1b	500/1/10	1.2	40	100	11.5
4	1b	250/1/10	0.3	40	100	23.0
5	1a	250/1/10	0.3	40	100	6.8
6		250/0/10	0.3	40	98	0.1

^a Reactions performed in toluene under 20 bar H₂, temperature specified with KOtBu as a base. Conversion and selectivity were determined by ¹H NMR. ^b Substrate molar concentration. ^c Alcohol/ester ratio.

these cases, the preferential formation of the corresponding allyl alcohols was observed, with good selectivity.

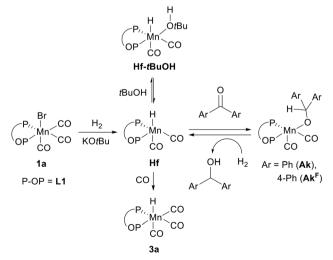
Mechanistic spectroscopic results

An interesting aspect of catalytic hydrogenation using non-bifunctional $[Mn(X)(L-L)(CO)_3]$ (X = Br, OTf, alkyl) complexes concerns their activation to generate the unsaturated hydride $[Mn(H)(L-L)(CO)_2]$, which is responsible for catalysis. For complex **B**, it has been clearly shown that activation proceeds *via* migratory insertion followed by hydrogenolysis, leading to butyraldehyde and $[Mn(H)(dippe)(CO)_2]$. Alternatively, it has been proposed that CO dissociation in $[Mn(O^sBu)(dippe)(CO)_3]$, followed by hydrogen coordination and alkoxide protonation can also lead to the active species. In addition, the hydride $[Mn(H)(H_2)(L-L)(CO)_2]$ has been proposed as the key species in reactions involving complex **D**, although the route leading to it is not fully understood.

In light of the above, we investigated the activation of compounds 1 under hydrogenation conditions (Scheme 4). We observed that compound 1a reacts with KOtBu (3 equivalents) under 0.5 bar $\rm H_2$ at room temperature in toluene- $\rm d_8$. However, this reaction proceeds very slowly due to the low solubility of the base. The addition of 20 $\rm \mu L$ of THF

30 % conversion after 1 h at room temperature. Alternatively, a faster reaction was observed is the base is dispersed by sonication (15 min; Fig. 6a and b; see SI for additional experiments). The reaction between 1a and KOtBu also took place in the absence of hydrogen, but resulted in a complex mixture, while no reaction between 1a and H2 was observed without base. Under H2, the reaction with base is apparent from a colour change in the solution from yellow-orange to pale-yellow. In the hydride region of the ¹H NMR spectrum, a very broad hump composed by two overlapping broad signals at -8.6 and -9.4 ppm, and a doublet of doublets for 3a in a 6:1 ratio, were detected (Fig. 7a). Lowering the temperature to -80 °C did not reach the slow exchange regime, although at -40 °C it was observed that the broad signal split into three still broad resonances centred at -7.6, -8.2, and -10.3 ppm in an approximate 1:3:2 ratio. In the ³¹P{¹H} NMR spectrum at 25 °C (toluene- d_8), a broad signal appears in the phosphite region (201.8 ppm), along with two broad signals in the phosphine region (70.2 and 66.9 ppm), and doublets corresponding to 3a, with unreacted 1a present in a 6:1:3 ratio, respectively (Fig. 7b). At -40 °C, the phosphine region of the 31P{1H} NMR experiment also showed a splitting into three broad signals. These observations indicate the formation of a mixture of fluxional hydrides (Hf) upon the reaction of 1a with KOtBu under H2. Exposure of this mixture

to the NMR sample increased the reaction rate, showing ca.



Scheme 4 Generation and reactions of key unsaturated Mn(H)(L1) (CO)₂ (Hf).

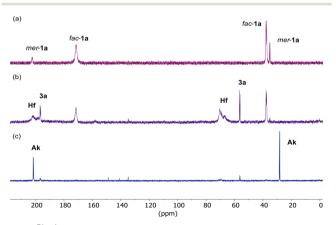


Fig. 6 31 P{ 1 H} NMR (202 MHz, toluene- d_{8}): spectra of 1a (a), activated 1a by reaction with H₂ and KOtBu after 15 min sonication (b), reaction of the latter with benzophenone (5 equiv., c).

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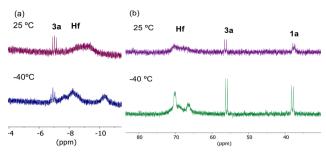


Fig. 7 1 H (400 MHz, a) and 31 P{ 1 H} NMR (162 MHz, b) spectra of activated 1a in toluene-da

to a CO atmosphere leads to conversion into 3a. After 15 min, the ratio of Hf to 3a is 2:1, which evolves to 0.3:1 after 2 h. Alternatively, broad resonances centred at -9.1 and 1.0 ppm are observed in the ²H NMR, in an approximate 1:1 ratio. The latter signal can be assigned to tBuOD, likely involved in a coordination/decoordination process. These experiments suggest that Hf corresponds to a mixture of isomers based on the Mn(H)(L1)(CO)₂ fragment which can be stabilized by solvent coordination. As well, computational studies show that these species can also be stabilized by an agostic interaction involving a tBu group (see below).

Furthermore, **Hf** reacts with benzophenone (3–5 equiv.), turning the solution deep red. This reaction is evinced by the disappearance of the hydride signal in the ¹H NMR and the appearance of a very broad resonance at 5.65 ppm (5.44 ppm in the ²H NMR for the deuteration experiment). In the ³¹P{¹H} NMR, a set of narrow doublets centred at 201.4 and 28.3 ppm with ${}^{2}J_{PP}$ coupling constant of 87 Hz is observed (Fig. 6c). Upon reintroducing H₂ (0.5 bar), the solution fades to pale orange, the fluxional hydride signals reappeared in the ¹H NMR, and catalytic hydrogenation proceeded, yielding Ph₂CHOH. The aforementioned doublets in the ³¹P{¹H} NMR remain visible until the latter stages of the reaction. Similarly, reaction of Hf with 4,4'-difluorobenzophenone yields two doublets in the $^{31}\text{P}\{^{1}\text{H}\}$ NMR at 201.3 and 28.5 ppm ($^{2}J_{PP}$ = 88 Hz), a broad signal in the ¹H NMR at 5.38 ppm, and two broad signals in the ¹⁹F{¹H} NMR at -115.4 and -117.0 ppm (Fig. 8a and b). At low temperature, no appreciable changes were observed in the former signal while the latter splits into two singlets which appeared narrow at -40 °C at -116.5 and -117.0 ppm, corresponding to two non-equivalent ¹⁹F nuclei (Fig. 8e), which parallel data reported by Baratta and coworkers for an Os-OCH(4-F-Ph)₂ alkoxide.²⁸ In turn, the signal at ca. -115 ppm should correspond to (4-F-Ph)2CHOH generated from the residual H₂ present in solution. This signal appears broadened with respect to that of the free alcohol attributable to an exchange between free and coordinated alcohol. The signal at -117.0 ppm disappeared upon substrate consumption by reaction with H2, raising the signal of the alcohol. Monitoring of the hydrogenation replenishing the H₂ atmosphere showed a clean hydrogenation (Fig. 8c and d). These results agree with the formation of alkoxides $Mn(OCHAr_2)(L1)(CO)_2$ (Ar = Ph (Ak), 4-F-Ph (Ak^F)) via reaction of Hf with the diarylketone, and

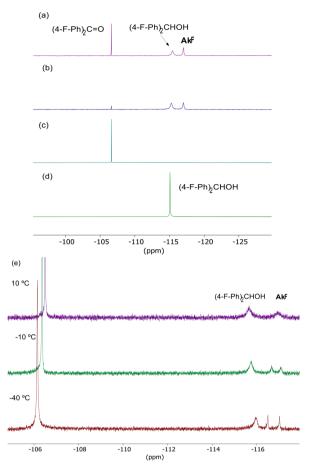


Fig. 8 $^{19}\text{F}\{^1\text{H}\}$ NMR (282 MHz, toluene- d_8) spectra of reaction between activated 1a and 4,4'-difluorobenzophenone (1 equiv.) after 15 min (a); after 45 min (b). Reaction with 4,4'-difluorobenzophe-none (5 equiv.): immediately after ketone addition (c); after 6 h reaction under 0.5 bar H₂ (d). $^{19}F(^{1}H)$ NMR (376 MHz, toluene- d_8) VT spectra (e) of reaction between activated 1a and 4,4'-difluorobenzophenone (5 equiv.).

subsequent hydrogenation to generate the corresponding diarylcarbinols. Attempts to isolate alkoxide intermediates were unsuccessful due to sample degradation during work-up.

Computational study

Catalyst activation. To support the experimental observations, we carried out DFT studies of the key steps involved in the activation of complexes 1. As a reasonable starting point, we considered the formation of Mn(OtBu)(L1) (CO)₃ (4) upon reaction of 1a with KOtBu.^{29,30} According to literature precedents proposing either CO dissociation^{7,23b} or alkoxide migration³¹ in related alkoxide-diphosphine derivatives, we examined in detail both activation routes in alkoxide 4. We studied the fac1, fac2 and mer1 isomers of 4.32 Among these, the fac2 isomer was found to be the most stable, with fac1 and mer1 lying 2.9 and 6.5 kcal mol⁻¹ higher in free energy, respectively.

In the CO dissociation route (Fig. 9), release of the CO ligand trans to the phosphite in fac1-4 leading to a pentacoordinated

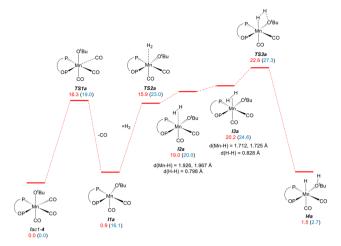


Fig. 9 General scheme for the activation of *fac1*-4 by CO dissociation. Numerical values correspond to relative free (red) and electronic energies (blue, in parentheses) in kcal mol^{-1} relative to *fac1*-4.

alkoxide intermediate I1a is almost thermoneutral ($\Delta G = 0.9$ kcal mol⁻¹) and proceeds with a moderate free energy barrier of 16.3 kcal mol⁻¹ (TS1a). Hydrogen coordination to Ia1 can take place either trans to CO or to the phosphite ligand. The former pathway, which locates the alkoxide trans to the phosphite fragment is energetically preferred and leads to a dihydrogen complex I2a which lays 19.0 kcal mol⁻¹ above fac1-4. This complex features a rather unactivated H2 ligand (d(Mn-H) = 1.926, 1.967 Å; d(H-H) = 0.798 Å). The subsequent alkoxide protonation step (TS3a) represents the highest overall barrier in this pathway ($\Delta G^{\ddagger} = 22.6 \text{ kcal mol}^{-1}$), yielding a hydride-tBuOH complex I4a ($\Delta G = 1.5 \text{ kcal mol}^{-1}$). IRC analysis of TS3a leads back to a dihydrogen complex I3a ($\Delta G = 20.2 \text{ kcal mol}^{-1}$) nearly isostructural to I2a but with a more activated H2 ligand, as shown by Mn-H and H-H distances (d(Mn-H) = 1.712, 1.725 Å; d(H-H) = 0.828 Å). The small energy difference between **I2a** and I3a (ca. 1.2 kcal mol⁻¹) suggests facile interconversion between these species. Finally, hydride-alcohol complex I4a is expected to exchange readily the tBuOH ligand for a ketone. In the case of benzophenone, the equilibrium favours the k^{1} -O ketone adduct by 1.1 kcal mol⁻¹. The activation profile via CO dissociation parallels that reported by Beller and co-workers for tert-butoxide generated from C (R = H, R' = Me), although the barriers found for *fac1-4* are around 5 kcal mol⁻¹ lower.¹⁰

For the fac2-4 isomer, CO dissociation also proceeds with a moderate barrier (**TS1b**, $\Delta G^{\ddagger} = 15.7$ kcal mol⁻¹) in an endergonic step (5.4 kcal mol⁻¹), while for the least stable alkoxide mer1-4, the CO dissociation barrier is even lower (**TS1c**, $\Delta G^{\ddagger} = 8.0$ kcal mol⁻¹) and the process slightly exergonic (-0.9 kcal mol⁻¹). Worth to note, the release of CO is accompanied by a significant shortening of the Mn–O bond (e.g. 2.206 Å in fac1-4 vs. 1.839 in **I1a**). In contrast, significantly high barriers ($\Delta E > 30$ kcal mol⁻¹) have been computed for the dissociation of CO in either fac1 or mer1 isomers of **1a** and **3a**. As in the profile depicted for fac1-4, alkoxide protonation remains the rate-limiting step in the cases of fac2-4 and mer1-4, with corresponding **TS3b** and **TS3c** lying 2.6 and 2.3 kcal mol⁻¹ in free energy above **TS3a**.

On the other hand, a lower-energy pathway was identified for the activation of 4 involving nucleophilic attack of the coordinated OtBu on a CO ligand (Fig. 10).33,34 In fac1-4, this attack to the CO ligand trans to phosphite (TS1a') proceeds with a low barrier ($\Delta G^{\ddagger} = 9.1 \text{ kcal mol}^{-1}$), leading to a Mn-C bound carboxylate intermediate I1a' ($\Delta G = 4.6 \text{ kcal mol}^{-1}$). Hydrogen coordination yields a dihydrogen complex $\mathbf{I2a'}$ ($\Delta G = 5.4$ kcal mol⁻¹), which undergoes protonation at the carboxylate carbon to form an H-bound formate complex I3a' ($\Delta G = 10.5$ kcal mol⁻¹). This intermediate undergoes fast isomerisation to the O-bound formate I4a' ($\Delta G = -0.8 \text{ kcal mol}^{-1}$). The highest overall barriers in this pathway are associated with hydrogen coordination TS2a' and protonation TS3a' (both 13.0 kcal mol⁻¹), which compete favourably with those in the CO dissociation route. The alternative OtBu migration pathway from the most stable alkoxide isomer fac2-4 is less favourable, with a TS for carboxylate protonation (TS3b') 4.7 kcal mol⁻¹ higher in free energy than TS3a'. Finally, dissociation of tert-butyl formate from I4a' by tBuOH or benzophenone is thermodynamically favourable ($\Delta G = -2.9$ and -4.1 kcal mol⁻¹, respectively). However, no tert-butyl formate was detected experimentally. We have observed that under reaction conditions used for catalyst activation, this ester reacts with KOtBu to produce tBuOH and CO (see SI for further details), 35 the latter potentially responsible for the formation of Mn(H)(L1) (CO)₃ observed in experiments described above.

Benzophenone hydrogenation. We next examined the mechanism of ketone hydrogenation catalysed by the present system. To reduce the number of diastereomeric intermediates, we focused on the hydrogenation of benzophenone rather than acetophenone, as both substrates are readily hydrogenated by **1a.** As a reference, we followed the key features of the *innersphere* mechanism previously reported for acetophenone hydrogenation catalysed by Mn(H)(dippe)(CO)₂. ^{6d}

Initially, we considered isomers of the unsaturated hydride $Mn(H)(L1)(CO)_2$ (5, Fig. 11). Based on the activation mechanisms considered, formate dissociation in I4a' (or tBuOH release in I4a)

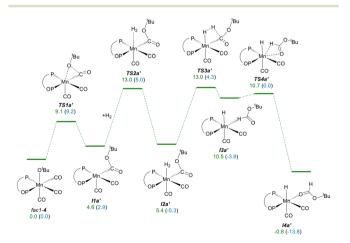


Fig. 10 General scheme for the activation of *fac1*-4a by OtBu migration. Numerical values correspond to relative free (green) and electronic energies (blue, in parentheses) in kcal mol^{-1} relative to *fac1*-4.

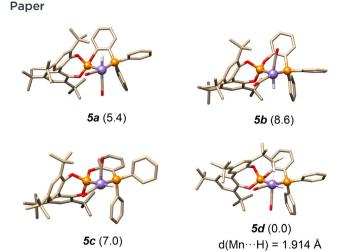


Fig. 11 Optimized geometries for Mn(H)(L1)(CO)₂ isomers (5a-5d). Numerical values correspond to relative free energies in kcal mol⁻¹ relative to 5d. Hydrogens have been omitted for clarity except those of the methyl involved in an agostic interaction in 5d

leads to the pentacoordinated hydride 5a. Given the expected facile phosphite atropisomerisation, diastereotopic isomer 5b was also considered.³⁶ A plausible isomerisation route involves hydride migration to the equatorial plane. This process is indeed feasible, with relatively low free energy barriers for the conversion of 5a to 5d (TSad: 9.8 kcal mol⁻¹) and 5b to 5c (TSbc: 11.7 kcal mol⁻¹). These results suggest a facile exchange between these unsaturated hydrides, consistent with spectroscopic observations. Among the isomers, 5d is the more stable one as the result of an

agostic interaction generated by a C-H of a tert-butyl substituent. Hydrides 5 adopt a distorted square planar geometry, with an available coordination site trans to either phosphite or a carbonyl ligand. Therefore, these species should readily coordinate an alcohol or carbonyl substrate to form the corresponding octahedral complexes. The hydrogenation pathway was examined for hydrides 5a-5d, leading to four routes a to d (Fig. 12, Table 3). The reaction begins with formation of a hydride-ketone precomplex I5, which evolves via TS5 to a k^{1} -O-benzophenone complex **I6**. This complex may isomerise through **TS6** to a k^2 -O,C complex I7, which undergoes hydride insertion (TS7) to yield an agostic alkoxide I8 (path b). Alternatively, hydride insertion can occur directly from I6 (paths a, c and d). Release of the agostic interaction via TS8 affords a pentacoordinated alkoxide I9, which is considerably more stable ($\Delta G = -2.5$ to -15.2 kcal mol⁻¹) than the preceding agostic species. 19 is suitable for hydrogen coordination (TS9), forming a dihydrogen-alkoxide complex I10. Finally, alkoxide protonation via TS10 yields the hydride-alcohol complex I11. A notable feature of the mechanism is the remarkable stability of alkoxides 19, being 19c the most stable, $\Delta G^{\circ} = -21.3 \text{ kcal mol}^{-1} \text{ relative to the starting materials.}$ According to the energy span model³⁷ analysis of these profiles, the turnover-determining intermediate (TDI) and turnoverdetermining transition states (TDTS) are 19 and TS10, respectively, across all four cycles. The more favourable TS for alkoxide protonation corresponds to path c (TS10c), which also contains the most stable alkoxide I9c. Moreover, considering the small structural differences found among the 19 alcoxides and their expected highly dynamic nature, it is reasonable to expect

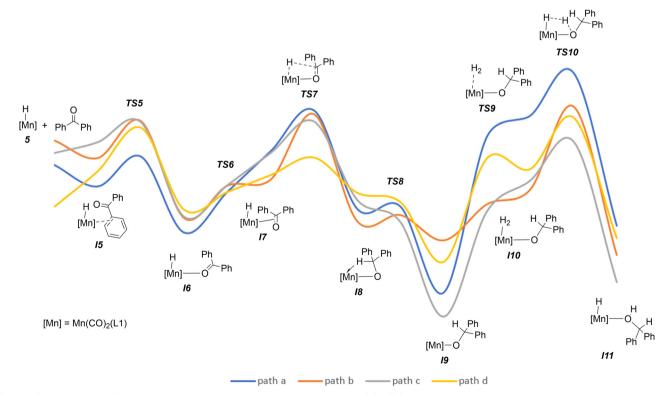


Fig. 12 Free energy profiles for benzophenone hydrogenation catalysed by Mn(H)(L1)(CO)₂.

Species $\Delta G (\Delta E) (\mathbf{d})$ $\Delta G (\Delta E) (\mathbf{c})$ $\Delta G (\Delta E) (\mathbf{a})$ $\Delta G (\Delta E) (\mathbf{b})$ -1.6 (-1.3) 0.0(0.0)-7.0(-9.9) $5 + Ph_2C = O$ 1.6 (1.9) 15 -4.4(-22.8)-0.6(-20.5)1.4 (-17.3) -2.4(-21.3)TS5 -0.4(-18.0)4.1(-14.2)4.0(-14.1)3.4(-13.5)16 -10.4 (-30.2) -8.5(-29.0)-8.3(-28.2)-7.4(-26.9)TS₆ -4.2 (-23.0) -3.5(-22.8)17 TS7 5.5 (-18.0) 5.0(-13.7)4.1(-19.4)-0.6(-20.5)-7.3 (-30.1) -8.9(-29.5)-6.1(-26.4)-5.2(-28.8)-8.9 (-29.5) -8.1 (-29.5) TS8 -7.0(-27.4)-6.4(-26.3)19 -18.2 (-38.4)-11.4(-32.5)-21.3 (-41.6) -14.2(-34.3)-0.7(-29.8)TS9 2.1(-27.2)-6.7(-35.5)-7.6(-36.7)4.8 (-30.9) -3.2(-37.6)-3.6 (-39.5) 0.9 (-34.6) **I10 TS10** 10.4 (-20.1) 6.0(-32.1)1.5(-29.9)4.2(-26.8)**I11** -9.4 (-43.8) -13.3 (-48.2) -16.8 (-51.8) -11.5 (-45.4)

Table 3 Calculated Energies for benzophenone hydrogenation catalysed by $Mn(CO)_2(H)(L1)$ by paths a to \mathbf{d}^a

that they can easily interconvert. Upon these considerations, it can be assumed that the dominant pathway in the catalysis will correspond to the formation of **I9c** and subsequent steps *via* path **c**. Accordingly, this alkoxide would be the resting state of the catalytic cycle, in agreement with the persistent observation of **Ak/Ak^F** species upon NMR monitoring of the catalytic hydrogenation.

Comparison with the dippe-based catalyst and alkoxide trap. Given the promising catalyst activity exhibited by 1a, we compared its hydrogenation cycle with that of reference dippe-based catalyst. Using the same computational methodology, we calculated the hydrogenation profile of benzophenone catalysed by Mn(H)(dippe)(CO)2 (see SI for details). The barrier for hydride migratory insertion is indeed found to be lower for dippe (1.1 kcal mol⁻¹) than for L1 catalyst (4.1 kcal mol⁻¹). Moreover, the TS for the alkoxide protonation step is somewhat lower in free energy in the case of dippe (-0.6 vs. 1.5 kcal mol⁻¹), as well as the relevant pentacoordinated alkoxide ($-21.7 \text{ vs. } -21.3 \text{ kcal mol}^{-1}$). Overall, the energetic span³⁸ for the cycle of the dippe catalyst amounts 21.1 kcal mol⁻¹, only 1.7 kcal mol⁻¹ lower than for L1 catalyst (22.8 kcal mol⁻¹). From this small difference, within the accuracy of the DFT method, 39 it seems reasonable not to expect a remarkable difference in catalyst activity between both catalysts.40

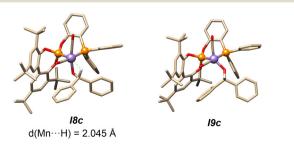


Fig. 13 Optimised geometries for alkoxide complexes I8c and I9c (all hydrogens except the alkoxide β one have been omitted for clarity).

Due to the strong metal-oxygen bonds, alkoxides can exhibit high stability, which may pose a severe drawback for catalysis. This has been related to donation from the lone pair on the alkoxide oxygen to a suitable unoccupied metal d orbital, resulting in a strong M-OR multiple bond. This effect is particularly critical in hydrogen borrowing reactions and the term alkoxide trap has been coined to describe it. 41 To explore this effect in our system, we examined the metalalkoxide interaction in 19c in more detail. This intermediate adopts a distorted trigonal bipyramidal geometry (Fig. 13), with the phosphite, alkoxide and one CO ligand occupying the equatorial plane (P(phosphite)-Mn-O and (CO)_{eq}-Mn-O angles of 129.4° and 135.1°, respectively), while the apical positions are occupied by the other CO and the phosphine ligands (P(phosphine)-Mn-(CO)_{ax} angle of 173.4°). Moreover, the Mn-O distance is significantly shorter than in the preceding agostic intermediate I8c (1.8436 Å vs. 1.9717 Å). A natural bonding orbital (NBO)42 analysis revealed a Wiberg bond order of 0.51 for I9c, notably higher than the 0.36 found for I8c. In addition, second-order perturbation theory analysis indicated considerable donor-acceptor interactions between the alkoxide oxygen lone pairs of 19c and antibonding orbitals on Mn-C (carbonyl) and Mn-P (phosphite) (Fig. 14), with stabilisation energies (ΔE^2) of 25.6, 33.5 kcal mol⁻¹ for the Mn-C and 48.3 kcal mol⁻¹ for the Mn-P.43 These findings agree with a particularly strong Mnalkoxide interaction in I9c.

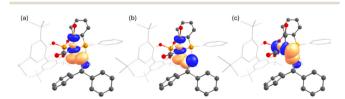


Fig. 14 Donor acceptor interactions between alkoxide oxygen lone pairs and Mn–C (carbonyl) (a and b) and Mn–P (phosphite) (c) antibonding orbitals in complex **I9c**.

^a Values in kcal mol⁻¹ from 5c + benzophenone.

Conclusions

In this contribution, we have described the synthesis and characterisation of Mn(I) complexes of the type Mn(Br) (CO)₃(P-OP) (1), bearing phosphine-phospite (P-OP) ligands. These complexes exist in solution as mixtures of the fac and mer isomers, with the fac one being predominant. IR spectroscopy data reflect the lower donor ability of P-OP ligands compared to bis(trialkylphosphines), which are commonly used in previously reported non-bifunctional Mn catalysts. Complexes 1 are effective in the hydrogenation of a broad range of aldehydes and ketones under mild conditions. A combined spectroscopic and computational study support a catalyst activation mechanism involving nucleophilic attack of the alkoxide on a coordinated CO ligand, as well as a nonbifunctional inner sphere hydrogenation pathway.

A key aspect of the catalytic cycle is the formation of a remarkably stable pentacoordinated alkoxide intermediate. This intermediate determines the energetic span of the cycle, rather that barriers associated with the more demanding hydride migration or alkoxide protonation steps. This feature, inherent to catalysts operating by an inner sphere mechanism, seems critical in catalyst activity. These results are of practical significance, as they suggest that a wide variety of potential Mn catalysts precursors can readily be prepared in a single step from Mn(Br)(CO)₅ and commercially available bidentate phosphorous ligands.44 This modularity is particularly appealing for catalyst screening in asymmetric hydrogenation, 45 an area where most applications to date have relied on specifically designed PNP and PNN tridentate ligands for bifunctional catalysts.46 Further studies on the scope and enantioselective applications of the Mn-POP catalysts reported herein are currently underway and will be disclosed in due course.

Conflicts of interest

There are no conflicts to declare.

Data availability

Supplementary Information: experimental details of the synthesis and characterization of Mn complexes and procedures for catalytic hydrogenation reactions. NMR spectra of mechanistic experiments, X-ray crystallographic data for 1a, computational details and a coordinate file for structures calculated. See DOI: https://doi.org/10.1039/D5CY00906E.

CCDC 2468788 (1a) contains the supplementary crystallographic data for this paper.⁴⁷

The data supporting this article have been included as part of the supplementary information (SI).

Conflicts of interest

There are no conflicts to declare.

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