

## Solvent-free ketone hydrogenations catalyzed by molybdenum complexes†

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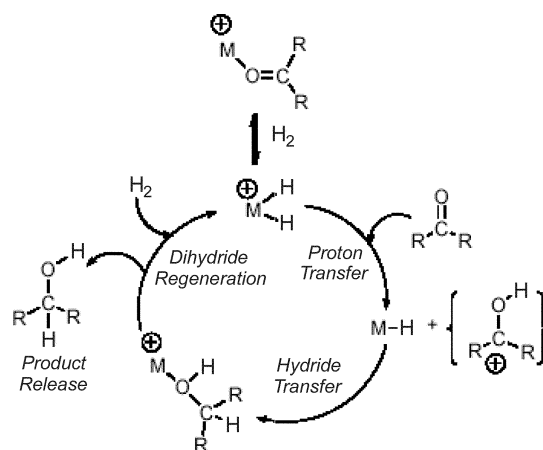
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$\text{Et}_2\text{C}=\text{O}$  is hydrogenated under solvent-free conditions using a catalyst prepared by hydride abstraction from  $\text{HMo}(\text{CO})_2[\eta^5\text{-}\eta^1\text{-C}_5\text{H}_4(\text{CH}_2)_2\text{PCy}_2]$ ; the catalyst functions at low catalyst loadings (< 0.4 mol%).

Environmental concerns provide a compelling incentive to develop chemical reactions that minimize waste production. The development of solvent-free (or 'solventless') reactions<sup>1,2</sup> is an especially attractive goal in the context of Green Chemistry,<sup>3</sup> since solvents are used on a large scale (over 15 billion kilograms of organic solvents produced worldwide annually!).<sup>1</sup> Catalytic hydrogenations of ketones and other organic substrates are traditionally carried out using platinum-group metals like rhodium and ruthenium,<sup>4</sup> though there are a few examples of catalysts not requiring precious metals. Darensbourg and co-workers reported the catalytic hydrogenation of ketones at 125 °C using 5 mol%  $[\text{W}(\text{CO})_5(\text{OAc})]^-$  as the catalyst precursor.<sup>5</sup> Our research on the reactivity of metal hydrides has led to a class of homogeneous hydrogenation catalysts using the base metals molybdenum and tungsten.<sup>6</sup> Research on these 'Cheap Metals for Noble Tasks' offers the potential for development of new types of catalysts that may provide cost savings and potentially other advantages over conventional homogeneous catalysts. One goal of our research is to develop catalysts based on inexpensive metals that may be useful in industrial processes to replace stoichiometric reagents like  $\text{LiAlH}_4$  or  $\text{NaBH}_4$ . Our efforts thus far have concentrated on using the mechanistic understanding gained from studies of proton transfer and hydride transfer reactions of metal hydrides to guide the rational design of catalysts. A series of ketone complexes,  $[\text{CpM}(\text{CO})_2(\text{PR}_3)(\eta^1\text{-Et}_2\text{C}=\text{O})]^+\text{BAR}'_4^-$  [ $\text{R} = \text{Ph}$  or  $\text{Me}$ ;  $\text{M} = \text{Mo}$  or  $\text{W}$ ;  $\text{Ar}' = 3,5\text{-bis(trifluoromethyl)phenyl}$ ], were shown to function as catalyst precursors for the hydrogenation of ketones under mild conditions (room temperature, 4 atm  $\text{H}_2$ ).<sup>6</sup> The proposed mechanism for these ionic hydrogenations is shown in Scheme 1.

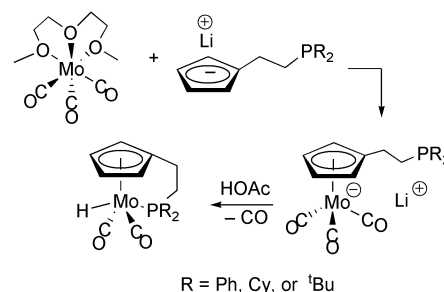
The turnover rates are relatively slow, however, and the catalysts suffer decomposition. We report here a new generation of Mo catalysts that exhibits substantially improved lifetimes, and which are shown to be effective for the hydrogenation of ketones under solvent-free conditions and low catalyst loadings.

The appearance of phosphonium cations,  $\text{HPR}_3^+$ , in catalytic reactions using  $[\text{CpM}(\text{CO})_2(\text{PR}_3)(\eta^1\text{-Et}_2\text{C}=\text{O})]^+$  suggested that the decomposition pathway involved dissociation of a phosphine, which is protonated under the reaction conditions. We sought to prepare catalysts with improved lifetimes by suppression of phosphine dissociation through chelation of the phosphine to the cyclopentadienyl ring by a two-carbon bridge. Reaction of  $(\text{CO})_3\text{Mo}(\text{diglyme})$ <sup>7</sup> with  $\text{Li}^+[\text{C}_5\text{H}_4(\text{CH}_2)_2\text{PR}_2]^-$ <sup>8</sup> produced  $\text{Li}^+[\text{Mo}(\text{CO})_3[\eta^5\text{-C}_5\text{H}_4(\text{CH}_2)_2\text{PR}_2]]^-$ . IR spectra of the  $\nu(\text{CO})$  bands were similar to those previously analyzed in detail for  $\text{Li}^+[\text{Mo}(\text{CO})_3\text{Cp}]^-$ ,<sup>9</sup> and  $^{31}\text{P}$  NMR peaks at  $\delta -13.2$  ( $\text{R} = \text{Ph}$ ),  $-1.8$  ( $\text{R} = \text{Cy}$ ) and  $31.8$  ( $\text{R} = \text{'Bu}$ ) were indicative of uncoordinated phosphines. Protonation of the anionic complexes with  $\text{HOAc}$  led



Scheme 1

to formation of the molybdenum hydrides  $\text{HMo}(\text{CO})_2[\eta^5\text{-}\eta^1\text{-C}_5\text{H}_4(\text{CH}_2)_2\text{PR}_2]^+$  and expulsion of one CO as the phosphine

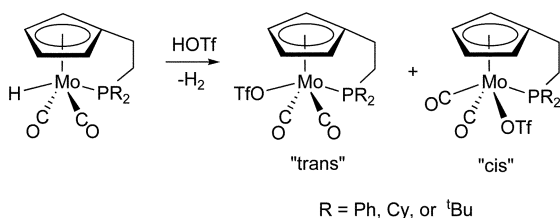


$\text{R} = \text{Ph}, \text{Cy}, \text{or 'Bu}$

coordinates to the metal. The metal hydrides exhibit broad  $^{31}\text{P}$  NMR resonances at  $\delta 74.4$  ( $\text{R} = \text{Ph}$ ),  $-80.6$  ( $\text{R} = \text{Cy}$ ) and  $103.8$  ( $\text{R} = \text{'Bu}$ ), consistent with coordination of the phosphine to the metal. The  $^{31}\text{P}$  NMR resonance of  $\text{HMo}(\text{CO})_2[\eta^5\text{-}\eta^1\text{-C}_5\text{H}_4(\text{CH}_2)_2\text{PCy}_2]$  at  $-89$  °C de-coalesces into two sharper resonances ( $\omega_{1/2} \approx 7$  Hz) at  $\delta 78.7$  (98%) and  $89.3$  (2%). The  $^1\text{H}$  NMR spectrum of  $\text{HMo}(\text{CO})_2[\eta^5\text{-}\eta^1\text{-C}_5\text{H}_4(\text{CH}_2)_2\text{PCy}_2]$  recorded at  $-89$  °C also indicates 98% *trans* isomer. These spectra indicate that the hydrides exist as an interconverting mixture of *cis* and *trans* isomers. Isomerization between the *trans* and *cis* isomers was reported previously for closely related complexes with unsubstituted Cp ligands such as  $\text{CpMo}(\text{CO})_2(\text{PPh}_3)_2\text{H}$ ,<sup>10</sup>  $\text{CpMo}(\text{CO})_2(\text{PMe}_3)_2\text{H}$ ,<sup>11</sup> and  $\text{CpMo}(\text{CO})_2(\text{PCy}_3)_2\text{H}$ .<sup>12</sup> Whereas such isomerizations are well-known, it is notable that the *trans* isomer strongly predominates in  $\text{HMo}(\text{CO})_2[\eta^5\text{-}\eta^1\text{-C}_5\text{H}_4(\text{CH}_2)_2\text{PCy}_2]$ , in contrast to  $\text{HMo}(\text{CO})_2(\text{PCy}_3)_2$  where the *cis* isomer is favored by a ratio of 9:1.<sup>12</sup> The structure of  $\text{HMo}(\text{CO})_2[\eta^5\text{-}\eta^1\text{-C}_5\text{H}_4(\text{CH}_2)_2\text{PCy}_2]$  was determined by single crystal X-ray diffraction and indicates the *trans* isomer in the solid state; details of the structure will be given in a full paper.

The metal hydrides,  $\text{HMo}(\text{CO})_2[\eta^5\text{-}\eta^1\text{-C}_5\text{H}_4(\text{CH}_2)_2\text{PR}_2]$ , react cleanly with HOTf (OTf =  $\text{OSO}_2\text{CF}_3$ ) at room temperature to form *cis*- and *trans*- $\text{Mo}(\text{CO})_2[\eta^5\text{-}\eta^1\text{-C}_5\text{H}_4(\text{CH}_2)_2\text{PR}_2](\text{OTf})$ , presumably through unobserved dihydride or dihydrogen complexes that

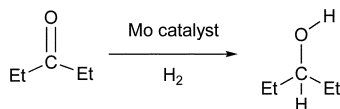
† Electronic supplementary information (ESI) available: additional spectroscopic data and description of the synthetic procedures. See <http://www.rsc.org/suppdata/cc/b4/b401760a/>



eliminate H<sub>2</sub>. Clean hydride transfer reactivity from HMo(CO)<sub>2</sub>[η<sup>5</sup>:η<sup>1</sup>-C<sub>5</sub>H<sub>4</sub>(CH<sub>2</sub>)<sub>2</sub>PR<sub>2</sub>] to Ph<sub>3</sub>C<sup>+</sup>BF<sub>4</sub><sup>−</sup> in CD<sub>3</sub>CN is observed, producing complexes with acetonitrile ligands, *trans*- and *cis*-Mo(CO)<sub>2</sub>[η<sup>5</sup>:η<sup>1</sup>-C<sub>5</sub>H<sub>4</sub>(CH<sub>2</sub>)<sub>2</sub>PR<sub>2</sub>(NCCD<sub>3</sub>)]<sup>+</sup>BF<sub>4</sub><sup>−</sup>. The *cis* and *trans* isomers of these complexes are readily distinguished by their <sup>1</sup>H NMR spectra. The *trans* isomers have a plane of symmetry and exhibit two sets of resonances for the C<sub>5</sub>H<sub>4</sub> protons. In contrast, the *cis* isomer has no plane of symmetry, so its cyclopentadienyl protons appear as four separate multiplets.

In our earlier studies, the ketone complexes [CpM(CO)<sub>2</sub>PR<sub>3</sub>(Et<sub>2</sub>C=O)]<sup>+</sup>BAR'<sub>4</sub><sup>−</sup> (M = Mo, W; R = Ph, Me) were isolated and used as the catalyst precursors. Catalysis from CpM(CO)<sub>2</sub>(PCy<sub>3</sub>)H was initiated by carrying out the hydride transfer *in situ*, without isolation of the ketone complex. Similar reactions of HMo(CO)<sub>2</sub>[η<sup>5</sup>:η<sup>1</sup>-C<sub>5</sub>H<sub>4</sub>(CH<sub>2</sub>)<sub>2</sub>PPh<sub>2</sub>] with Ph<sub>3</sub>C<sup>+</sup>BAR'<sub>4</sub><sup>−</sup> with 1–2 equivalents of Et<sub>2</sub>C=O gave spectral evidence for the formation of the ketone complexes, but pure ketone complexes were not isolated. Thus the catalytic reactions were carried out by hydride transfer from the metal hydride to Ph<sub>3</sub>C<sup>+</sup>BAR'<sub>4</sub><sup>−</sup> *in situ*, as was done for the PCy<sub>3</sub> complexes previously.

Initial conditions for the catalytic hydrogenations were identical to those used earlier in the non-bridged systems (30 mM metal hydride + 30 mM Ph<sub>3</sub>C<sup>+</sup>BAR'<sub>4</sub><sup>−</sup> in CD<sub>2</sub>Cl<sub>2</sub> under 4 atm H<sub>2</sub> at 23 °C,



10 equivalents of Et<sub>2</sub>C=O (initially 300 mM). Under these conditions, the C<sub>2</sub>-PCy<sub>2</sub> catalyst produced 2.8 turnovers in 6 h, indicating that it is less reactive than the catalyst formed from CpMo(CO)<sub>2</sub>(PCy<sub>3</sub>)H, which produced about 8.6 turnovers in 6 h. Although the new C<sub>2</sub>-bridged catalyst is initially less active than the related complex without the C<sub>2</sub> bridge, an advantage of the C<sub>2</sub>-bridged complex is its much longer lifetime compared with the unbridged catalyst precursor. While these conditions provided a direct comparison of the bridged vs. unbridged catalysts and afforded the convenience of direct NMR tube monitoring of the reaction, they were not ideal since it was necessary to periodically replenish the reaction tube with more ketone and H<sub>2</sub>. Solvent-free hydrogenations were carried out neat Et<sub>2</sub>C=O, and the results are summarized in Table 1.

The PCy<sub>2</sub>-bridged systems give higher turnovers than analogs with either a PPh<sub>2</sub> or P<sup>t</sup>Bu<sub>2</sub> bridge. The C<sub>2</sub>-bridge that chelates the cyclopentadienyl to the phosphine clearly confers substantial additional stability to the complex, as shown by the experiments at 50 and 75 °C. In contrast, the unchelated systems reported earlier showed some decomposition even at room temperature. The BAR'<sub>4</sub><sup>−</sup> anion gives superior performance compared with the BF<sub>4</sub><sup>−</sup> anion, presumably due to more facile decomposition pathways available to the BF<sub>4</sub><sup>−</sup> complexes. Another improvement over the unchelated earlier systems is that complexes with a bound triflate ligand give catalysis, though as shown in the table for reactions with HMo(CO)<sub>2</sub>[η<sup>5</sup>:η<sup>1</sup>-C<sub>5</sub>H<sub>4</sub>(CH<sub>2</sub>)<sub>2</sub>PCy<sub>2</sub>], the BAR'<sub>4</sub><sup>−</sup> counterion provides a better performance than the complex with a bound triflate. Although most experiments were carried out at 4 atm H<sub>2</sub>, a higher pressure can be beneficial. Of particular note is the complete hydrogenation of neat Et<sub>2</sub>C=O catalyzed by 0.35 mol% Mo complex in 8 days at 50 °C at 55 atm H<sub>2</sub>.

**Table 1** Hydrogenation of Et<sub>2</sub>C=O by HMo(CO)<sub>2</sub>[η<sup>5</sup>:η<sup>1</sup>-C<sub>5</sub>H<sub>4</sub>(CH<sub>2</sub>)<sub>2</sub>PR<sub>2</sub>] + Ph<sub>3</sub>C<sup>+</sup>BAR'<sub>4</sub><sup>−</sup> or Mo(CO)<sub>2</sub>[η<sup>5</sup>:η<sup>1</sup>-C<sub>5</sub>H<sub>4</sub>(CH<sub>2</sub>)<sub>2</sub>PR<sub>2</sub>](OTf). 4 atm H<sub>2</sub>, except where noted

R	A <sup>−</sup>	T/°C	Mo/mol%	TON(total) t = 10 days <sup>a</sup>
Ph	BAR' <sub>4</sub> <sup>−</sup>	50	0.35	62 [1]
Cy	BAR' <sub>4</sub> <sup>−</sup>	23	0.35	23 [ $< 1$ ]
Cy	BAR' <sub>4</sub> <sup>−</sup>	50	0.35	132 [10]
Cy	BAR' <sub>4</sub> <sup>−</sup>	50	0.35	283 [34] <sup>b</sup>
Cy	BF <sub>4</sub> <sup>−</sup>	50	0.35	99 [6]
Cy	OTf	50	0.35	120 [4]
Cy	OTf	75	0.086	462 [16]
<sup>t</sup> Bu	BAR' <sub>4</sub> <sup>−</sup>	50	0.35	82 [6]

<sup>a</sup> TON (turnover number) after 10 days. The number in brackets indicates the TON for the ether condensation product, (Et<sub>2</sub>CH)<sub>2</sub>O. <sup>b</sup> H<sub>2</sub> pressure of 55 atm; hydrogenation complete at t = 8 days.

This new generation of Mo catalysts was rationally designed from mechanistic principles to disfavor a decomposition pathway identified for previously studied complexes. Several advantages were found with these new complexes, including low catalyst loadings (<0.4 mol%), higher thermal stability, substantially longer lifetimes (hundreds of turnovers), and utility under solvent-free conditions. Further improvements are being sought to produce catalysts that might provide attractive replacements for stoichiometric hydrogenation reagents like LiAlH<sub>4</sub>.

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## Notes and references

† Spectral data for HMo(CO)<sub>2</sub>[η<sup>5</sup>:η<sup>1</sup>-C<sub>5</sub>H<sub>4</sub>(CH<sub>2</sub>)<sub>2</sub>PCy<sub>2</sub>]: <sup>1</sup>H NMR (400 MHz, CD<sub>2</sub>Cl<sub>2</sub>): δ −5.81 (d, <sup>2</sup>J<sub>PH</sub> = 26.8, 1H, MoH), 1.24–2.00 (m, 22H, Cy), 2.38 (m, 2H, PCH<sub>2</sub>), 2.47 (m, 2H, C<sub>5</sub>H<sub>4</sub>CH<sub>2</sub>), 4.96 (br, 2H, α-C<sub>5</sub>H<sub>4</sub>), 5.09 (m, 2H, β-C<sub>5</sub>H<sub>4</sub>); <sup>31</sup>P{<sup>1</sup>H} NMR (162.0 MHz, CD<sub>2</sub>Cl<sub>2</sub>): δ 80.6 (br, ω<sub>1/2</sub> = 200 Hz); <sup>13</sup>C{<sup>1</sup>H} NMR (100.6 MHz, CD<sub>2</sub>Cl<sub>2</sub>): δ 25.8 (br, PCH<sub>2</sub>), 26.7 (s, *m*- or *p*-Cy), 27.6 (d, <sup>2</sup>J<sub>CP</sub> = 13 Hz, *o*-Cy), 29.0 (s, *m*- or *p*-Cy), 37.0 (d, <sup>2</sup>J<sub>CP</sub> = 23 Hz, *ipso*-Cy), 37.3 (v br, C<sub>5</sub>H<sub>4</sub>CH<sub>2</sub>), 81.8 (s, *o*-C<sub>5</sub>H<sub>4</sub>), 87.4 (s, *m*-C<sub>5</sub>H<sub>4</sub>), 125.1 (d, <sup>3</sup>J<sub>CP</sub> = 6 Hz, *ipso*-C<sub>5</sub>H<sub>4</sub>), 234 (v br, CO); IR (THF): ν(CO) = 1927 (s), 1848 (vs) cm<sup>−1</sup>; Anal. calc. for C<sub>21</sub>H<sub>31</sub>O<sub>2</sub>PMo (442.4): C, 57.02; H, 7.06. Found: C, 56.92, H, 6.99%. Additional spectroscopic data and a description of the synthetic procedures are provided in the ESI.†

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