Activation of molecular oxygen by a molybdenum complex for catalytic oxidation†

Antoine Dupé,†a Martina E. Judmaier,†a Ferdinand Belaj,ab Klaus Zanggerb and Nadia C. Mösch-Zanettia

A sterically demanding molybdenum(VI) dioxo complex was found to catalytically activate molecular oxygen and to transfer its oxygen atoms to phosphines. Intermediate peroxo as well as reduced mono-oxo complexes were isolated and fully characterized. Monomeric Mo(IV) mono-oxo species proved to be of an unusual nature with the coordinated phosphine trans to the oxo group. The reduced molybdenum centers can activate O₂ to form a stable Mo(IV) oxo–peroxo complex unambiguously characterized by single crystal X-ray diffraction analysis. NMR experiments demonstrate that both oxygen atoms of the peroxo unit are transferred to an accepting substrate, generating the Mo(IV) intermediate and restarting the catalytic cycle.

Although many iron, manganese and copper complexes are known to react with dioxygen,9 only rare examples of molecular oxygen activation by molybdenum have been previously reported,10,11 including one by our group,12 and the reactivity of these oxo–peroxo molybdenum is limited. Few homogeneously molybdenum catalyzed oxidations employing molecular oxygen were reported. A bimetallic molybdenum/copper catalyst was disclosed by Osborn and coworkers for the oxidation of alcohols.13 It represents a “Wacker-type reaction” where the alcohol is oxidized by molybdenum but reoxidation is mediated by the copper co-catalyst and not by molecular oxygen directly. Selected reports can be found in literature where O₂ was used in Mo catalyzed oxidation chemistry14 but high catalyst loadings were needed and/or it remains unclear whether autooxidation is occurring.

In the course of our ongoing research on high-valent molybdenum-oxo complexes bearing Schiff-base ligands and their reactivity in OAT reactions,15–17 we report herein the synthesis and characterization of a new molybdenum(VI) dioxo complex which can be reduced and subsequently activate dioxygen to form a new molybdenum(VI) oxo–peroxo complex. This activation proceeds via the formation of a five-coordinated molybdenum(VI) mono-oxo complex or a highly unusual trans-[MoO(PMe₃)₂]⁺ intermediate which was characterized by NMR spectroscopy and elemental analysis. Furthermore, we demonstrate that the molybdenum(VI) oxo–peroxo complex is also active in OAT reaction and able to transfer both oxygen atoms of the peroxo moiety to an accepting substrate. Benchmark oxidation of tertiary phosphine18 confirms the catalytic activity of the complexes. This reactivity is a new step toward the use of oxygen as oxidant in molybdenum-catalyzed oxidation reactions.

Introduction

High-valent molybdenum-oxo complexes are of considerable interest as catalysts for oxidation reactions.1,2 In nature, molybdenum oxotransferases are a broad class of enzymes that transfer an oxygen atom to or from a substrate, using mainly water as a source of oxygen.3 The active site of these enzymes consists of a molybdenu(VI) center substituted by at least one oxo group and one or two molybdopterin ligands.4 In order to mimic the activity of such enzymes, a wide range of model compounds containing a high valent [MoO₂]²⁺ core have been prepared.5 While oxygen atom transfer (OAT) capability of such complexes can be investigated using phosphines or sulfides as oxygen accepting substrates, they are also commonly used as catalysts for alkene epoxidation reactions and have thus found wide applications in industry.6 In the most efficient systems, tert-butyl hydroperoxide or hydrogen peroxide solutions are used as oxidant.1,7 However, following the principles of sustainable chemistry, the use of molecular oxygen as oxidant would be highly desirable; it is abundant, cheap, readily available and ideally does not lead to the formation of side-products.8 Despite these advantages, controlling the reactivity of dioxygen with transition metal centers is a challenge.

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Results and discussion

The molybdenum-dioxo complex [MoO₂L₂] 1 was synthesized by addition of a solution of the ligand 2,4-di-tert-butyl-6-((tert-butylamino)methyl)phenol (HL)¹⁹ in toluene to a solution of 1 equiv. of [MoO₂Cl₂] in toluene in presence of an excess trimethylamine (Scheme 1). After stirring for 15 h, filtration and washing with cold pentane, 1 was obtained as a orange solid in good yield (64%). The ¹H NMR spectrum reveals the formation of a single, symmetric isomer as only one set of resonances for both coordinated ligands is observed. The IR spectrum of 1 exhibits two strong ñMo=O bands at 885 and 912 cm⁻¹ for both the symmetric and asymmetric stretching mode of the cis-[MoO₂]²⁺ fragment, in good accordance with the literature.¹⁶,²⁰ Mass spectrometry as well as elemental analysis confirmed the formation of complex 1 as [MoO₂L₂].

This structure was confirmed by single crystal X-ray diffraction analysis. Suitable crystals were obtained from concentrated solution of 1 in toluene (Fig. 1). Crystal data and structure refinements are presented in the Experimental section. Complex 1 exhibits a six-coordinate metal center in a distorted octahedral geometry.

Reactivity of the dioxo complex 1 in oxygen atom transfer (OAT) reactions was studied using trimethylphosphine and triphenylphosphine as oxygen acceptor substrates, allowing easy monitoring by ³¹P NMR spectroscopy. Complex 1 was first reacted with an excess (4–5 equiv.) trimethylphosphine in toluene under inert conditions (Scheme 2).

The reaction was indicated by a quick change of color from deep orange to crimson and ³¹P NMR measurements reveal the formation of OPMe₃ and further reduced molybdenum(IV) complex 2. After evaporation of the solvent and excess PMe₃, then re-dissolution of the crude material in cold heptane, OPMe₃ is removed via subsequent filtration over a pad of Celite. The pure reduced complex 2 was isolated as a highly sensitive to moisture and air, crimson solid in excellent yield (87%). Interestingly, ¹H and ¹³C NMR spectra revealed the formation of a symmetric compound as only one set of resonances for both coordinate ligands is observed (Table 1). Characteristic signals in the ¹H NMR spectrum in benzene-d₆ are given at 8.33 ppm (imine proton), 7.42 and 7.19 ppm (aromatic protons). The ³¹P NMR spectrum of a concentrated solution of 2 in benzene-d₆ points to the existence of a single Mo=PMe₃ species (−9.47 ppm) further evidenced by the occurrence of a doublet at 0.91 ppm with the integration of nine protons in the ¹H NMR spectrum.

The symmetric coordination in complex 2 has not been described in the literature up to now. In such type of OAT reactions, either the formation of a dimeric Mo(v)–O–Mo(v) species is observed, or the free coordination site is captured by a phosphine in cis position to the [MoO]²⁺ metal core, forming complexes of the type [MoO(PR₃)L₂]¹₂,¹⁵,²¹ or [MoO(OPR₃)L₂].²² Such complexes render the geometry around the metal center non-symmetric and therefore lead to two sets of resonances

![Scheme 1 Synthesis of Mo–dioxo complex 1.](Image)

![Scheme 2 Synthesis of molybdenum(IV) complex 2.](Image)

**Table 1** ¹H NMR characteristic signals shifts in ppm for complexes 1, 2, 3 and 4 in benzene-d₆

<table>
<thead>
<tr>
<th>Compd.</th>
<th>Ar–CHN</th>
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<td>4</td>
<td>8.63, 8.55</td>
<td>7.60, 7.49</td>
<td>7.19, 7.19</td>
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for both coordinate ligands in NMR analysis. Our results point to the symmetric coordination of the PMe3 molecule in trans position to the Mo=O moiety. Although an equilibrium between a trans and cis species is in principle feasible, this is very unlikely as we observe narrow peaks in NMR spectroscopy. Furthermore, low temperature $^{31}$P NMR spectroscopy in toluene-d$_8$ at $\text{−30 \degree C}$ shows only one signal (see ESI†). This unusual arrangement is presumably caused by the high steric demand of the ligand. Two isomers are conceivable with the phosphine and the oxo groups trans to each other, namely the trans-N,N isomer depicted in Scheme 2 and the trans-N,O isomer, but the latter seems sterically too congested to exist.

ESI-MS measurements and elemental analysis corroborates the formation of a monomeric $[\text{MoO(PMe}_3\text{)}\text{L}_2]$ complex. Information about the molecular size of the complex was obtained from 2D DOSY diffusion measurements on a sample containing complex 2 and free ligand in benzene-d$_8$. For the free ligand (HL), a diffusion coefficient $D = 8.805 \text{ (log(m^2 s^{-1}))}$ corresponding to $1.57 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ was found, while complex 2 diffuses with a $D = 8.878 \text{ (log(m^2 s^{-1}))}$ corresponding to $1.32 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$. Based on the Stokes–Einstein equation, the relative hydrodynamic radii of two components are related to the diffusion coefficients by $D_1/D_2 = r_2^3/r_1^3$. Therefore, the experimental diffusions coefficients of complex 2 and free ligand correspond to relative hydrodynamic radii of 1.18 : 1. Such an increase of 18% of the diameter of the complex relative to HL can only be explained by a monomer. In addition, the DOSY analysis of a sample containing the dioxo complex 1 and the reduced complex 2 showed similar diffusion for both complexes (see ESI†).

The OAT reaction of complex 1 with 2 equiv. PPh$_3$ in benzene-d$_8$ at room temperature as well results in a color change from deep orange to purple. After 5 h under stirring, an NMR sample was taken. $^1$H and $^{13}$C NMR spectra exhibited again one set of resonances for both coordinate ligands, indicating formation of a new symmetric compound $[\text{MoOL}_2]$ 3. Characteristic signals in $^1$H NMR in benzene-d$_8$ (Table 1) are given at 8.21 ppm (imine proton), 7.47 and 7.24 ppm (aromatic protons). $^{31}$P NMR confirmed formation of OPPh$_3$ (signal at 24.78 ppm) but showed that the other equivalent of PPh$_3$ does not coordinate the molybdenum center and thus remains free (signal at 5.41 ppm). Evaporation of the solvent led to a highly air sensitive purple powder which contains 3, OPPh$_3$ and PPh$_3$. Removal of OPPh$_3$ was performed by filtration of a heptane solution of the mixture over dry Celite, which however did not remove residual PPh$_3$. Thus, sublimation of residual PPh$_3$ at 100 °C was attempted to isolate 3, but only lead to decomposition of the complex. Nevertheless, its sensitivity towards air as well as $^1$H and $^{31}$P NMR spectroscopy lead us to believe that the monooxo $[\text{MoOL}_2]$ complex 3 is formed in situ rather than a Mo(v) dimer or a Mo(iv) phosphino species. The monomeric structure of 3 was confirmed by DOSY analysis, with a diffusion coefficient similar to that obtained for complex 2.

Although complexes with the $[\text{MoO(O}_2\text{)}]$$_2^{2+}$ or $[\text{MoO}_2\text{O}_2]$$_2^{2+}$ cores are relatively abundant in the literature, as complexes thereof are available from the reaction of $[\text{MoO}_3]$ and the appropriate ligand in aqueous H$_2$O$_2$, the activation of molecular oxygen by molybdenum compounds is scarce in the literature. As previously described by our group, re-oxidation of the molybdenum(iv) complex type $[\text{MoO(PMe}_3\text{)}\text{L}_2]$ with molecular oxygen either results in the formation of $[\text{MoO}_2]$$_2^{2+}$ or $[\text{MoO}_2\text{O}_2]$$_2^{2+}$ complexes, depending on the steric demand in the ligand backbone. When benzene-d$_8$ solutions of 2 and 3 were exposed to dry molecular oxygen, color change from crimson to orange for complex 2 and from purple to orange for 3 occurred. $^1$H and $^{13}$C NMR spectra indicate the formation of the same, non-symmetric compound in both reactions, as two sets of resonances for both coordinated ligands are observed (e.g. in the $^1$H NMR spectra 2 × Ar–CHN at 8.55 and 8.63 ppm, Table 1). Such behavior is in good accordance to the literature regarding the formation of a $[\text{MoO(O}_2\text{)}]$$_2^{2+}$ complex, as the coordination of the O$_2$ molecule in cis position to the [MoO]$_2^{2+}$ renders the geometry around the metal center non-symmetric. It is noteworthy that this $[\text{MoO}_2\text{O}_2]$$_2^{2+}$ complex 4 can be synthesized directly by reacting 1 with a 5-fold excess phosphine under O$_2$ atmosphere. After purification, 4 was isolated as an orange solid in 93% yield (Scheme 3).

Single crystals suitable for X-ray diffraction analyses of complex 4 were obtained from concentrated THF solutions layered with pentane at room temperature. Crystal data and structure refinements are presented in the Experimental section. The structure reveals a hepta-coordinated metal center in a distorted pentagonal bi-pyramidal geometry (Fig. 2). The metal center is ligated by one terminal oxygen atom, a η$^2$-peroxo moiety and two bidentate Schiff base ligands. The terminal oxygen atom is found to be in cis position to the η$^2$-peroxo moiety. All these features as well as bonds lengths and angles values are in good accordance with similar $[\text{MoO}_2\text{O}_2]$$_2^{2+}$ complexes reported previously in the literature.$^{10,12,24}$

The re-oxidation of the reduced $[\text{MoO(PMe}_3\text{)}\text{L}_2]$ complex 2 with molecular O$_2$, yielding the $[\text{MoO}_2\text{O}_2]$$_2^{2+}$ complex 4 (Scheme 3), provided an interesting information. The $^{31}$P NMR spectra measured directly after exposition of 2 to O$_2$ showed that the phosphate attached to the Mo is released as a free phosphine when 4 is formed. The same NMR sample, maintained under O$_2$ atmosphere was submitted again for analysis after 24 h. The $^{31}$P NMR spectra revealed that the equivalent of

![Scheme 3](image-url)
Although the reaction does not go to completion, $^1$H NMR spectra show formation of a new molybdenum species and OPMe$_3$ rendering the system reactive. Such labilization of phosphine ligands due to a second oxygen atom is either concerted or occurs much faster. This was corroborated by kinetic experiments using UV-Vis spectroscopy. The OAT reaction from complex 1 with a 100-fold excess PMe$_3$ (pseudo-first order conditions) to form the reduced complex 2 was found to have a rate constant $k = 0.003 \text{ s}^{-1}$. The corresponding reaction of complex 4 with 100 equiv. PMe$_3$ and the same concentration for the complex and phosphine was found to be orders of magnitude slower as hardly any reaction occurred in the observed timeframe (see ESI†).

As both the dioxo and oxo-peroxo complexes are active in OAT reaction, catalytic oxidation of PMe$_3$ was investigated. In the literature, the molybdenum complexes which activate O$_2$ could not catalytically oxidize phosphines. [MoO(O$_2$)(CN)$_4$]$_2$-[PPh$_4$]$_2$ is capable of oxidizing 3 mol PPh$_3$ per 2 mol molybdenum in the presence of molecular O$_2$, but no further oxidation of PPh$_3$ was obtained due to conproportionation of the dioxo Mo(IV) and the monooxo Mo(II) intermediates. Although PMe$_3$ is easily oxidized without any metal in presence of water and air, the stability of PMe$_3$ against dry O$_2$ in dry benzene-$_d_6$ solutions was confirmed by running a blank experiment (see ESI†). For the catalytic run, a solution of 1 (10 mg, 14 μmol) in benzene-$_d_6$ was prepared and placed under O$_2$ atmosphere. Then 100 equivalents PMe$_3$ were added and the reaction was left to stir for 24 h (Scheme 4). The reaction was monitored by $^1$H and $^{31}$P NMR analysis. Integration of PMe$_3$ and OPMe$_3$ signals after 24 h showed the conversion of 19 equivalents PMe$_3$ to OPMe$_3$. After evaporation of the solvent and unreacted phosphine, mass balance confirmed formation of OPMe$_3$ besides the residue of the catalyst. Control experiments in the presence of sodium molybdate or [MoO$_2$(acac)$_2$] did not lead to formation of OPMe$_3$. The reactivity of 1 is limited by free PMe$_3$ formed during the re-oxidation had been converted to OPMe$_3$. Thus, when 2 reacted with O$_2$ as presented in Scheme 3, substitution of the phosphine by O$_2$ occurred and only subsequently PMe$_3$ was oxidized to OPMe$_3$ by the complex 4 (see Fig. S3 in ESI†). These observations are noteworthy as phosphine is usually strongly coordinated, so that prior oxidation is required for its displacement. Here, the steric demand of the ligand and the trans-effect resulting from the presence of the oxo group leads to a weakly coordinated PMe$_3$ rendering the system reactive. Such labilization of phosphine ligands due to a trans-effect was already observed with other Mo complexes. The fact that the free PMe$_3$ equivalent could be oxidized under O$_2$ atmosphere in presence of 4 lead us to investigate the role of the oxo-peroxo complex as possible catalyst for the oxidation of phosphine using O$_2$, as described thereafter. In order to exclude auto oxidation of PMe$_3$ and to prove the reactivity of the oxo-peroxo complex in OAT, the reaction of 4 with 2 equiv. PMe$_3$ in exclusion of O$_2$ was investigated (Scheme 4). Monitoring the reaction by $^1$H and $^{31}$P NMR spectroscopy revealed that the oxo-peroxo complex 4 is able to oxidize tertiary phosphines, but more importantly that both atoms of the peroxo group are involved in this transfer. Although the reaction does not go to completion, $^1$H NMR spectra show formation of a new molybdenum species and OPMe$_3$ in a 1 : 2 ratio, along with unreacted PMe$_3$ and complex 4. As shown in Fig. 3, after $t = 5$ h approx. 25% conversion is observed and after $t = 30$ h 50%. This Mo intermediate exhibits a single set of signal very similar to that of the Mo(IV) monooxo complex 2 (e.g. signals at 8.34, 7.40 and 7.21 ppm). The small differences between the $^1$H NMR signals of the observed Mo intermediate and 2 can be explained by differences in the coordination of the phosphine. In the intermediate, PMe$_3$ is only weakly interacting with Mo but is not fully coordinated. This explanation is supported by the $^1$H NMR signal of the weakly interacting PMe$_3$ (0.86 ppm, $J_{P-C} = 4.2$ Hz), which is different from free PMe$_3$ (0.81 ppm, $J_{P-C} < 2$ Hz) and from the fully bound PMe$_3$ in 2 (0.91 ppm, $J_{P-C} = 7$ Hz). During the course of the reaction, no formation of a plausible Mo(IV) dioxo intermediate (complex 1) was observed, indicating that the transfer of the first oxygen atom from the peroxo unit is the rate determining step of the process, while transfer of the second oxygen atom is either concerted or occurs much faster.

The molecular structure of complex 4 is shown in Fig. 2. Thermal ellipsoids have been drawn at 50% probability level. Hydrogen atoms are omitted for clarity.

**Scheme 4** OAT reaction of the oxo-peroxo complex 4 in exclusion of O$_2$ in benzene-$d_6$. 

**Fig. 2** Molecular structure of complex 4. Thermal ellipsoids have been drawn at 50% probability level. Hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and angles (°): Mo1–O1 1.6909(10); Mo1–O2 1.9487(10); Mo1–O3 1.9447(10); Mo1–N1 2.2548(11); Mo1–N2 2.2162(11); O2–O3 1.4332(13); O1–Mo1–O11 170.37(4); O2–Mo1–O31 155.69(4); O3–Mo1–O31 153.96(4); N1–Mo1–N3 165.72(4); O1–Mo1–O2 99.17(5); O1–Mo1–O3 101.82(5); O1–Mo1–O31 91.99(4); O1–Mo1–N1 91.57(4).
decomposition of the complex, but is a successful progress toward the use of molecular oxygen as sole oxidant in catalytic OAT reactions.

Conclusion

We were able to prepare a new molybdenum(VI) dioxo complex 1 which is active in oxygen atom transfer reaction to tertiary phosphines, allowing the isolation of the unusual trans-[MoO-(PMe3)L2] complex 2. The activation of molecular oxygen by the reduced species yields the oxo-peroxo complex [MoO(O2)-L2] 4 in excellent yield. 4 is also active in OAT and NMR spectroscopy studies show that both atoms of the peroxo group are transferred to phosphine. Hence, the molybdenum (VI) dioxo complex 1 exhibits promising results as catalyst for oxidations using O2 as the oxidant.

Experimental section

All reactions have been carried out under nitrogen using standard Schlenk or glovebox techniques. [MoO2Cl2] was purchased from Sigma-Aldrich and used in the Glovebox without further purification. The Schiff base ligand was synthesized according to previously published literature.19 Solvents were purified via a Pure-Solv MD-4-EN solvent purification system from Innovative Technology, Inc. The 1H and 13C NMR spectra were recorded on a Bruker Optics Instrument 300 MHz. Peaks are denoted as singlet (s), doublet (d), doublet of doublets (dd), triplet (t) and multiplet (m), Ar denotes aromatic protons. Chemical shifts are reported in ppm and are referenced using the residual solvent peak. To obtain self-diffusion coefficients we used two-dimensional diffusion ordered spectroscopy (DOSY).26 The employed pulse sequence was a bipolar pulse pair longitudinal eddy current delay (BPP-LED) sequence, using 32 scans per increment, 60 ms diffusion delay time, 1 ms gradient pulses and variation of the gradient strength in 32 increments, linearly varied between 2 and 95% of maximum (which is 53.5 G cm−1). DOSY analysis was performed using the Bruker DOSY package of TopSpin 3.1. All DOSY measurements were carried out at 300 K on a Bruker Avance III 500 MHz NMR spectrometer using a 5 mm TXI probe with z-axis gradients. IR spectra were measured as solid samples on a Bruker Alpha P Diamond FTIR-ATR spectrometer or as liquid samples in benzene on a Bruker FT-MIR matrix MF in situ spectrometer using a glass fiber optic probe. ESI-MS spectra were recorded in acetonitrile on an Agilent 1100 Series LC/MSD (SL type). Elemental analyses were carried out using a Heraeus Vario Elementar automatic analyzer at the Institute of Inorganic Chemistry at the University of Technology in Graz.
Ligand HL (500 mg, 1.7 mmol, 2 equiv.) was dissolved in 5 ml of dry toluene and slowly added to a suspension of [MoO₂Cl₂] (180 mg, 0.9 mmol, 1 equiv.) in 5 ml of dry toluene under inert conditions. Dry triethylamine (0.26 mL, 1.9 mmol, 2.2 equiv.) was then added. The formation of the complex was immediately indicated by a quick change of color from pale yellow to deep red. To ensure complete complex formation, the solution was stirred 5 h at room temperature. The mixture was then filtered with a cannula and the solvent was removed in vacuo. The residue was washed thrice with 10 ml of cold pentane to afford complex 1 as an orange solid in 64% yield (407 mg). Single crystals suitable for X-ray diffraction analyses were obtained by slow evaporation from concentrated toluene solution at room temperature.

$^1$H NMR (300 MHz, benzene-d₆, ppm) $\delta$ = 8.33 (s, 1H, Ar–CH(N)), 7.66 (d, $^3$J_H-H = 2.7 Hz, 1H, Ar–H), 7.15 (d, $^3$J_H-H = 2.7 Hz, 1H, Ar–H), 1.56 (s, 9H, NC(CH₃)₃), 1.33 (s, 9H, Ar–C(CH₃)₃), 1.30 (s, 9H, Ar–C(CH₃)₃).

Anal. Calc. for MoO₃N₂PC₆₃H₆₀: C, 64.38; H, 9.09; N, 3.66. Found: C, 64.25; H, 9.23; N, 3.38%.

$[^{19}$F] NMR (100 mg, 0.14 mmol, 1 equiv.) was dissolved in dry benzene (5 ml) followed by the addition of excess PMe₃ (53 mg, 70 µL, 0.70 mmol, 5 equiv.). The OAT was indicated by a quick change of color from orange to dark red. The solution was stirred for 30 minutes, followed by exposure of this solution to dry molecular oxygen for 5 minutes. The reaction solution quickly changed the color from dark violet to orange. The mixture was left to stir for 30 minutes and the solvent was removed in vacuo. The product was dissolved in heptane (5 ml) and twice filtered over a pad of Celite. [MoO₂L₂] was obtained as an orange solid. Yield: 87 mg (93%). For elemental analyses, the complex was dissolved in minimum amount of CH₂Cl₂ and again filtered over a pad of Celite. Single crystals suitable for X-ray diffraction analyses were obtained from concentrated THF solutions layerd with pentane.

$^1$H NMR (300 MHz, benzene-d₆, ppm) $\delta$ = 8.63 (s, 1H, Ar–CH(N)), 8.55 (s, 1H, Ar–CH(N)), 7.60 (d, $^3$J_H-H = 2.4 Hz, 1H, Ar–H), 7.49 (d, $^3$J_H-H = 2.4 Hz, 1H, Ar–H), 7.19 (d, $^3$J_H-H = 2.4 Hz, 2H, Ar–H), 1.87 (s, 9H, NC(CH₃)₃), 1.74 (s, 9H, NC(CH₃)₃), 1.41 (s, 9H, Ar–C(CH₃)₃), 1.27 (s, 9H, Ar–C(CH₃)₃), 1.23 (s, 9H, Ar–C(CH₃)₃), 1.09 (s, 9H, Ar–C(CH₃)₃).

$^{31}$P NMR (121 MHz, benzene-d₆, 298 K, ppm) $\delta$ = -9.47 (Mo – P(CH₃)₃).

IR (FT-IR, benzene, cm⁻¹): v = 1605 (s, C=N), 1542 (s), 1460 (s), 1436 (s), 1396 (s), 1362 (m), 1307 (s), 1256 (s), 1165 (s), 932 (s, Mo=O), 836 (m).

ESI-MS (50 V) m/z (%): 690.3 (100) [M – HP(CH₃)₃].
Oxygen atom transfer reactivity of \([\text{MoO(O}_2\text{L}_2] (4)\]

\[\text{[MoO(O}_2\text{L}_2] (25 mg, 0.035 mmol, 1 equiv.) was dissolved in dry benzene-\text{d}_6 under inert conditions in a Young NMR tube. 2 equivalent PMe_3 (8 \mu L, 0.07 mmol) was added using a micro-pipette. The OAT reaction was monitored by \(^1\text{H} \) and \(^{31}\text{P} \) NMR spectroscopy.\]

**Catalytic oxidation of trimethylphosphine**

\[\text{[MoO(O}_2\text{L}_2] (complex 1, 10 mg, 14 \mu \text{mol}) was placed in a Schlenk flask in the glovebox. The Schlenk flask was evacuated then refilled with dry O\(_2\). Dry benzene-\text{d}_6 (2 mL) and trimethylphosphine (108 mg, 0.15 \mu L, 1.4 mmol, 100 equiv.) were added and the reaction was left to stir under O\(_2\) atmosphere for 24 h. The reaction was monitored by \(^1\text{H} \) and \(^{31}\text{P} \) NMR at \(t = 4 \) h, 20 h and 24 h. After removal of the solvent, the mass balance was calculated and the yield of OPM\(_3\) confirmed by integration of the signals in the \(^1\text{H} \) NMR spectrum at \(t = 24 \) h (yield = 19%). To confirm the stability of PMe\(_3\) under O\(_2\) atmosphere, a blank reaction was monitored by \(^1\text{H} \) and \(^{31}\text{P} \) NRM at \(t = 4 \) h, 20 h and 24 h. After removal of the solvent, the mass balance was calculated and the yield of OPM\(_3\) confirmed by integration of the signals in the \(^1\text{H} \) NMR spectrum at \(t = 24 \) h (yield = 19%).\]

**OAT kinetic study**

In the glovebox, a solution of 7 mg of complex 1 in 5 mL toluene (2 \(\times\) 10\(^{-3}\) mol L\(^{-1}\)) and a solution of 15 mg PMe\(_3\) in 1 mL toluene (0.2 mol L\(^{-1}\)) were prepared. Using a micro-pipette, 100 \mu L of the solution containing the complex was placed in a quartz cuvette and 2 mL toluene were added. Then 100 \mu L of the solution containing PMe\(_3\) were added and the cuvette was sealed with a Teflon stopper and parafilm. The sample was removed from the glovebox and the measurement immediately started. The reaction was monitored by the disappearance of the signal at 430 nm, at room temperature using a Cary50 Conc. UV-Vis spectrophotometer under PC control using the kinetics program “Scan” included with the instrument software. The same procedure was followed preparing a solution of 7 mg of complex 4 in 5 mL toluene (2 \(\times\) 10\(^{-3}\) mol L\(^{-1}\)).

**Structure determination**

For X-ray structure analyses the crystals were mounted onto the tip of glass fiber and data collection was performed at 100 K using graphite monochromated Mo K\(\alpha\) radiation (\(\lambda = 0.71073 \) \AA) with a BRUER-AXS SMART APEX II diffractometer equipped with a CCD detector. Essential details of the crystal-data and structure refinements for compounds 1 and 4 are summarized in Table 2. Crystallographic data for the structures of compounds 1 and 4 have been deposited with the Cambridge Crystallographic Data Center [CCDC 1413968 for 1, CCDC 1413969 for 4].

**Crystal structure determination of 1.** The structure was solved by direct methods (SHELXS-97) and refined by full-matrix least-squares techniques against \(F^2\) (SHELXL-2014/6). The non-hydrogen atoms were refined with anisotropic displacement parameters without any constraints. The H atoms of the phenyl rings as well as the H atoms bonded to the C atom of a C=\(\equiv\)N double bond were put at the external bisectors of the C-C-X angles at C-H distances of 0.95 \AA and common isotropic displacement parameters were refined for these H atoms of the same ligand. The H atoms of the methyl groups were refined with common isotropic displacement parameters.
for the H atoms of the same tert-butyl group and idealized geometries with tetrahedral angles, enabling rotation around the C–C bonds, and C–H distances of 0.98 Å.

**Crystal structure determination of 4.** The structure could be solved (SHELXS-97) by interpretation of the Patterson map (second solution) in the non-centrosymmetric space group C2, but not in centrosymmetric C2/c. After completion of the molecule an inversion center could be detected and the structure was refined by full-matrix least-squares techniques against F² (SHELXL-2014/6) in the centric space group C2/c after an appropriate shift of the origin. A void of approx. 188 Å³ is occupied by a THF molecule disordered over two orientations lying near a center of symmetry or by a n-pentane molecule at the inversion center. The ratio of the refined occupation factors is 0.768(6) to 0.232(6). The non-hydrogen atoms of the solvent molecules were refined with isotropic displacement parameters without any constraints. The H atoms of the phenyl rings were put at the external bisectors of the C–C–C angles at C–H distances of 0.95 Å and common isotropic displacement parameters were free to refine. The H atoms H10 and H30 were put at the external bisector of the C–C–C angle at a C–H distance of 0.95 Å but the individual isotropic displacement parameters were free to refine. The H atoms of the methyl groups were refined with common isotropic displacement parameters for the H atoms of the same group and idealized geometries with tetrahedral angles, enabling rotation around the C–C bond, and C–H distances of 0.98 Å.

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**Notes and references**


