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Biomimetics of the [FeFe]-hydrogenase enzyme: Identification of kinetically favoured apical-basal $[Fe_2(CO)_4(\mu\text{-}H)\{\kappa^2\text{-}Ph_2PC(Me_2)PPh_2\}(\mu\text{-}pdt)]^+$ as a proton-reduction catalyst

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This paper is dedicated to the memory of Professor (Lord) Jack Lewis, an inspiration to us all.

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ABSTRACT

Reaction of $[Fe_2(CO)_6(\mu\text{-}pdt)]$ with the small bite-angle diphosphine 2,2′-bis(diphenylphosphino)propane gave the chelated complex $[Fe_2(CO)_4\{\kappa^2\text{-}Ph_2PC(Me_2)PPh_2\}(\mu\text{-}pdt)]$. This exists in solution as a mixture of non-interconverting dibasal and apical-basal isomers which slowly rearrange to the bridged isomer, $[Fe_2(CO)_4\{\mu\text{-}Ph_2PC(Me_2)PPh_2\}(\mu\text{-}pdt)]$, upon heating. X-ray structures of the dibasal and bridged isomers reveal an increase of *ca.* 19° in the PCP bond angle upon diphosphine movement from chelated to bridged positions. To probe the relative stability of these isomers, DFT calculations have been carried out and the bridged isomer is found to lie 3.8 and 1.3 kJ mol^{-1} lower in energy than the dibasal and apical-basal chelated isomers respectively. Protonation of the bridged isomer with $HBF_4\cdot Et_2O$ is slow and gives an unstable product. In contrast, both chelated isomers protonate rapidly and cleanly to initially yield apical-basal $[Fe_2(CO)_4(\mu\text{-}H)\{\kappa^2\text{-}Ph_2PC(Me_2)PPh_2\}(\mu\text{-}pdt)][BF_4]$, which rearranges slowly to the dibasal isomer. The latter has been crystallographically characterized, protonation resulting in only very minor metric changes with the iron–iron bond length and diphosphine coordination being essentially unchanged. Electrochemical studies have been carried out in MeCN, and for the chelated isomers separate redox features are seen for the dibasal and apical-basal isomers. The chelated isomers are proton reduction catalysts in acetonitrile in the presence of $HBF_4\cdot Et_2O$. Proton reduction occurs at −1.58 V *via* the kinetically favoured apical-basal hydride cation. DFT calculations have been used to study the mechanism of formation of H_2 and are consistent with competing CECE and CEECC mechanisms, the branch point being the protonation or one-electron reduction of the 35-electron species $[Fe_2(CO)_4(\mu\text{-}H)\{\kappa^2\text{-}Ph_2PC(Me_2)PPh_2\}(\mu\text{-}pdt)]$.

1. Introduction

The sustainable generation of hydrogen as an energy carrier in order to realise a fossil-free economy has prompted enormous interest in the chemistry of dithiolate-bridged diiron complexes as models of the H-cluster active site of [FeFe]-hydrogenases [1]. Prompted by theoretical studies by Tye, Hall and Darensbourg [2] suggesting that asymmetry of the diiron centre was a desirable feature of biomimetic models, we [3–6] and others [7–21] have prepared a range of chelated complexes of the type $[Fe_2(CO)_4(\kappa^2\text{-}$diphosphine$)(\mu$-dithiolate$)]$ in which the diphosphine discriminates the two iron sites both sterically and electronically. In solution the chelated diphosphine exists in both dibasal (**bb**) and apical-basal (**ab**) forms and in some instances the bridged isomer, $[Fe_2(CO)_4(\mu$-diphosphine$)(\mu$-dithiolate$)]$, is also accessible [3–6,22–27]. Indeed, we have recently prepared and tested as proton reduction catalysts both bridged and chelated isomers of $[Fe_2(CO)_4\{Ph_2PN(allyl)PPh_2\}(\mu\text{-}pdt)]$ (pdt = propanedithiolate), with the chelated isomer showing superior catalytic properties [6]. In light of these results, we have focused our continuing efforts towards functional biomimetics of the H-cluster active site on the

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preparation of new chelated complexes, $[Fe_2(CO)_4(\kappa^2$-diphosphine)(μ-dithiolate)]. In earlier work we showed that the small bite-angle diphosphine, bis(diphenylphosphino)methane (dppm), reacts with $[Fe_2(CO)_6(\mu$-pdt)] (**1**) to initially afford $[Fe_2(CO)_5(\kappa^1$-dppm)(μ-pdt)], which loses a further carbonyl upon heating to yield $[Fe_2(CO)_4(\mu$-dppm)(μ-pdt)] [4]. On one occasion we also isolated small amounts of the chelated isomer, $[Fe_2(CO)_4(\kappa^2$-dppm) (μ-pdt)], which we were able to crystallographically characterize [4], but we have since not been able to reproduce this result and thus cannot carry out an electrocatalytic study of this complex.

It is known that alkyl substitution of one or more of the backbone protons in dppm results in the formation of ligands that are both more basic and possess a smaller bite angle than dppm, thus favouring chelate formation [28–40]. Both of these features were appealing to us for the preparation of readily protonated $[Fe_2(CO)_4(\kappa^2$-diphosphine) (μ-pdt)] complexes. While a number of backbone-functionalised dppm-derivatives have been reported, they are generally prepared "on metal" from coordinated dppm upon deprotonation of a backbone proton, followed by quenching with electrophiles [30–33]. Such ligands are not easily prepared "off-metal" as they result from the nucleophilic substitution of dihaloalkanes, $RCHX_2$ or R_2CX_2, by the diphenylphosphide anion, Ph_2P^-. The latter is a poor nucleophile and both the steric and electronic changes to central carbon atom upon alkyl substitution make it less susceptible to nucleophilic attack. Two diphosphines that are accessible *via* this route are the methyl-substituted derivatives, 1,1′-bis(diphenylphosphino)ethane, $Ph_2PCH(Me)PPh_2$ [30] and 2,2′-bis(diphenylphosphino)propane, $Ph_2PC(Me_2)PPh_2$ [30]. The former can be isolated in moderate yields and is relatively air-stable, while the latter is formed in lower yields and is oxygen sensitive, presumably reflecting its greater basicity. Both diphosphines are known to favour chelate complexes [30–40] and thus we have attempted to prepare hydrogenase biomimetics containing these ligands.

Herein we report the successful synthesis of $[Fe_2(CO)_4\{\kappa^2$-$Ph_2PC(Me_2)PPh_2\}(\mu$-pdt)] and investigate its ability to act as a proton reduction catalyst. In solution it exits as a mixture of non-interconverting apical-basal and dibasal isomers that display different oxidation and reduction potentials, a situation that has not previously been reported to our knowledge. Protonation by $HBF_4\cdot Et_2O$ rapidly and cleanly affords the apical-basal hydride-cation $[Fe_2(CO)_4(\mu$-H$)\{\kappa^2$-$Ph_2PC(Me_2)PPh_2\}(\mu$-pdt)$][BF_4]$, which only slowly converts to the thermodynamically favourable dibasal isomer, and thus we propose that it is the kinetically favoured apical-basal complex which is the active proton reduction species. The experimental work presented throughout is supported and illuminated by DFT calculations that allow a detailed analysis of this system.

2. Results and discussion

2.1. Synthesis and structural characterization of $[Fe_2(CO)_4\{\kappa^2$-$Ph_2PC(Me_2)PPh_2\}(\mu$-pdt)] (**2**)

In attempting to prepare a [FeFe]-hydrogenase biomimic of the type $Fe_2(CO)_4\{\kappa^2$-PXP$\}(\mu$-pdt) (where PXP is a small-bite angle diphosphine ligand), we initially studied the reaction of $[Fe_2(CO)_6(\mu$-pdt)] (**1**) with 1,1′-bis(diphenylphosphino)ethane but the results of these efforts were largely disappointing (see ESI). We then turned our attention to 2,2′-bis(diphenylphosphino)propane and this proved to be far more successful. Thus, when acetonitrile was added to a mixture of **1**, $Ph_2PC(Me_2)PPh_2$ and $Me_3NO.2H_2O$ in a 1:1:2.5 ratio, the initially orange solution darkened rapidly, becoming nearly black after 30 min. The mixture was heated at 70 °C for a further 4 h and after work-up afforded the target chelated complex $[Fe_2(CO)_4\{\kappa^2$-$Ph_2PC(Me_2)PPh_2\}(\mu$-pdt)] (**2**) in 63% yield as a mixture of dibasal (**2bb**) and apical-basal (**2ab**) isomers (Scheme 1). The IR spectrum revealed three terminal carbonyl stretching bands at 2018vs, 1949s and 1896 m cm^{-1} consistent with the formulation. In order to fully establish the nature of **2**, an X-ray crystal study was performed, the results of which are displayed in Fig. 1 and its caption.

The most interesting feature is the dibasal arrangement of the diphosphine (**2bb** in Scheme 1) with P(1) lying *trans* to S(1) and P(2) *trans* to S(2) [P(1)–Fe(1)–S(1) 163.23(2), P(2)–Fe(1)–S(2) 156.11(2)°], while the C(1) carbonyl occupies the apical site lying approximately *trans* to the metal–metal vector [C(1)–Fe(1)–Fe(2) 146.19(6)°]. The diphosphine subtends a bite angle of 74.53(2)°, which is identical to that of 74.55(4)° in the analogous dppm-derivative [4], but some 3° greater than observed in related bis(-diphenylphosphino)amine complexes [3,6]. The angle at the backbone carbon in **2** of 90.54(7)° is significantly smaller than that of 93.5(2)° in $[Fe_2(CO)_4(\kappa^2$-dppm) (μ-pdt)] [4] as a result of the *gem*-dimethyl effect [28,29]. Isomer **2bb** was also examined by DFT and the optimized structure, which is shown in Fig. 2, is in agreement with the solid-state structure. Table 1 lists the nature charges and Wiberg indices computed for **2bb**. The Fe_1 and Fe_2 atoms exhibit charges of −1.38 and −1.66, respectively, and the Wiberg bond indices (WBI) for the metal–metal bond is 0.44 being consistent with a formal Fe–Fe bond.

Analysis of the $^{31}P\{^1H\}$ NMR spectrum of the reaction mixture after *ca.* 30 min showed a prominent pair of doublets at 7.6 and 37.2 ppm (J_{PP} 67.5 Hz), which we tentatively assign to intermediate $Fe_2(CO)_5\{\kappa^1$-$Ph_2PC(Me_2)PPh_2\}(\mu$-pdt)], this being supported by the observation of small absorptions at 2045 and 1981 cm^{-1} in the IR spectrum. Thus, it seems that the reaction proceeds in an analogous manner to that observed for dppm [4]. A $^{31}P\{^1H\}$ NMR spectrum in $CDCl_3$ of the crude reaction mixture after 4 h also showed resonances for the chelated isomer, along with a small resonance at 86.9 ppm associated with the bridging isomer (*vide infra*) but this was formed in <3% yield.

2.2. Relationship between dibasal and apical-basal isomers

The solid-state structure for $[Fe_2(CO)_4\{\kappa^2$-$Ph_2PC(Me_2)PPh_2\}(\mu$-pdt)] is based on the dibasal isomer **2bb**, and attempts to obtain single crystals of the apical-basal isomer (**2ab**) were unsuccessful. In solution dibasal (**2bb**) and apical-basal (**2ab**) isomers co-exist (Scheme 1) as revealed by the presence of two singlets in the $^{31}P\{^1H\}$ NMR spectrum at 52.4 and 77.2 ppm in CD_2Cl_2 (50.8 and 75.5 ppm in $CDCl_3$) in an approximate 2:1 ratio. The $^{31}P\{^1H\}$ NMR chemical shift was assigned to the isomers on the basis of previous work which established that the apical-basal isomer appears downfield of the dibasal isomer [6–11]. The ^1H NMR spectrum is also more complicated than might at first be expected as both isomers have inequivalent methyl groups (all coupled to phosphorus) and either four (dibasal) or six (apical-basal) different protons on the dithiolate backbone. Such isomerism is common in complexes of this type [3–19] with the apical-basal isomer generally being preferred. For example in the dppp analogue of **2**, namely $[Fe_2(CO)_4\{\kappa^2$-$Ph_2P(CH_2)_3PPh_2\}(\mu$-pdt)], the ratio of apical-basal to dibasal isomers is 12:1 [5], although we recently found that for the small bite-angle diphosphine complexes $[Fe_2(CO)_4\{\kappa^2$-$Ph_2PN(R)PPh_2\}(\mu$-pdt)] the dibasal isomer predominated in solution [6].

For the isomeric mixture based on **2**, we have carried out DFT calculations which revealed that the apical-basal isomer **2ab** is lower in energy by 1.3 kJ mol^{-1} than the dibasal form **2bb**; on the basis of this energy difference we predict a K_{eq} of 1.6 which is opposite to the 2:1 ratio of **2bb**:**2ab** found by ^{31}P NMR spectroscopy. In solution at room temperature, a single phosphorus