

# Computational study of the spin-forbidden H<sub>2</sub> oxidative addition to 16-electron Fe(0) complexes †

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The spin-forbidden oxidative addition of H<sub>2</sub> to Fe(CO)<sub>4</sub>, Fe(PH<sub>3</sub>)<sub>4</sub>, Fe(dpe)<sub>2</sub> and Fe(dmpe)<sub>2</sub> [dpe = H<sub>2</sub>PCH<sub>2</sub>CH<sub>2</sub>PH<sub>2</sub>, dmpe = (CH<sub>3</sub>)<sub>2</sub>PCH<sub>2</sub>CH<sub>2</sub>P(CH<sub>3</sub>)<sub>2</sub>] has been investigated by density functional theory using a modified B3PW91 functional. All 16-electron fragments are found to adopt a spin triplet ground state. The H<sub>2</sub> addition involves a spin crossover in the reagents region of configurational space, at a significantly higher energy relative to the triplet dissociation asymptote and, for the case of Fe(CO)<sub>4</sub>·H<sub>2</sub>, even higher than the singlet dissociation asymptote. After crossing to the singlet surface, the addition proceeds directly to the classical *cis*-dihydride product. Only for the Fe(CO)<sub>4</sub> was it possible to locate a stable energy minimum for the non-classical tautomer (dihydrogen complex), but the energy difference between this minimum and the tautomerisation transition state inverts when taking into account the zero-point energy correction. The geometries at the crossing points indicate a "side-on" approach of the H<sub>2</sub> molecule to the metal for the Fe(CO)<sub>4</sub>, Fe(CO)<sub>2</sub>(PH<sub>3</sub>)<sub>2</sub> and Fe(PH<sub>3</sub>)<sub>4</sub> systems. These geometries are more reactants-like for the Fe(CO)<sub>4</sub> system and more product-like for the Fe(PH<sub>3</sub>)<sub>4</sub> system. The crossing point geometry for the Fe(dpe)<sub>2</sub> system, on the other hand, is nearly C<sub>2</sub>-symmetric. The presence of an energy barrier on going from <sup>3</sup>FeL<sub>4</sub> + H<sub>2</sub> to the crossing point is in agreement with the slow observed rates for addition of H<sub>2</sub> to these unsaturated organometallic fragments.

## Introduction

It has recently been shown that thermal reactions implicating more than one spin surface are common in different areas of transition metal chemistry, including oxo-transfer, C–H activation, metal-catalysed polymerisation, and bioinorganic chemistry.<sup>1–5</sup> Besides the obvious situations where reactants and products have different spin, it is also possible that reagents in a particular spin state are transformed into products of the same spin, *via* one or more intermediates of different spin and an even number of spin crossovers. This event was shown to have profound effects on reaction rates<sup>6</sup> and on product distributions.<sup>7</sup> In many cases, however, the very short lifetime of the intermediates does not allow their direct identification by experimental methods. The correct interpretation of reaction rates and mechanisms, therefore, requires the explicit computation of the point in configuration space at which the system crosses from one spin surface to another. This is the point at minimum energy within the seam of crossing between the two surfaces, or Minimum Energy Crossing Point (MECP).<sup>8–12</sup> The ability to locate and characterise MECPs between potential energy surfaces of different spin for realistic transition-metal containing systems, first demonstrated in ref. 6, is key to understanding spin-forbidden reactions.<sup>13</sup>

Among organometallic reaction intermediates, Fe(CO)<sub>4</sub> has attracted considerable attention. Its ground state triplet is now solidly established both at the experimental<sup>14–22</sup> and theoretical levels.<sup>23–33</sup> The experimental observation that the spin-forbidden CO addition to yield singlet Fe(CO)<sub>5</sub> is *ca.* 400 times slower than the spin-allowed addition to Fe(CO)<sub>3</sub> has prompted the proposition<sup>15</sup> that this extra barrier is related to the need to

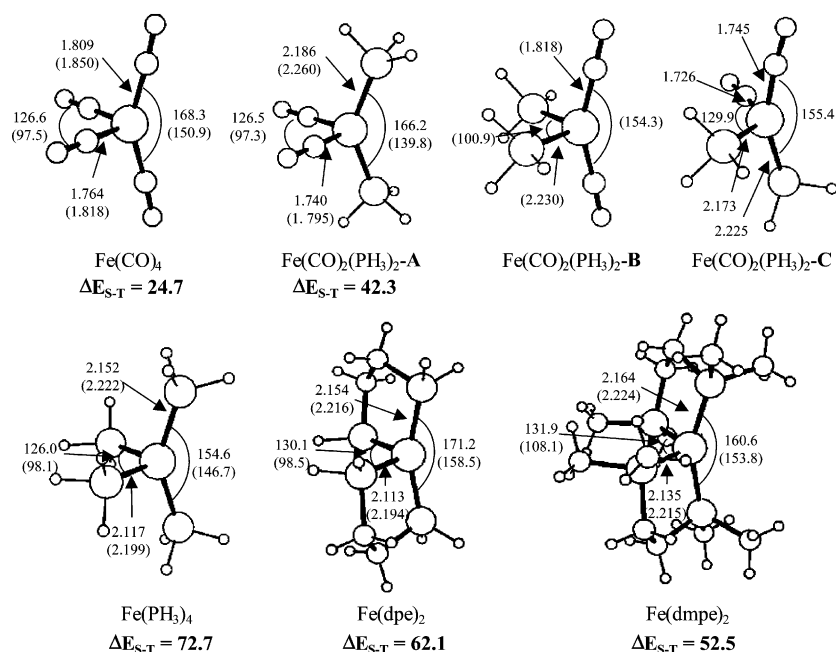
achieve a suitable geometry for the spin crossing to occur, *i.e.* the need to reach a MECP. The explicit calculation of the MECP for this reaction has only recently been carried out<sup>33</sup> and a good agreement was obtained between the computed and the experimental activation barriers, in support of the mechanistic proposition. This observation is relevant because the spin-forbidden CO additions to other 16-electron triplet complexes have been shown to be limited by a normal steric barrier while the crossing point resides on the down-slope leading to the product.<sup>34,35</sup>

The oxidative addition of dihydrogen to unsaturated transition metal complexes is another reaction of fundamental importance to organometallic chemistry and homogeneous catalysis. The H<sub>2</sub> oxidative addition to Fe(CO)<sub>4</sub> has been investigated experimentally<sup>16</sup> and theoretically.<sup>28</sup> The experimental study has shown that the reaction rate is three orders of magnitude slower than the H<sub>2</sub> addition to related electronically unsaturated complexes, a phenomenon tentatively attributed to the spin-forbidden character of the process. The theoretical study, however, did not include the explicit calculation of the MECP. A related process is the H<sub>2</sub> oxidative addition to M(dmpe)<sub>2</sub> (M = Fe and Ru; dmpe = Me<sub>2</sub>PCH<sub>2</sub>CH<sub>2</sub>PMe<sub>2</sub>).<sup>36,37</sup> Interestingly, the rate constant for H<sub>2</sub> addition is 7500 times smaller for Fe(dmpe)<sub>2</sub> than for Ru(dmpe)<sub>2</sub>, whereas the CO addition is diffusion-controlled for both complexes. A theoretical study on model M(PH<sub>3</sub>)<sub>4</sub> (M = Fe, Ru) compounds shows that the Ru species adopts a singlet ground state, whereas the Fe species adopts a triplet ground state. The study, however, did not include a thorough analysis of the spin crossover region.<sup>38</sup>

In this contribution, we intend to examine in more detail (*i.e.* including the explicit MECP computation) the reaction coordinate for the spin-forbidden H<sub>2</sub> oxidative addition to the already investigated Fe(CO)<sub>4</sub> and Fe(PH<sub>3</sub>)<sub>4</sub> systems, and to extend the study to the mixed-ligand Fe(CO)<sub>2</sub>(PH<sub>3</sub>)<sub>2</sub> system, to the less approximate Fe(dpe)<sub>2</sub> model (dpe = PH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>PH<sub>2</sub>) of the real Fe(dmpe)<sub>2</sub> complex, as well as to the real complex itself.

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Electronic supplementary information (ESI) available: Cartesian coordinates for all optimized geometries (4 pages). See <http://www.rsc.org/suppdata/dt/b3/b302916f/>



**Fig. 1** Optimized geometries (distances in Å, angles in degrees; values above are for the singlet, below in parentheses for the triplet) and triplet-singlet gaps ( $\Delta E_{S-T}$  in  $\text{kJ mol}^{-1}$ ) of the 16-electron Fe(0) systems.

## Results and discussion

### Singlet and triplet 16-electron Fe(0) complexes

When studying chemical reactivity, it is essential to use a computational method which is as accurate as possible, and this can be very hard to achieve in transition metal chemistry given the delicate balance of exchange and correlation effects, the frequently poor performance of the simplest correlated *ab initio* methods such as MP2, and the need for very large basis sets. By and large, density functional theory (DFT) has been found to give very good results in the study of inorganic and organometallic systems. However, in a previous study,<sup>33</sup> different density functionals were found to predict very different energetic properties for the Fe(CO)<sub>4</sub> + CO system, both for the spin-state splitting between triplet and singlet Fe(CO)<sub>4</sub>, and for the bond energy. After extensive calibration using accurate *ab initio* methods (CCSD(T) with large basis sets), it was concluded that the best description of this system is obtained using a modified form of the hybrid B3PW91 functional. This new functional, referred to as B3PW91\*, is identical to B3PW91 except that the coefficient  $c_3$  describing the mixing of “exact”, Hartree-Fock, exchange is reduced to 0.15 (vs. 0.20 in B3PW91). This reduced mixing of exact exchange has been found by others to give better agreement for spin-state splittings in other iron compounds.<sup>39</sup> In our present calculations, we have used this B3PW91\* functional throughout, together with the same type of flexible, polarised basis set also used in ref. 33, so that the results should be directly comparable.

As well as considering anew the potential energy surfaces for addition of H<sub>2</sub> to Fe(CO)<sub>4</sub>, our calculations were extended to derivatives containing two CO and two PH<sub>3</sub> ligands, and to others containing four P-donor ligands. All systems investigated, and relevant bond distances and angles, are shown in Fig. 1. The Fe(CO)<sub>2</sub>(PH<sub>3</sub>)<sub>2</sub> system can exist as three possible isomers, identified as **A**, **B** and **C** in Fig. 1. Among these, only isomer **A** gave a stable minimum in both spin states. Isomer **B** only gave a triplet minimum, while isomer **C** only gave a singlet minimum. Singlet **B** reverted to singlet **A** during the optimisation, whereas triplet **C** reverted to triplet **A**. The most stable isomer is **A** for both spin states.

All 16-electron Fe(0) complexes were found to adopt a triplet ground state, the triplet-singlet gap being higher for the tetrakis(phosphine) complexes, intermediate for the bis(phosphine)-

dicarbonyl complex, and lowest for the tetracarbonyl complex. This trend agrees with that obtained at the BP86 level by Macgregor *et al.*<sup>38</sup> on going from Fe(CO)<sub>4</sub> to Fe(PH<sub>3</sub>)<sub>4</sub>. Amongst the phosphine derivatives, the triplet-singlet gap varies in the order Fe(PH<sub>3</sub>)<sub>4</sub> > Fe(dpe)<sub>2</sub> > Fe(dmpe)<sub>2</sub>, so that the dpe complex is a better model than the PH<sub>3</sub> complex for the real dmpe system. Alkyl substitution makes dpe and especially dmpe a better  $\sigma$ -donor, as confirmed by the greater negative Mulliken charge on iron in the order Fe(PH<sub>3</sub>)<sub>4</sub> < Fe(dpe)<sub>2</sub> < Fe(dmpe)<sub>2</sub>, for both spin states. The consequent stronger donating power in the dpe and dmpe complexes is consistent with the lower triplet-singlet energy gap, although this comparison cannot be extended to CO because of  $\pi$  bonding effects.

The geometries are essentially identical in their gross features for all systems. Both the L<sub>ax</sub>-Fe-L<sub>ax</sub> and L<sub>eq</sub>-Fe-L<sub>eq</sub> angles are wider for the singlet geometries relative to the corresponding triplets, whereas all bond distances are slightly shorter in the singlet structures. The distance to any given ligand is systematically longer when this is located in the axial position, no matter the spin state. The distances obtained for Fe(PH<sub>3</sub>)<sub>4</sub> are only marginally but systematically longer than those obtained for the same molecule at the BP86 level,<sup>38</sup> for both spin states. For singlet Fe(CO)<sub>4</sub>, whose geometry has recently been determined experimentally by ultrafast electron diffraction methods, the optimized geometry is in excellent agreement with the experiment (Fe-C<sub>ax</sub> 1.81(3) Å; Fe-C<sub>eq</sub> 1.77(3) Å; C<sub>ax</sub>-Fe-C<sub>ax</sub> 169(2)°; C<sub>eq</sub>-Fe-C<sub>eq</sub> 125(3)°).<sup>22</sup> Substitution effects give the expected trends. Thus, replacement of two CO ligands with as many PH<sub>3</sub> ligands leads to a Fe-C bond shortening for the two residual CO ligands in Fe(CO)<sub>2</sub>(PH<sub>3</sub>)<sub>2</sub> (independently on the spin state and stereochemistry), a phenomenon attributable to the increase of Fe-CO  $\pi$  back-bonding. Analogously, the further replacement of the two residual CO ligands, leading to Fe(PH<sub>3</sub>)<sub>4</sub>, is accompanied by a Fe-PH<sub>3</sub> bond shortening, again independently on the spin state and stereochemistry. This effect may be attributed to an analogous increase of Fe-PH<sub>3</sub>  $\pi$  back-bonding. The effect of changing the nature of the phosphorus donor on going from Fe(PH<sub>3</sub>)<sub>4</sub> through Fe(dpe)<sub>2</sub> to Fe(dmpe)<sub>2</sub> is only marginal on the Fe-P bond lengths.

### Products of H<sub>2</sub> addition to the 16-electron Fe(0) complexes

The addition of H<sub>2</sub> to the above mentioned 16-electron Fe(0) species ultimately affords dihydride products. The energy gains

**Table 1** Computed relative energies and free energies at 298 K for the H<sub>2</sub> addition to 16-electron Fe(0) systems

	$\Delta E/\text{kJ mol}^{-1}$	$\Delta G/\text{kJ mol}^{-1}$	$\nu(\text{Fe-H}) \text{ sym./cm}^{-1}$	$\nu(\text{Fe-H}) \text{ asym./cm}^{-1}$	$\nu(\text{H-H})/\text{cm}^{-1}$
<sup>1</sup> Fe(CO) <sub>4</sub> + H <sub>2</sub>	126.52	77.32			
<sup>3</sup> Fe(CO) <sub>4</sub> + H <sub>2</sub>	100.79	45.15			
<sup>1/3</sup> Fe(CO) <sub>4</sub> ·H <sub>2</sub>	132.97				
Fe(CO) <sub>4</sub> (H <sub>2</sub> )	27.80	27.12	1848.7	995.0	2313.8
TS (C-NC)	29.09	22.42	1989.0	1984.2	(574.9) <sup>a</sup>
Fe(CO) <sub>4</sub> (H) <sub>2</sub>	0.00	0.00	1986.7	1970.0	–
<sup>1</sup> Fe(CO) <sub>2</sub> (PH <sub>3</sub> ) <sub>2</sub> -A + H <sub>2</sub>	136.22	84.97			
<sup>1</sup> Fe(CO) <sub>2</sub> (PH <sub>3</sub> ) <sub>2</sub> -C + H <sub>2</sub>	151.80	95.53			
<sup>3</sup> Fe(CO) <sub>2</sub> (PH <sub>3</sub> ) <sub>2</sub> -A + H <sub>2</sub>	93.91	33.41			
<sup>3</sup> Fe(CO) <sub>2</sub> (PH <sub>3</sub> ) <sub>2</sub> -B + H <sub>2</sub>	118.25	58.34			
<sup>1/3</sup> Fe(CO) <sub>2</sub> (PH <sub>3</sub> ) <sub>2</sub> -A·H <sub>2</sub>	135.00				
Fe( <i>c</i> -CO) <sub>2</sub> ( <i>t</i> -PH <sub>3</sub> ) <sub>2</sub> ( <i>c</i> -H) <sub>2</sub>	0.00	0.00	1922.9	1900.3	
Fe( <i>c</i> -CO) <sub>2</sub> ( <i>c</i> -PH <sub>3</sub> ) <sub>2</sub> ( <i>c</i> -H) <sub>2</sub>	3.50	2.08	1978.0 <sup>b</sup>	1905.6 <sup>c</sup>	–
Fe( <i>t</i> -CO) <sub>2</sub> ( <i>c</i> -PH <sub>3</sub> ) <sub>2</sub> ( <i>c</i> -H) <sub>2</sub>	6.70	3.84	1974.0	1965.0	–
Fe( <i>c</i> -CO) <sub>2</sub> ( <i>c</i> -PH <sub>3</sub> ) <sub>2</sub> ( <i>t</i> -H) <sub>2</sub>	37.25	36.20	1934.0	1796.4	–
<sup>1</sup> Fe(PH <sub>3</sub> ) <sub>4</sub> + H <sub>2</sub>	191.57	128.78			
<sup>3</sup> Fe(PH <sub>3</sub> ) <sub>4</sub> + H <sub>2</sub>	118.91	58.78			
<sup>1/3</sup> Fe(PH <sub>3</sub> ) <sub>4</sub> ·H <sub>2</sub>	148.31				
Fe(PH <sub>3</sub> ) <sub>4</sub> (H) <sub>2</sub>	0.00	0.00	1890.8	1879.0	–
<sup>1</sup> Fe(dpe) <sub>2</sub> + H <sub>2</sub>	181.41	128.43			
<sup>3</sup> Fe(dpe) <sub>2</sub> + H <sub>2</sub>	119.34	62.67			
<sup>1/3</sup> Fe(dpe) <sub>2</sub> ·H <sub>2</sub>	154.98				
Fe(dpe) <sub>2</sub> (H) <sub>2</sub>	0.00	0.00	1889.1	1876.4	–
<sup>1</sup> Fe(dmpe) <sub>2</sub> + H <sub>2</sub>	190.75	139.05			
<sup>3</sup> Fe(dmpe) <sub>2</sub> + H <sub>2</sub>	138.25	77.18			
Fe(dmpe) <sub>2</sub> (H) <sub>2</sub>	0.00	0.00	1874.3	1859.6	–

<sup>a</sup> Imaginary frequency. <sup>b</sup> Mostly *trans* to PH<sub>3</sub>. <sup>c</sup> Mostly *trans* to CO.

associated to the oxidative addition processes are shown in Table 1 for all systems. Relative to the 16-electron singlet precursor, the exothermicity increases as the number of P-donor ligands increases. This correlates with the better ability of the P-donor ligands to stabilise the formally higher oxidation state. For the mixed CO/PH<sub>3</sub> system, the most stable oxidative addition product is again derived from isomer A. The energy of the other isomers increases as the  $\sigma$ -donating power of the ligands *trans* to H increases (CO < PH<sub>3</sub>  $\ll$  H), in agreement with well known arguments of  $\sigma$  competition and *trans* labilisation.<sup>40,41</sup> Therefore, all further investigations along the H<sub>2</sub> oxidative addition coordinate (see next section) were carried out on this isomer only. The dpe model is worse than the PH<sub>3</sub> model for the dmpe complex in terms of reproducing the energy gain of the H<sub>2</sub> oxidative addition from the singlet state. Both models are equally inappropriate, on the other hand, for what concerns the energy gain from the triplet state. The only experimental data available to compare our results with concerns the tetracarbonyl series. From the activation energies for H<sub>2</sub> dissociation from Fe(CO)<sub>4</sub>(H)<sub>2</sub> and for H<sub>2</sub> addition to triplet Fe(CO)<sub>4</sub>,  $\Delta H$  for dissociation was determined to be  $88 \pm 8 \text{ kJ mol}^{-1}$ .<sup>16</sup> Our computed value of  $\Delta H$ ,  $89.5 \text{ kJ mol}^{-1}$  is in excellent agreement with this value. Previous calculations<sup>28</sup> at the BP86 level also gave good agreement for  $\Delta H$ , but with a very low singlet/triplet energy splitting, whereas the B3LYP and BLYP functionals gave a poor  $\Delta H$ . These observations are consistent with our survey of many different functionals<sup>33</sup> and confirm our impression that B3PW91\* gives accurate results for these iron-containing systems.

Only in the case of Fe(CO)<sub>4</sub> was it possible to identify an intermediate dihydrogen complex as a stable local minimum. This is  $27.1 \text{ kJ mol}^{-1}$  less stable than the dihydride product (*cf.*  $25.9 \text{ kJ mol}^{-1}$  at the BP86 level).<sup>28</sup> Its geometry and selected parameters are shown in Fig. 2, together with those of all classical dihydride products. The transition state (TS) between the non-classical and classical products has also been optimised. The nature of the resulting geometry as a first-order

saddle point is confirmed by the frequency analysis, which shows a single imaginary frequency corresponding to the H<sub>2</sub> stretch, see Table 1. Its energy is only slightly higher than the non-classical minimum ( $1.2 \text{ kJ mol}^{-1}$ , *cf.*  $1.7 \text{ kJ mol}^{-1}$  at the BP86 level<sup>28</sup>), in agreement with a very facile conversion to the final product. Thus, there is good agreement between the results obtained with the BP86 and B3PW91\* functionals. However, we note that the energy difference between the non-classical isomer and the TS is reversed upon adding the zero-point energy correction and further addition of the thermal and entropy contributions maintains this reversal. This would seem to suggest that this non-classical isomer is probably not a true intermediate in the H<sub>2</sub> oxidative addition process.

For the Fe(PH<sub>3</sub>)<sub>4</sub> and Fe(dpe)<sub>2</sub> systems, partial geometry optimisations were carried out with a frozen Fe(H<sub>2</sub>) unit, keeping the Fe–H and H–Fe–H parameters fixed at the values found for the Fe(CO)<sub>4</sub>(H)<sub>2</sub> complex. The resulting structures, which were  $56.1$  and  $44.4 \text{ kJ mol}^{-1}$  higher in energy than the corresponding dihydride products, were then further refined freely and collapsed back to the dihydride products. Given the greater donor ability of phosphine ligands relative to CO and the doubtful intermediacy of the non-classical isomer even for the tetracarbonyl system (*vide supra*), this is not an unexpected result. In fact, using Hammond's postulate arguments, it is easy to accept that the greater exothermicity of the insertion for the mixed CO/PH<sub>3</sub> and for the all-phosphine systems would make the small barrier to insertion present in the Fe(CO)<sub>4</sub> system completely disappear.

The structures of the products obtained from Fe(CO)<sub>4</sub> have already been extensively discussed previously.<sup>28</sup> In particular, the calculations reproduced the experimental preference for a *cis*-dihydride structure relative to the *trans* isomer. Therefore, we did not consider the *trans* structure in our calculations. Relative to that study, which used the BP86, BLYP and B3LYP functionals, all distances are slightly shorter and angles are approximately identical. All these parameters are quite close to those experimentally determined for *cis*-FeH<sub>2</sub>(CO)<sub>4</sub>.<sup>42</sup> The

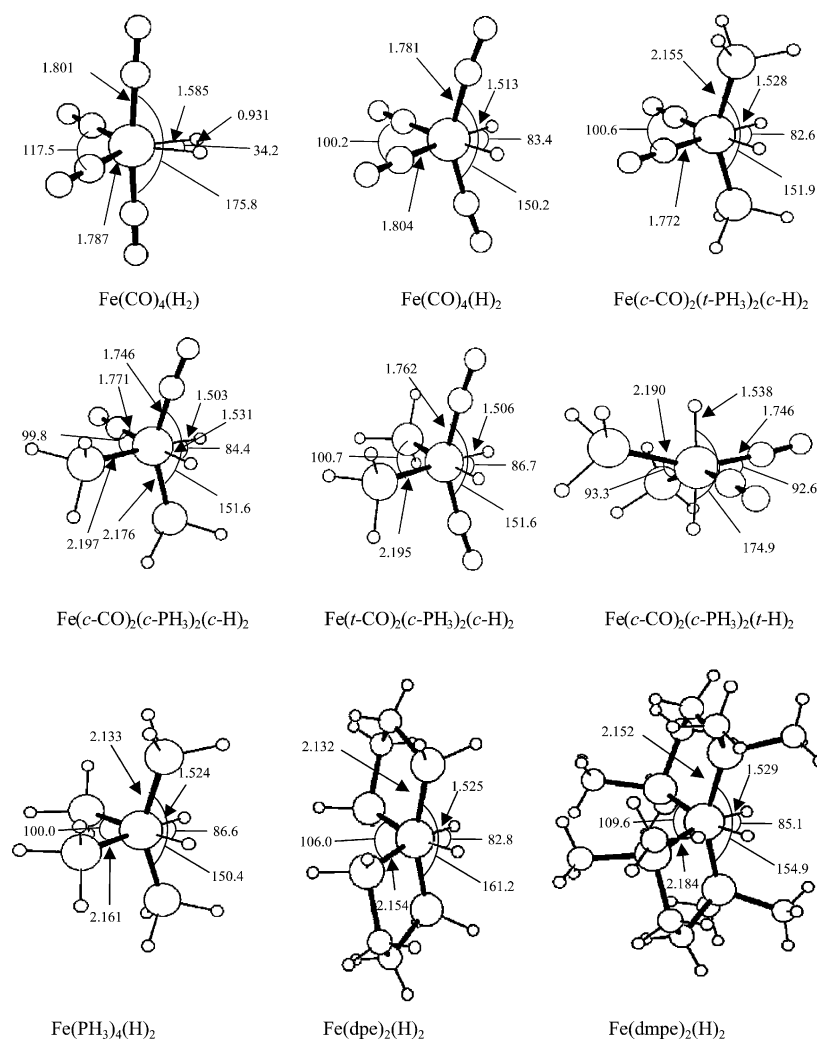


Fig. 2 Optimized geometries (distances in Å, angles in °) of the dihydride products.

geometry of the  $\text{FeH}_2$  moiety is approximately identical in all dihydride products. On going from the singlet  $\text{FeL}_4$  to the corresponding *cis*- $\text{FeH}_2\text{L}_4$  species, all  $\text{Fe-L}_{\text{ax}}$  bonds (*trans* to each other) shorten, a phenomenon which may be due to going from effective  $\text{Fe}(0)$  to  $\text{Fe}(\text{II})$ , whereas all  $\text{Fe-L}_{\text{eq}}$  bonds (*trans* to H ligands) lengthen, a phenomenon which can be attributed to the strong *trans*-influence of the hydride ligand. There appears to be only one structural determination for a *cis*- $\text{FeH}_2\text{L}_4$  complex having  $\text{L} = \text{P-donor ligand}$ , *i.e.* with  $\text{L} = \text{PPh}(\text{OEt})_2$ .<sup>43</sup> An appropriate check of the computational accuracy is prevented by the high uncertainty on the  $\text{Fe-H}$  distance [1.50(5) Å], due to the determination by X-ray diffraction, and by the electronic difference between the phosphonite ligands [ $\text{Fe-P}_{\text{ax}}$  2.128(7) Å;  $\text{P}_{\text{eq}}$  2.149(3) Å] and the phosphines used in our models. There is a rather good agreement, however, between the computed values and those observed in this structure. Other related structurally characterised compounds, *e.g.*  $\text{FeH}_2(\text{dppm})_2$ ,<sup>44</sup>  $\text{FeH}_2(\text{dppe})_2$ ,<sup>45</sup> and  $\text{FeH}(\text{HBH}_3)(\text{dppe})_2$ ,<sup>46</sup> adopt the alternative *trans* geometry.

The computed  $\text{Fe-H}$  stretching frequencies follow a clear trend, being lower when the coordination sphere is more donating/less  $\pi$ -accepting [*e.g.*  $\text{Fe}(\text{CO})_4\text{H}_2 \gg \text{Fe}(\text{PH}_3)_4\text{H}_2 > \text{Fe}(\text{dpe})_2\text{H}_2 > \text{Fe}(\text{dmpe})_2\text{H}_2$ ]. This trend cannot be attributed to  $\pi$  competition effects, since the  $\text{Fe-H}$  bonds do not have a  $\pi$ -bonding component. A similar trend has been noted previously for hydride ligand when the metal is oxidised and the reasons for this trend have been critically discussed.<sup>47</sup> For instance, the  $\text{Fe-H}$  stretching vibrations in a series of  $\text{Fe}(\text{II})$  complex  $\text{Cp}^*\text{FeH}(\text{LL})$  are found at lower frequencies than the corresponding vibrations in the related  $\text{Fe}(\text{III})$  complexes

$[\text{Cp}^*\text{FeH}(\text{LL})]^+$ ,<sup>48,49</sup> and the same trend is observed for  $[\text{Cp}^*\text{WH}_3(\text{dppe})]^n+$  on going from  $n = 0$  to  $n = 1$ .<sup>50</sup> We can therefore associate the computed trend of  $\text{Fe-H}$  stretching frequencies in compounds  $\text{Fe}(\text{L})_4\text{H}_2$  to a similar tuning of the metal electron density by the nature of the ancillary ligands. For the series of  $\text{Fe}(\text{CO})_2(\text{PH}_3)_4\text{H}_2$  isomers, the frequencies clearly respond to the influence of the *trans* ligands and correlate with the  $\text{Fe-H}$  distances.

### Minimum energy crossing points

To study the reactivity in these systems, it is of course also necessary to locate the critical point for  $\text{H}_2$  addition to the triplet reactant. In all the systems studied here, this is the MECP between the triplet and singlet surfaces in the reactant region of both potential energy surfaces. At first sight, it may appear inadequate to consider only the energetics of the MECP. In the language of transition state theory, the need to cross from one surface to another adds an extra "transmission factor", usually smaller than unity, to the overall rate coefficient. This explains why two reactions with an identical MECP energy, but with much stronger spin-orbit coupling in one case than in the other, will occur at different rates. However, non-adiabatic versions of transition state theory show that the transmission factor only varies quadratically with the strength of spin-orbit coupling.<sup>51</sup> Furthermore, spin-orbit coupling constants between the singlet and triplet wavefunctions are probably rather similar at all the MECPs discussed here. In contrast, the MECP energies described here are significantly different from system to system, and the rate coefficient varies exponentially

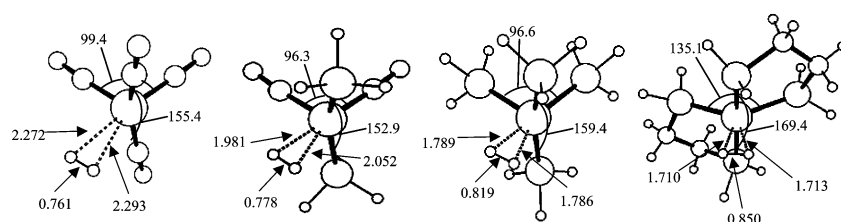


Fig. 3 Optimized geometries (distances in Å, angles in degrees) of the MECPs.

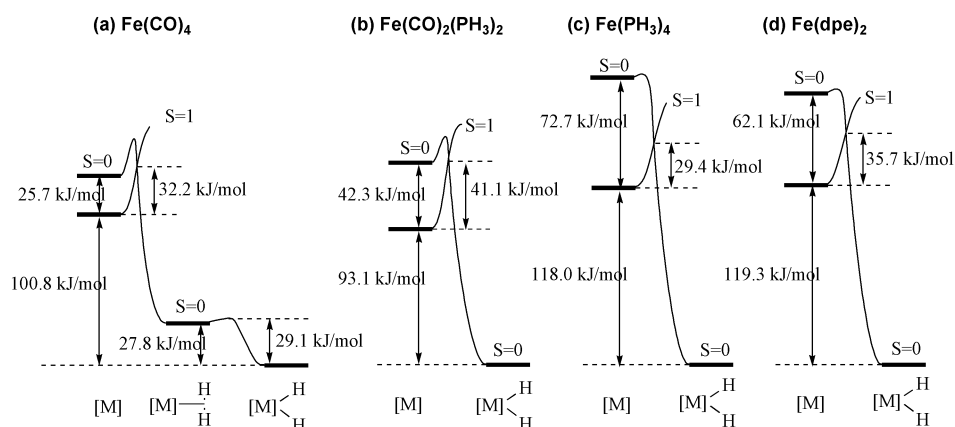


Fig. 4 Relative energies of the  $\text{FeL}_4 + \text{H}_2$  systems [ $\text{FeL}_4 = \text{Fe}(\text{CO})_4$  (a);  $\text{Fe}(\text{CO})_2(\text{PH}_3)_2$  (b);  $\text{Fe}(\text{PH}_3)_4$  (c);  $\text{Fe}(\text{dpe})_2$  (d)], including the MECP.

with MECP energy.<sup>51</sup> To an excellent first approximation, therefore, we focus on the energetics of the MECPs only in this work.

We have located the MECP for approach of dihydrogen to  $\text{Fe}(\text{CO})_4$ , to isomer A of  $\text{Fe}(\text{CO})_2(\text{PH}_3)_2$ , and to the all-phosphine systems  $\text{Fe}(\text{PH}_3)_4$  and  $\text{Fe}(\text{dpe})_2$ , and the optimised structures are shown in Fig. 3, with the corresponding energetics in Table 1 and in Fig. 4. In the carbonyl, mixed CO/ $\text{PH}_3$  and  $\text{PH}_3$  systems, the optimized MECP has the incoming  $\text{H}_2$  molecule lying “side-on” to the metal, in the plane formed by the two “equatorial” ligands, and roughly *trans* to one of them. In other words,  $\text{H}_2$  does *not* approach along the  $C_2$  axis of symmetry of the unsaturated fragment, which would be the least-motion pathway for addition to the singlet. The approach of  $\text{H}_2$  from the “side” of the  $\text{Fe}(\text{L})_4$  moiety is similar to the MECP structure found for the  $\text{CO} + \text{Fe}(\text{CO})_4$  system, where this mode of approach was found to give rise to a lower energy MECP as compared to approach along the  $C_2$  axis.<sup>33</sup> This preference for not approaching along the  $C_2$  axis may be due to the fact that in the triplet state, the  $a_1$  singly-occupied orbital in  $^3\text{Fe}(\text{CO})_4$  has some 4s character and is more repulsive at longer range than the other,  $b_1$  symmetric singly-occupied orbital, which does not have any 4s character. The MECP for the  $\text{Fe}(\text{dpe})_2$  system is the “latest” and most product-like, and this may explain why it adopts  $C_2$  symmetry, as the singlet state is more attractive with this type of approach, especially at short M–H distances.

In a simple one-dimensional model, the geometry of the crossing point between the repulsive triplet and attractive singlet states would be correlated with the singlet–triplet energy gap of the fragment  $\text{M}(\text{L})_4$ . For the tetracarbonyl, mixed CO/ $\text{PH}_3$  and tetra- $\text{PH}_3$  systems, for which the triplet–singlet energy splitting increases in this order, this expected correlation is indeed observed, as can be seen in Fig. 3: the  $\text{Fe}(\text{CO})_4 \cdot \text{H}_2$  MECP is “earliest”, with  $r(\text{Fe}–\text{H}) = ca. 2.2 \text{ \AA}$ , whereas the other two systems have  $r(\text{Fe}–\text{H}) = ca. 2.0$  and  $1.8 \text{ \AA}$ , respectively. For the  $\text{Fe}(\text{dpe})_2$  system, however, the correlation breaks down, since this has a smaller singlet–triplet gap than the  $\text{Fe}(\text{PH}_3)_4$  system, yet the MECP is as noted previously the “latest” of all those systems studied, with  $r(\text{Fe}–\text{H}) = 1.71 \text{ \AA}$ , and a symmetric,  $C_2$ ,  $\text{H}_2$  bonding geometry as in the final adduct. This is probably due to the fact that as noted previously (see *e.g.* ref. 6) the one-dimensional model for crossing is inadequate: *all* the geometric coordinates need to be the same at the MECP, whereas the

geometries of the metallic fragment in its two spin states are not the same. In the present case, the geometry of the MECP is determined not only by the singlet–triplet gap, the degree of Fe– $\text{H}_2$  repulsion in the triplet and of attraction in the singlet, but also by issues relating to the extent to which the structure of the singlet and the triplet need to distort so as to reach a common geometry. Clearly, the latter factor must explain why the  $\text{Fe}(\text{dpe})_2 \cdot \text{H}_2$  MECP is “later” than the  $\text{Fe}(\text{PH}_3)_4 \cdot \text{H}_2$  one, despite the larger energy splitting in the latter. Related to this issue, it is also interesting to note that the internal geometry of the  $\text{FeL}_4$  core in the MECP geometries is closer to the free *triplet*  $\text{FeL}_4$  molecule for the first three systems, and closer to the free *singlet*  $\text{FeL}_4$  molecule for the dpe system (*cf.* Fig. 1 and Fig. 3).

The *energy* for the MECPs is also of interest. As can be seen in Fig. 4, all of the MECPs lie higher in energy than the corresponding  $^3\text{FeL}_4 + \text{H}_2$  dissociation asymptote. In fact, the  $^1\text{Fe}(\text{CO})_4 \cdot \text{H}_2$  MECP even lies higher in energy than the *singlet* dissociation asymptote, and the MECP in the  $\text{Fe}(\text{CO})_2(\text{PH}_3)_2$  system is very close in energy to the singlet asymptote. This situation is impossible to explain in the one-dimensional picture, given that the  $^1\text{Fe}(\text{CO})_4 \cdot \text{H}_2$  interaction is almost purely attractive, but this is again due to the need to bring both fragments to a common geometry. The relatively high energy of the MECPs in all cases suggests that the rate of addition of  $\text{H}_2$  to unsaturated fragments  $\text{FeL}_4$  should proceed significantly more slowly than the collisional or diffusion rate, and this has indeed been observed experimentally. Gas-phase addition to  $\text{Fe}(\text{CO})_4$  (under high-pressure limiting conditions)<sup>16</sup> is *ca.* three orders of magnitude slower than is typical for addition of  $\text{H}_2$  to other coordinatively unsaturated species, and  $\text{Fe}(\text{dmpc})_2$  reacts with dihydrogen roughly 7500 times slower than does  $\text{Ru}(\text{dmpc})_2$ ,<sup>36,37</sup> – the reaction in the latter case involves only singlet states and, based on calculations carried out for the  $\text{Ru}(\text{PH}_3)_4$  model, does not involve an energy barrier. In this sense, our predictions are in very good agreement with experiment: the slow observed rates for addition of  $\text{H}_2$  to these unsaturated organometallic fragments are due to the existence of a barrier on the adiabatic potential energy surface, due to the need to cross from one spin state to another. In previous work, we have shown that the height of such barriers can be related to reactivity for CO addition to  $\text{Fe}(\text{CO})_4$ <sup>33</sup> and for CO and  $\text{N}_2$  addition to  $\text{Cp}^*\text{Mo}(\text{Cl})(\text{PMe}_3)_2$ .<sup>34,35</sup> In future work, we plan to use a non-adiabatic

version of transition-state theory<sup>33</sup> to evaluate whether our calculated barrier heights lead to correct prediction of rates for addition of H<sub>2</sub> and other small molecules to Fe(CO)<sub>4</sub> and Fe(dmp)<sub>2</sub>. At present, it appears that the fairly large energy barriers required to reach the MECPs may lead to predicted rates which are too low, which suggests that further refinement of the level of theory may be necessary to achieve quantitative accuracy.

## Conclusions

The present computational investigation explores for the first time the details of the spin crossing region for the H<sub>2</sub> oxidative addition to a spin triplet 16-electron fragment. The approach of the H<sub>2</sub> molecule, a weak ligand, to spin triplet FeL<sub>4</sub> is initially repulsive and necessitates significant molecular rearrangement before reaching the crossover region, leading to a significant energy barrier for the reaction. This situation is analogous to that observed for the oxidative addition of C–H bonds to spin triplet CpIr(PH<sub>3</sub>)<sub>7</sub> and to Cp<sub>2</sub>W, Cp\*<sub>2</sub>W and CH<sub>2</sub>(C<sub>5</sub>H<sub>4</sub>)<sub>2</sub>W,<sup>52</sup> whereas the addition of stronger ligands such as CO may occur without the presence of a spin crossover barrier.<sup>1,2</sup>

## Computational details

All calculations were carried out using the Gaussian 98 program code,<sup>53</sup> together with a modified form of the B3PW91 functional, and flexible polarized basis sets. Specifically, the *c*<sub>3</sub> coefficient in Becke's original three-parameter fit to thermochemical data<sup>54</sup> was changed to 0.15, to give the "B3PW91\*" functional. For Fe, C and O and P, the triple-zeta basis sets of Schäfer *et al.*<sup>55</sup> were used. These basis sets were augmented with two diffuse, 4p-like functions ( $\alpha = 0.134915$  and  $0.041843$ )<sup>56</sup> and an f polarisation function ( $\alpha = 1$ ) on iron; and by one d polarisation function on C, O and P ( $\alpha = 0.8, 1.2$  and  $0.55$ , respectively). The hydrogen atoms of the incoming H<sub>2</sub> molecule also used the triple-zeta basis,<sup>55</sup> with one p polarisation function ( $\alpha = 0.75$ ), whereas the hydrogen atoms on the phosphine ligands were treated with a split-valence basis set.<sup>55</sup> All minima and transition states were fully optimised and characterised by computing vibrational frequencies at the same level of theory. MECPs were optimised using the code developed by one of the authors<sup>12</sup> together with Gaussian98.<sup>53</sup> The MECP optimisation procedure is based on minimising a generalised gradient found at any geometry by combining the computed energies and gradients at that point on the two potential energy surfaces. The gradient contains one term pointing towards the hyperspace in which the two surfaces intersect, and one term pointing towards lower energies within this hypersurface. The mixed Fortran/shell script code (ref. 12, this program is available upon request) creates Gaussian input files for both spin states at a given geometry, calls Gaussian, extracts energies and gradients from the output files, tests for convergence, and cycles.

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