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Vidar Jensen, Rinaldo Poli. Theoretical Investigation of the Low-Energy States of $\text{CpMoCl}(\text{PMe}_3)_2$ and Their Role in the Spin-Forbidden Addition of N_2 and CO . *Journal of Physical Chemistry A*, 2003, 107 (9), pp.1424-1432. 10.1021/jp027212y . hal-03283691

HAL Id: hal-03283691

<https://hal.science/hal-03283691>

Submitted on 19 Jul 2021

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Theoretical Investigation of the Low Energy States of CpMoCl(PMe₃)₂ and Their Role in the Spin Forbidden Addition of N₂ and CO

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Received:

Abstract:

A recent computational investigation of Jahn-Teller effects in unsaturated 16-electron d⁴—d⁶ [CpML_n] complexes (Abu-Hasanayn, F.; Cheong, P.; Oliff, M. *Angew. Chem.* **2002**, *41*, 2120) highlighted the typical presence of two spin triplet and two singlet states of competing stability in these complexes and pointed out the necessity to account for more than one electronic state in studies of such complexes. Consequently, we have reinvestigated the addition of N₂ to all the four low-energy states of CpMoCl(PH₃)₂, a reaction for which previously only one singlet and one triplet state has been considered (Keogh, D. W.; Poli, R. *J. Am. Chem. Soc.* **1997**, *119*, 2516). The

present study was performed using density functional theory (DFT) and the thus obtained relative stabilities of the four electronic states of the educt are in good accord with those obtained using a multi-reference MP2 method. The spin singlet ground state of the 18e⁻ product of N₂ addition turns out to be derived from the fourth lowest state (2¹A') of the 16e⁻ educt, immediately demonstrating the importance of accounting for more than one triplet and one singlet state in such reactions. The barrier to N₂ addition was found to arise from the enthalpic cost of obtaining identical geometries for this singlet state and the spin triplet ground state of the educt (³A'') in the minimum energy crossing point (MECP). With a spin triplet ground state reactant complex, a triplet—singlet MECP defining the rate limiting step, and a singlet product, our calculated activation (14.4 kcal/mol) as well as reaction enthalpies (21.2 kcal/mol) of N₂ addition to CpMoCl(PMe₃)₂ are found to be within the experimental error bars of those measured for Cp*MoCl(PMe₃)₂. For the corresponding reaction with CO, there is a delicate balance between the transition state (TS) of addition on the triplet potential energy surface (PES) and the point of crossing between the triplet and singlet PES. Our optimized TS and MECPs for this reaction suggest that the rate is controlled by the barrier defined by the spin triplet TS, with spin inversion occurring after this point. Our calculated activation enthalpy (6.7 kcal/mol) based on the spin triplet TS is in excellent agreement with that measured for Cp*MoCl(PMe₃)₂.

Introduction

Thermal reactions that involve more than one spin potential energy surface (PES) are becoming the topic of increasing interest.¹⁻⁴ These are either processes leading from reagents in a particular spin state to products in a different spin state, or processes involving an even number of spin state changes along the reaction pathway, leading to products in the same spin state as the reagents. In the latter case, the point at which the spin change occurs (minimum energy crossing point, or MECP) may be located at a lower energy than that of the transition states (TSs) on the diabatic PES of the reagents and products. When this happens, the reaction can be considered to benefit from a spin acceleration phenomenon.⁵

This general area, also termed “multiple state reactivity” or “spin crossover reactivity”, is quite distinct from the more widely appreciated field of photochemical reactivity since no photon-coupled excitation or decay processes are involved. It has been shown to be relevant in gas-phase reactions of highly unsaturated metal-containing fragments,⁶⁻⁹ in biochemically relevant processes,¹⁰⁻¹³ in C–H activation processes by organometallic complexes,^{14,15} and in olefin polymerization catalysis.¹⁶⁻²⁰ Unsaturated organometallic complexes (*e.g.* with less than 18 electrons in the valence shell) may be energetically stabilized by the adoption of a ground state with two or more unpaired electrons and stable examples of this family of molecules now abound.²¹ Spin crossover reactions may therefore be more common than previously appreciated in organometallic chemistry.

A few years ago, one of us carried out experimental and theoretical investigations of the addition process of CO and N₂ to the 16-electron spin triplet complex Cp*MoCl(PMe₃)₂,²² leading to the spin singlet 18-electron adducts, Cp*MoCl(PMe₃)₂(L) (L = CO, N₂). The large difference between the rates (CO reacts ca. 3 orders of magnitude faster than N₂) is at odds with

the essentially equivalent rate that was previously determined for several other 16-electron intermediates. The calculations, which were carried out at the MP2/LANL2DZ level on the CpMoCl(PH₃)₂ model, allowed an interpretation of the phenomenon on the basis of a greater spin-change related enthalpic barrier for the N₂ addition process. The calculations along the reaction coordinate of addition involved only the triplet surface that derives from the ground state of the educt and the singlet state surface that derives from the adduct. A recent theoretical study by Abu-Hasanayn *et al.*,²³ however, has pointed out the typical presence of more than one electronic configuration in each spin state for 16-electron fragments, leading to different states with similar energy. We have therefore decided to reinvestigate our system under this new light and report our findings in the following.

Computational Details

All geometry optimizations were performed using the three-parameter hybrid density functional method of Becke (termed B3LYP),²⁴ as implemented in the Gaussian98 set of programs.²⁵ Stationary points were optimized and characterized using algorithms involving analytic calculation of the first and second derivatives of the energy. The PESs of N₂ and CO addition were explored using linear transit (LT) calculations, i.e. series of geometry optimizations using constrained (frozen) Mo—N₂ and Mo—CO distances. In addition, the LT optimizations for the 2¹A' state of CpMoCl(PH₃)₂ were performed with the angle Mo-N-N constrained to the value optimized for the addition product in order to avoid complexation of the second N atom. For N₂ addition to CpMoCl(PH₃)₂, these optimizations were performed within C_s symmetry in order to distinguish between the different electronic states and the curvature of the PES was monitored by calculation of the Hessian matrix. The reported structures always involve the energetically lowest

of the two possible rotational conformations of the cyclopentadienyl ligand in the C_s symmetrical complexes. The unrestricted formulation was used for triplet states whereas singlet states were obtained within the restricted formulation in order to avoid spin contamination. Numerical integrations were performed using the “ultrafine” grid of Gaussian98, consisting of 99 radial shells and 590 angular points per shell, and the Gaussian98 default values were chosen for the self consistent field (SCF) and geometry optimization convergence criteria. Thermochemical values were computed within the harmonic-oscillator, rigid-rotor, and ideal-gas approximations. MECPs were located using the method described by Harvey *et al.*²⁶ whereas the corresponding frequencies were calculated from an effective Hessian matrix.^{26,27}

The B3LYP-optimized geometries were subjected to single-point (SP) energy calculations where indicated. In addition to the already described B3LYP method, SP calculations were performed using the BPW91 functional which contains the local exchange-correlation potential developed by Vosko *et al.*²⁸ augmented with Becke’s²⁹ non-local exchange corrections and Perdew and Wang’s³⁰ non-local correlation corrections. The SP calculations based on density functional theory (DFT) were performed using the “ultrafine” grid described above and the SCF procedure was converged to a RMS change of the density matrix below 1.0·10⁻⁶. For the 16-electron educts, CpMoCl(PH₃)₂, SP energy calculations were also performed using a variant of multi-reference second-order perturbation theory, the MRMP2 method of Nakano^{31,32} as implemented in the GAMESS-US set of programs.³³ This method gives results for the singlet–triplet splitting of methylene in close agreement with CASPT2. The reference wave functions were of the complete active space SCF type (CASSCF) and the active orbital space consisted of the three Mo 4d orbitals occupied in the triplet ground state, (³A”, d-occupancy (1a’)²(2a’)¹(a’)¹).

Such a four-electron-three-orbital CASSCF model space was used throughout. All valence electrons were correlated in the subsequent perturbational calculations.

The basis sets that were used for the geometry optimizations (termed DZP) are described as follows: Hay and Wadt effective core potentials (ECP)^{34,35} were used for the elements Mo, Cl and P. For Mo, the ECP replaced the 1s, 2s, 2p, 3s, 3p and 3d electrons whereas the 1s, 2s and 2p electrons were replaced for the Cl and P atoms. The 4s, 4p, 4d, 5s and 5p orbitals of Mo were described by the Hay and Wadt primitive basis set³⁵ contracted to [3s,3p,2d]. The 3s and 3p orbitals of Cl and P were described by Hay and Wadt primitive basis sets^{34,35} augmented with a single diffuse p primitive³⁶ and a single polarization d primitive³⁶ and contracted to [2s,3p,1d]. Oxygen, nitrogen, carbon and hydrogen atoms were described by standard Dunning and Hay valence double-zeta basis sets.³⁷ The basis sets of the atoms of the coordinating molecules (CO or N₂) were extended with a d polarization function.³⁶

The SP energy calculations involved basis sets (termed TZD2P) that were improved compared to those used during the geometry optimizations: For molybdenum, the Hay and Wadt primitive basis was extended with three f primitives ($\alpha_f = 1.8913, 0.6783, 0.2904$) and contracted to [4s,4p,3d,2f]. For Cl and P atoms, the extended Hay and Wadt primitive basis set described above was contracted to [3s,4p,1d]. For carbon atoms forming part of the cyclopentadienyl ring, the standard valence double-zeta basis set was extended with a diffuse p primitive³⁶ and a single d polarization primitive³⁶ and contracted to [3s,3p,1d]. For N, O and C atoms of the coordinating molecule (CO or N₂) this [3s,3p,1d] basis set was extended in the following manner: A diffuse s function was added even-temperedly and a second uncontracted d function was added by splitting (with a factor = 3) the values of the single polarization function exponents, leading to [4s,3p,2d] contracted basis sets.

Results and Discussion

Addition of N₂ to CpMoCl(PH₃)₂

Abu-Hasanayn *et al.*²³ recently pointed out the importance of accounting explicitly for two singlet and two triplet states in complexes such as CpMo(CO)₂Cl. Accordingly, one of the goals of the present study is to investigate the potential involvement of more than one electronic state of each spin (singlet and triplet) in reactions of N₂ and CO addition to Cp*MoCl(PMe₃)₂. We thus decided to calculate the four energetically lowest-lying potential curves of N₂ coordination to the computationally tractable CpMoCl(PH₃)₂ as shown in Figure 1. These linear transit (LT) calculations (series of optimizations with constrained Mo—N distances, see the Computational Details section) were performed under the assumption of C_s symmetry in order to cleanly define the various electronic states based on their differing total symmetry and/or orbital occupancy.

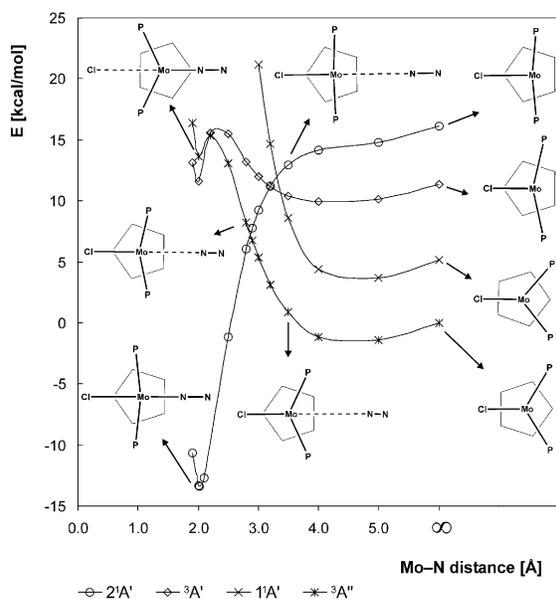


Figure 1. B3LYP/DZP LT curves for the coordination of N₂ to the four lowest electronic states of CpMoCl(PH₃)₂. The states are labeled according to the order in the educt. Key optimized structures are viewed along the Mo—Cp centroid axis. The constrained optimizations were

performed within C_s symmetry. We verified, however, that each structure along the LT curves involves the energetically most stable of the two possible C_s-symmetric rotational conformations of the Cp ring.

Starting with the educts, CpMoCl(PH₃)₂, vibrational analysis shows that the optimized C_s symmetric geometries given in Figure 1 are true minima for the triplet ground state (³A'', d-occupancy (1a')²(2a')¹(a'')¹) as well as the second singlet state (2¹A', (1a')²(a'')²). The lowest-lying states of each spin multiplicity are also well-defined in C₁ symmetry. For the ground state, no lower-lying point of C₁ symmetry could be found. Both 1¹A' ((1a')²(2a')²) and ³A' ((a'')²(1a')¹(2a)¹) are first-order saddle points. Relaxing the imposed symmetry restriction of the lowest-lying singlet state results in only minor geometric changes and a negligible lowering of the energy (0.03 kcal/mol). The excited triplet state carries a residual imaginary frequency (132i cm⁻¹) corresponding to a relative rotation of the two PH₃ groups from eclipsed to staggered conformation, but this conformational issue presumably is of minor importance for the present addition reactions.

The geometrical parameters and relative energies for the educts are given in Table 1. The large difference in P-Mo-P opening angles between the different states is perhaps the most striking feature; the two singlet states, for example, differ by more than 20°, P-Mo-P = 82.3° (1¹A') and 103.4° (2¹A'). The latter state thus can be characterized as having a geometry suitable for complexation of an additional ligand *trans* to Cl, and this geometric effect is brought about by a double occupancy of the a'' d-orbital. The angular parameters of the previously reported²² optimized structures of triplet and singlet CpMoCl(PH₃)₂ are in excellent agreement with the present angles for ³A'' and 1¹A'. In particular, the reported angle P-Mo-P = 83.8° for the singlet asymptote fragment assumed in the previous study identifies this state as the most stable singlet

(¹A'). Thus, the importance of considering more than one singlet state for the addition reaction is immediately evident when comparing with the potential curves in Figure 1. The ground state of the addition product, CpMoCl(PH₃)₂N₂, actually is derived from the second lowest singlet state in the educt (²A'). Moreover, in the educt and at long Mo—N distances, this state is actually the least stable of all the four considered. In the lowest-lying singlet state of the educt (¹A'), the potential a' acceptor orbitals are already occupied resulting in a strongly repulsive potential at Mo—N distances shorter than 4 Å. The singlet potential curves of N₂ and CO addition in the previous study drop in energy below 4 Å, which shows that the correct state (²A') was followed in the constrained optimizations. At 4 Å, however, these singlet curves implied several kcal/mol destabilization compared to infinitely separated educts as a result of the comparison to the ¹A' asymptote. The apparent resulting barrier was incorrectly interpreted as being caused by PH₃—N₂ repulsive interactions. The present ²A' potential is attractive already at long distances and describes Mo—N bond formation without a barrier. The other three potentials are also attractive at long distances. The two triplet states may in fact form meta-stable complexes with N₂. Since the 16e⁻ triplet complexes are already electronically saturated, the bond formation proceeds in concert with weakening of the other Mo—ligand bonds, in particular Mo—Cl and Mo—C of the Cp ring, and with moderate degree of delocalization of the two unpaired electrons from the metal to the ligands (mainly Cp and N₂). The result is an activated addition process. In the case of N₂, the activation needed is significant since the Mo—N bond being formed is the weakest of the Mo—ligand bonds in this complex and the process is endothermic. Interestingly, the preferred addition product spin triplet state is ³A' (and not the ground state of the educt, ³A''), which again underlines the importance of monitoring more than one electronic state of each spin multiplicity for the current system. The triplet addition product will be characterized in more detail in the case

of CO, for which full optimization of this product of addition to CpMoCl(PMe₃)₂ has been performed (vide infra).

Table 1. Geometry Parameters and Relative Energies of the Educts, CpMoCl(PH₃)₂.^a

	³ A''	³ A'	1 ¹ A'	2 ¹ A'
Mo–Cp(av) ^b	2.408	2.367	2.401	2.375
Mo–Cl	2.436	2.519	2.415	2.509
Mo–P	2.458	2.506	2.396	2.443
Cl–Mo–P	89.9	82.7	96.3	82.3
P–Mo–P	92.2	115.9	82.3	103.4
ΔE (B3LYP/TZD2P) ^c	0.0	11.2	5.6	16.5

^a Bond distances in angstroms, angles in degrees and energies in kcal/mol relative to the triplet ground state, ³A''. ^b Average Mo–C distance to the cyclopentadienyl ring. ^c SP calculation using the B3LYP/DZP geometry.

In the initial study²² the barrier associated with N₂ addition to CpMoCl(PH₃)₂ was approximated by the point of crossing of the spin triplet and singlet LT curves obtained using the Mo–N distance as the constrained variable. This point (at a distance Mo–N = 2.917 Å) was only ca. 1 kcal/mol higher than that calculated for a triplet complex early in the N₂ addition process (Mo–N = 3.917 Å). Minor changes in the computational methodology or in the model complex, e.g. such as increased steric bulk following the use of realistic phosphine groups, thus could reverse the picture and instead predict a barrier due to steric hindrance in the spin triplet entrance channel. However, our current energy profiles (Figure 1) place the crossing point at significantly higher energies than the first part of the spin triplet curve and thus strongly support the conclusion that the activation barrier of the addition process is actually controlled by the cost of changing the spin state.²² In other words, the preferred route seems to be for the system to follow the ³A'' state until reaching the region where this PES crosses the 2¹A' PES (at a distance

Mo—N = 2.8—2.9 Å), undergo spin inversion and follow the latter singlet state to the product. While the lower estimate of the activation energy of N₂ addition was taken to be 4.2 kcal/mol on the basis of LT curves in the initial study, our current curves suggest a barrier of 7–8 kcal/mol.

To further characterize this apparent two-state reaction we have now located the lowest point on the seam of crossing in the region of interest, i.e. the minimum energy crossing point (MECP), as depicted in Figure 2. Relative energies and geometrical parameters for the MECP and the spin singlet addition product are given in Table 2. The B3LYP/DZP optimized MECP is located at an Mo—N distance of 2.859 Å and has an energy 10.7 kcal/mol higher than that of the triplet educt asymptote. This implies an additional cost of obtaining identical triplet and singlet geometries amounting to 3–4 kcal/mol compared to the point of crossing of the LT curves. As expected the MECP is seen to have a geometry intermediate between the partially optimized singlet and triplet geometries in this region. The P-Mo-P angle for example, is 94.0° in the triplet and 105.8° in the singlet complex at a distance Mo—N = 2.9 Å and 97.8° in the MECP. At the MECP geometry the B3LYP/DZP description apparently involves a non-negligible basis set superposition error (BSSE), and our single-point (SP) energy calculations with larger basis sets shift the barrier upward by 3 kcal/mol, resulting in a final estimate ($\Delta E^\ddagger = 13.5$ kcal/mol) in excellent agreement with the experimental result for Cp*MoCl(PMe₃)₂ ($\Delta E^\ddagger = 14.5$ kcal/mol).²² The calculated exothermicity, however, is more than 12 kcal/mol lower than that experimentally determined for Cp*MoCl(PMe₃)₂ and this discrepancy will be examined in the section below concerning N₂ addition to CpMoCl(PMe₃)₂. The first section below deals with the (technical) validation of the quantum chemical description of the four low-lying electronic states of the educt. The chemically oriented reader may skip this section altogether.

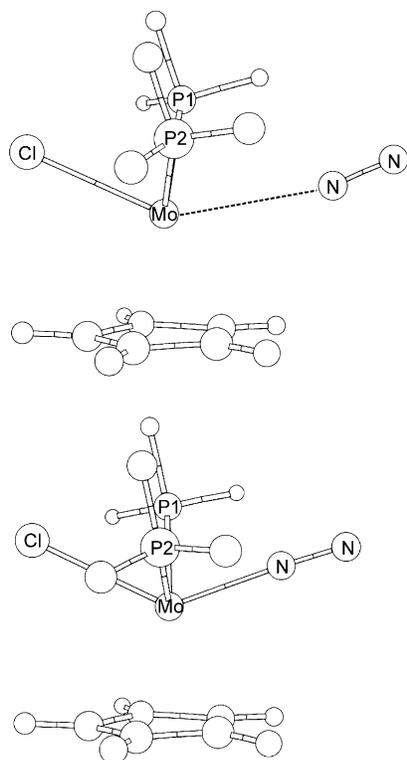


Figure 2. B3LYP/DZP optimized structures of the MECP between the $2^1\text{A}'$ and $3^1\text{A}''$ PESs during addition of N_2 to $\text{CpMoCl}(\text{PH}_3)_2$ (uppermost structure) and the spin singlet product of N_2 addition (lower). The latter structure is C_s -symmetric whereas the geometry of the MECP displays minor deviations from C_s symmetry.

Table 2. Geometry Parameters and Relative Energies of the MECP and Product of N₂ Addition to CpMoCl(PH₃)₂.^a

	MECP (³ A/ ¹ A)	Product (¹ A')
Mo–Cp(av) ^b	2.413	2.392
Mo–Cl	2.501	2.583
Mo–P1	2.471	2.470
Mo–P2	2.472	2.470
Mo–N	2.859	2.024
Cl–Mo–P1	79.5	74.0
Cl–Mo–P2	79.7	74.0
P–Mo–P	97.8	112.8
Cl–Mo–N	145.8	133.7
Mo–N–N	164.8	176.7
Cl–Mo–N–N	-30.8	180.0
ΔE (B3LYP/DZP)	10.7	-13.4
ΔE (B3LYP/TZD2P) ^c	13.5	-12.3
ΔH_{298} (B3LYP/TZD2P) ^c	13.6	-10.5

^a Bond distances in angstroms, angles in degrees and energies in kcal/mol relative to separated ground state educts. ^b Average Mo–C distance to the cyclopentadienyl ring. ^c SP calculation using the B3LYP/DZP geometry. The average of the singlet and triplet energies is used for the MECP ($\Delta\Delta E = |\Delta E_{\text{triplet}} - \Delta E_{\text{singlet}}| \leq 0.3$).

Stability of the Spin States: Validation of the Computational Approach

Because of the involvement of more than one spin-state in the current reactions it is of vital importance that these states are described with sufficiently even accuracy by the methods with which they are studied. Unfortunately, experimental excitation energies for the 16e⁻ educts,

CpMoCl(PR₃)₂, are not known and comparison has to be made against computational results from higher-level methods. The computationally more tractable model, CpMoCl(PH₃)₂, was chosen for the validation studies using a multi-configurational second-order perturbational method, MRMP2, in combination with basis sets essentially of the type triple-zeta plus diffuse functions and double polarization (termed TZD2P, see the Computational Details section). The reference CASSCF wave functions involved an active space of four electrons (the d electrons) and three orbitals, which should take into account the most important part of the static correlation expected in particular for the singlet states. This expectation is confirmed by the fact that the CASSCF wave function was found to be an equally good reference function in the four states studied for the 16e⁻ reactant, with the reference weight calculated to be 65% in all cases.

Turning now to the lowest-lying singlet state (1¹A'), its stability is seen to be highly dependent on the correlation treatment (see Table 3), with the non-vertical excitation energy from the triplet ground state (3³A'') being reduced from 15–20 kcal/mol calculated using HF and CASSCF to ca. 7 kcal/mol upon inclusion of dynamical correlation in the form of second-order perturbation theory. The earlier single-reference MP2 calculations,²² which did not involve polarization (correlating) functions, gave 10.9 kcal/mol for this excitation. Improving the correlation treatment and the basis sets compared to the present case is likely to stabilize this singlet even further. The true value for the singlet–triplet gap is probably somewhat lower than 7 kcal/mol, and thus in good accord with the DFT results (2.9 and 5.6 kcal/mol for BPW91 and B3LYP, respectively). The two other excitation energies are considerably less dependent on the correlation treatment. For the second triplet (3³A') which also has the same requirements as the ground state with respect to exchange, the different methods give virtually identical results. The second singlet state (2¹A') has the two d electron pairs in orbitals belonging to different irreducible representations and its

stability is much less dependent on the correlation treatment than that of the most stable singlet. MRMP2 predicts an energy difference from the triplet ground state within 3 kcal/mol from that of Hartree-Fock. We can thus conclude that the *ab initio* result probably is close to converged and that the DFT methods overestimate the stability of this state somewhat due to inadequacies in the exchange part of the functionals. The hybrid functional, B3LYP, includes some exact (HF) exchange and is 2 kcal/mol closer to the MRMP2 result than the pure density functional, BPW91.

Table 3. Energies of Excited States of CpMoCl(PH₃)₂ Given Relative to the Triplet Ground State,³A''^a

	³ A'	1 ¹ A'	2 ¹ A'
B3LYP/DZP	11.3	5.2	16.1
B3LYP/TZD2P ^b	11.2	5.6	16.5
BPW91/TZD2P ^b	10.9	2.9	14.5
RHF/TZD2P ^b	11.1	19.5	26.9
CASSCF/TZD2P ^b	11.1	16.2	20.5
MRMP2/TZD2P ^b	11.2	7.1	24.3

^a Electronic energies given in kcal/mol. ^b SP calculation using the B3LYP/DZP geometry.

Addition of N₂ to CpMoCl(PMe₃)₂

Addition of N₂ to CpMoCl(PMe₃)₂ is assumed to proceed in a qualitatively similar fashion to that described above for CpMoCl(PH₃)₂. Thus, for the more realistic PMe₃ analogue only the ground state triplet reactant, the singlet product and the MECF have been subjected to calculation in order to investigate the influence of the phosphine methyl groups. In other words, at any given point we only calculated the lowest state for each spin multiplicity which furthermore allowed us

to explore the potential surfaces without symmetry restrictions. The three optimized geometries are shown in Figure 3, with accompanying geometrical parameters and relative energies in Table 4. Only the educt, CpMoCl(PMe₃)₂, is seen to depart from C_s symmetry. The two trimethyl phosphine groups are rotated slightly away from an eclipsed conformation in order to reduce steric repulsion, resulting in a 1° difference between the two Cl-Mo-P angles. A similar but much more pronounced departure from symmetry is evident in the crystal structure of CpMoCl(dppe).³⁸ This difference between experiment and theory can be explained by the presence of the C₂H₄-bridge and the sterically more demanding Cp* ligand in the experimentally determined structure. Both these features contribute to a sharper P-Mo-P angle compared to our calculations on the Cp containing model, the difference amounting to 20°. The sharper P-Mo-P angle in turn, obviously increases the steric repulsion between the trimethyl phosphine groups resulting in a larger rotation away from the eclipsed conformation. Apart from the deviation in P-Mo-P angle already commented upon, the calculated geometrical parameters are in good accord with those available from related, experimentally determined structures, with the possible exception of the Mo—N and Mo—Cl distances of the singlet product, which are calculated to be too short and too long, respectively (see Table 4). A detailed comparison of these theoretically and experimentally obtained distances is perhaps not justified, however, since N/Cl disorder has been noted in the refinement of the X-ray structures.³⁹ A similar deviation (and possible explanation) was observed also for the MP2-optimized singlet product in the initial study.²² Finally, the located MECP is C_s symmetric but otherwise very similar to the MECP presented for the PH₃ analogue above. This confirms our assumption that the general features of the N₂ addition process should remain when going from PH₃ to PMe₃.

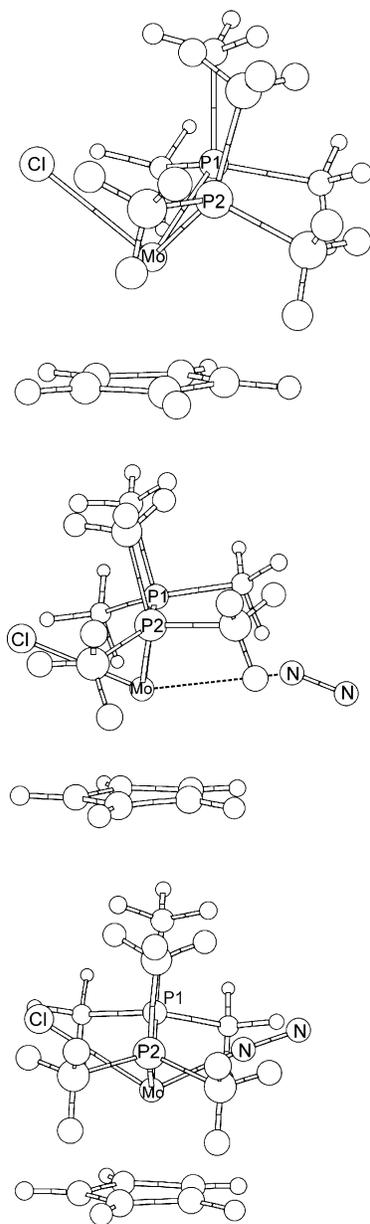


Figure 3. B3LYP/DZP optimized structures of the triplet educt (upper structure), MECP (middle) and spin singlet product (lower) of N_2 addition to $\text{CpMoCl}(\text{PMe}_3)_2$. The two latter structures are C_s -symmetric whereas the geometry of the educt deviates slightly from C_s symmetry.

Table 4. Geometry Parameters and Relative Energies of the Triplet Educt, MECP and Singlet Product of N₂ Addition to CpMoCl(PMe₃)₂.^a

	educt (³ A)		MECP (³ A''/ ¹ A')		product (¹ A')	
	calc	expt ^b	calc	expt ^c	calc	expt ^d
Mo–Cp(av) ^e	2.425	2.335(4)	2.425		2.403	2.328
Mo–Cl	2.464	2.416(1)	2.530		2.611	2.527
Mo–P1	2.476	2.428(1)	2.496		2.518	2.464
Mo–P2	2.467	2.413(1)	2.496		2.518	2.464
Mo–N			2.910		1.978	2.158
Cl–Mo–P1	89.2	83.59(4)	81.0		76.1	77.33
Cl–Mo–P2	90.1	92.94(5)	81.0		76.1	77.33
P–Mo–P	98.4	78.71(4)	103.9		126.1	114.4
Cl–Mo–N			151.1		123.3	131.5
Mo–N–N			152.8		175.9	
Cl–Mo–N–N			180.0		180.0	
ΔE (B3LYP/DZP)	0.0	0.0	11.8	14.0 ± 1.0	-16.6	-22.8 ± 2.1
ΔE (B3LYP/TZD2P) ^f	0.0	0.0	14.2	14.0 ± 1.0	-15.8	-22.8 ± 2.1
ΔH (B3LYP/TZD2P) ^f	0.0	0.0	14.3	14.0 ± 1.0	-13.3	-22.8 ± 2.1
ΔH (BPW91/TZD2P) ^f	0.0	0.0	14.4	14.0 ± 1.0	-21.2	-22.8 ± 2.1
ΔS (B3LYP/DZP)	0	0	-29	-20 ± 3	-38	-67 ± 7

^a Bond distances in angstroms, angles in degrees, energies/enthalpies in kcal/mol and entropies in cal/(mol•K). Energy data given relative to separated ground state educts. ^b Geometry parameters from X-ray crystal structure of CpMoCl(dppe).³⁸ ^c Activation parameters for N₂ addition to CpMoCl(PMe₃)₂.²² ^d Structural parameters calculated from fractional coordinates published for Cp*MoCl(PMe₃)₂(N₂).³⁹ Reaction energetics measured for N₂ addition to Cp*MoCl(PMe₃)₂.²² ^e Average Mo–C distance to the cyclopentadienyl ring. ^f SP calculation using the B3LYP/DZP geometry. The average of the singlet and triplet energies is used for the MECP ($\Delta\Delta E = |\Delta E_{\text{triplet}} - \Delta E_{\text{singlet}}| \leq 1.3$).

Perhaps somewhat surprising is the fact that the spin-inversion related barrier to N₂ addition remains practically identical when replacing PH₃ by PMe₃, demonstrating the minor influence of steric effects on the barrier height. Changing the DFT functional apparently also results in only minor difference in the calculated barrier height. The stability of the calculated activation enthalpy with respect to variation of both the model complexes and the method of calculation suggests that it is not only fortuitous that our best estimates are in excellent agreement with the measurements for Cp*MoCl(PMe₃)₂²². This further serves to underline that the rate of this addition reaction is indeed controlled by the spin-inversion process and that the MECP appears to be a good approximation to the adiabatic transition state formed by the avoided crossing and may provide useful estimates of the activation energies for spin flips.²⁻⁴ For the title compounds it was not deemed practical to perform accurate calculation of the spin-orbit coupling, and thus the transmission coefficient with which our enthalpic barrier is associated remains unknown. The fair agreement between the calculated and experimental entropic terms (Table 4), however, suggests that the spin-orbit coupling is large, as often found for compounds of second-row transition metals.¹⁻⁴

As mentioned above for the PH₃ analogue, the exothermicity of the N₂ addition process is less straightforward to predict. For the PH₃ analogue, we calculated an exothermicity more than 12 kcal/mol lower than that experimentally recorded for Cp*MoCl(PMe₃)₂. The realistic phosphine groups improves the estimate by 2–3 kcal/mol (Table 4) and most of the remaining error of almost 10 kcal/mol can probably be attributed to inadequacies in the B3LYP functional, most likely due to the correlation part. The pure density functional (BPW91) estimate is within the error bars of the experiment for the reaction (-22.8 ± 2.1 kcal/mol) as well as the activation enthalpy (14.0 ± 1.0 kcal/mol).

Addition of CO to CpMoCl(PMe₃)₂

Stabilization compared to separated reagents was noted at long Mo—N distances for the calculated potential curves of N₂ addition above. A similar stabilization for CO would imply that the highest point on the potential curve of coordination for the triplet state should not be located at long Mo—CO distances as found in the initial study,²² and it would require detailed theoretical investigation to judge whether the recorded activation enthalpy (5.0 kcal/mol) is due simply to a barrier to addition on the triplet PES or to the spin inversion process. Accordingly, we have calculated the LT potential curve of CO addition to the lowest-lying spin triplet (¹3A) and the second lowest singlet state (²1A) of CpMoCl(PMe₃)₂. For ²1A, only the section of the reaction coordinate for which this state can be expected to be the lowest-lying of singlet multiplicity (Mo—CO distance shorter than 3 Å) has been calculated in order to avoid using symmetry restrictions (*vide supra*). The two resulting potential curves are shown in Figure 4. Indeed, a barrier to CO addition on the triplet PES analogous to that calculated for N₂ (Figure 1) is evident. This time, however, the bond being formed (Mo—CO) is stronger than those being weakened (Mo—Cl and Mo—C of the Cp ring), and hence the triplet state bond formation for CO is found to occur earlier, at a longer Mo—ligand distance, and to require less activation than addition of N₂ (Figure 1). The origin of the barrier, rehybridization associated with simultaneous bond rupture and formation, however, remains the same in the two cases. The maximum on the LT curve is located close to a Mo—CO distance of 2.6 Å, whereas the two LT curves cross at a longer Mo—CO distance (2.9 Å) and at an energy ca. 1.5 kcal/mol lower than the maximum on the triplet curve. The latter result may suggest that the spin inversion takes place before reaching the classical barrier on the triplet PES, *i.e.*, that the reaction is qualitatively similar to that of N₂. However, the difference in energy between the point of crossing of the two LT curves and the

maximum on the triplet curve is tiny and a more detailed comparison between the triplet state barrier and the crossing region is required before drawing any conclusions regarding the nature of the barrier.

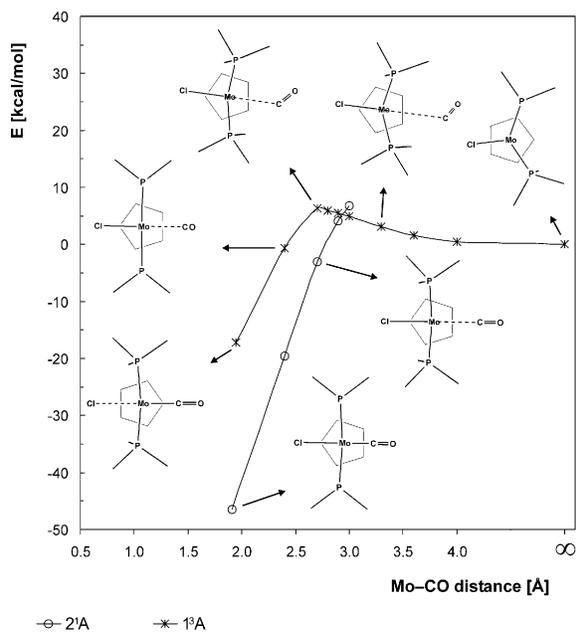


Figure 4. B3LYP/DZP LT curves for the coordination of CO to the lowest triplet state (1^3A) and the second lowest doublet state (2^1A) of CpMoCl(PMe₃)₂. The states are labeled according to the order in the educt assuming C_1 symmetry. Key optimized structures are viewed along the Mo—Cp centroid axis. The LT constrained optimizations were performed without symmetry restrictions. The points pertaining to the spin triplet educt (infinite Mo—CO distance) as well as the two addition products (the two leftmost points) involve full, unconstrained optimizations.

To this end, we have performed full optimization of the transition state (TS) of CO addition on the triplet PES as well as of two different MECPs between the two spin states, as shown in Figure 5 and with accompanying geometrical parameters and relative energies given in Table 5. The TS has a distance Mo—CO = 2.573 Å and is structurally and energetically similar to the LT

maximum in Figure 4. The imaginary frequency ($100i \text{ cm}^{-1}$) corresponds to a virtually pure Mo—CO stretching mode as expected. The optimized crossing points are both of shorter Mo—CO bonds and lower energies and must be characterized as being located after the spin triplet TS on the reaction coordinate. No MECP could be located at distances comparable to or longer than that of the triplet TS. The first MECP (MECP1, Mo—CO = 2.332 Å) is located between the TS and the product of addition, while MECP2 is structurally and energetically close to the product located on the diabatic spin triplet PES (see Figure 6). According to these results the reaction proceeds by coordination on the spin triplet PES and the system is likely to remain a spin triplet until reaching the classical TS. After the TS the system may undergo spin inversion en route to (MECP1) or at the triplet product (MECP2), with the latter alternative being the more likely. In other words, the barrier of the CO addition reaction is expected to be identical to that calculated for addition on the diabatic triplet PES and not to be due to the spin inversion process. This contrast to the N_2 addition is brought about by the difference in stability of the triplet product. Spin triplet minima were located also for the N_2 addition product (Figure 1), but these were found to be unstable with respect to the triplet educt asymptote by more than 10 kcal/mol and to be accompanied by significant activation barriers. As noted in the initial study,²² the formation of the triplet product is exothermic for CO because CO is the better ligand. N_2 on the other hand, is the weakest of all the ligands in the title complexes and the formation of a Mo— N_2 complex at the expense of weakening the bonds to the other ligands is disfavored. Comparison of the bond distances of the spin triplet addition product, $\text{CpMoCl}(\text{PMe}_3)_2(\text{CO})$ (Table 5), with those of the corresponding educt (Table 4) shows that the result of the addition of CO on the triplet PES is a 0.28 Å lengthening of the Mo—Cl bond and an increase of the average Mo—C distance of the Cp ring by 0.15 Å whereas the Mo—P bond lengths are affected by only 0.05–0.06 Å. The increase

in the average distance to the Cp carbon atoms reflects a reduction in hapticity of the Mo—Cp bond. Whereas in the reactant, all these Mo—C distances are in the range 2.387–2.470 Å, the cyclopentadienyl anion is unsymmetrically bonded in the triplet product, with corresponding distances 2.438–2.782 Å. These bond weakenings are also reflected in the fact that the two unpaired electrons, which are almost exclusively attributed to the metal in the triplet reactant (Mulliken spin density 1.91 *e*), are partly delocalized on the ligands in the triplet product, with a Mulliken spin density reduced to 1.56 *e* for the metal. Most of this difference in spin density is taken over by the cyclopentadienyl, in particular by the carbon atom with the longest Mo—C distance, and by CO. For the N₂ addition process, the BPW91/TZD2P calculated relative energies were seen to be in excellent agreement with experimental results for both the activation barrier and the overall reaction enthalpy (Table 4). Also for CO the agreement between the experimental and BPW91/TZD2P calculated activation enthalpy is convincing (within 2 kcal/mol, Table 5). The experimental CO addition reaction enthalpy is not available, but our calculations suggest a ΔH_{298} close to –50 kcal/mol.

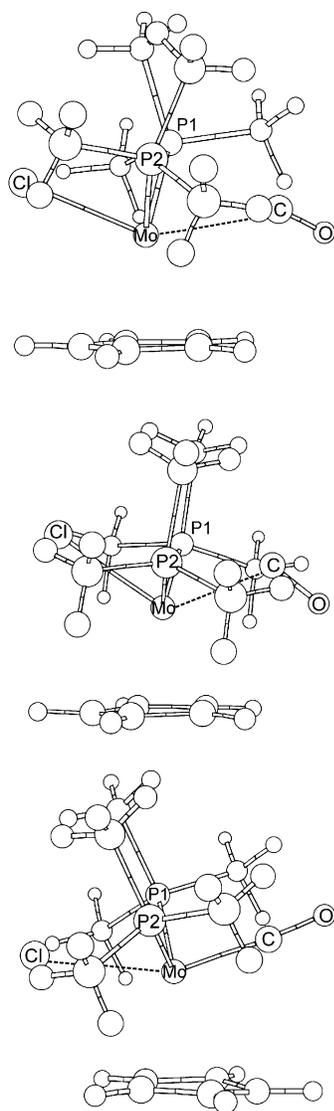


Figure 5. B3LYP/DZP optimized structures of the transition state (TS) of CO addition to CpMoCl(PMe₃)₂ on the lowest spin triplet PES (uppermost structure, C₁ symmetric, ³A) as well as the first (middle, ³A/¹A) and second (lower, ³A/¹A) located MECP. The two MECPs are close to C_s symmetric.

Table 5. Geometry Parameters and Relative Energies of Stationary Points and MECPs of CO Addition to CpMoCl(PMe₃)₂.^a

	TS (³ A)		MECP1 ^b (³ A/ ¹ A)		MECP2 ^b (³ A/ ¹ A)		Product (³ A')		Product (¹ A')	
	calc	expt ^c	calc	calc	calc	calc	calc	calc	calc	expt ^d
Mo–Cp(av) ^e	2.437		2.405	2.601	2.580	2.422	2.335(9)			
Mo–Cl	2.509		2.540	2.719	2.743	2.617	2.577(5)			
Mo–P1	2.532		2.547	2.521	2.522	2.509	2.469(2)			
Mo–P2	2.522		2.549	2.523	2.522	2.509	2.479(2)			
Mo–CO	2.573		2.332	1.948	1.946	1.913	1.874(11)			
Cl–Mo–P1	79.9		79.6	78.2	77.6	75.9	76.5(1)			
Cl–Mo–P2	85.0		79.5	78.1	77.6	75.9	79.7(1)			
P–Mo–P	101.4		128.4	118.0	117.1	128.1	116.6(1)			
Cl–Mo–CO	146.7		123.7	154.3	153.0	119.1	130.2(4)			
Mo–C–O	124.3		119.3	176.2	177.1	177.5				
Cl–Mo–C–O	-129.9		-179.3	1.4	0.0	180.0				
ΔE (B3LYP/DZP)	6.5	5.0 ± 0.3	1.2	-17.2	-17.2	-46.6				
ΔE (B3LYP/TZD2P) ^f	8.6	5.0 ± 0.3	3.3	-12.7	-13.7	-43.7				
ΔH (B3LYP/TZD2P) ^f	9.9	5.0 ± 0.3	4.0	-11.4	-11.4	-40.8				
ΔH (BPW91/TZD2P) ^f	6.7	5.0 ± 0.3	-2.8	-18.3	-17.1	-50.4				
ΔS (B3LYP/DZP)	-34	-35 ± 4	-32	-34	-30	-41				

^a Bond distances in angstroms, angles in degrees, energies/enthalpies in kcal/mol and entropies in cal/(mol•K). Energy data given relative to separated ground state educts. ^b The first and second MECP located on the reaction coordinate, respectively, as judged from the Mo–CO distances. ^c Activation parameters for CO addition to CpMoCl(PMe₃)₂.²² ^d X-ray crystal structure of Cp*MoCl(PMe₂Ph)₂(CO).³⁸ ^e Average Mo–C distance to the cyclopentadienyl ring. ^f SP calculation using the B3LYP/DZP geometry. For the MECPs, the average of the singlet and triplet energies is used ($\Delta\Delta E = |\Delta E_{\text{triplet}} - \Delta E_{\text{singlet}}| \leq 2.4$).

The calculated singlet product structure is in good accord with the X-ray crystal structure of $\text{Cp}^*\text{MoCl}(\text{PMe}_2\text{Ph})_2(\text{CO})$,³⁸ although with a somewhat too wide P-Mo-P angle as also noted for the N_2 addition product (vide supra). The geometries of the triplet product and MECP2 show that the initial binding of the new ligand (CO) is brought about by a weaker binding of all the other ligands, most notably by a reduction in hapticity for Cp. The state of the spin triplet addition product ($^3\text{A}'$) is identical to that found as the most stable for triplet $\text{CpMoCl}(\text{PH}_3)_2(\text{N}_2)$ (vide supra). Also the nearly C_s symmetric MECPs display an orbital occupancy for the triplet state commensurate with $^3\text{A}'$.

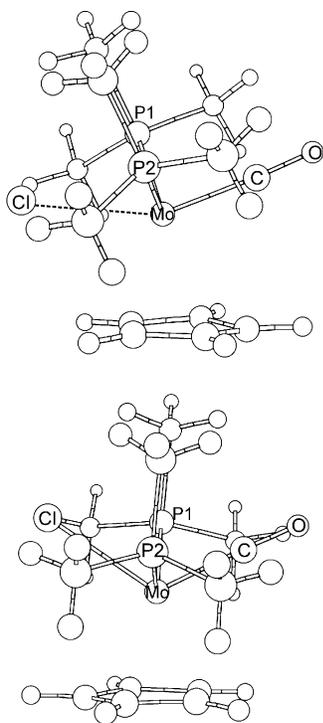


Figure 6. B3LYP/DZP optimized structures of the spin triplet (uppermost structure, $^3\text{A}'$) and singlet (lower, $^1\text{A}'$) product of CO addition to $\text{CpMoCl}(\text{PMe}_3)_2$.

Conclusions

We have studied the addition of the ligands N₂ and CO to the complexes CpMoCl(PR₃)₂ (R = H and Me) using DFT. It has been found necessary to include more than one electronic state of each spin multiplicity (triplet and singlet) to arrive at a qualitatively correct description of these addition reactions: The ground state of the 18e⁻ addition products is actually derived from the second lowest singlet state of the 16e⁻ educts (term symbol 2¹A' in case of a C_s symmetric complex), whereas the preferred state of the spin triplet addition products is derived from the second lowest triplet state of the 16e⁻ educt (3³A').

The current calculations firmly place the barrier of addition at Mo—ligand distances below 3 Å where the bond-breaking and forming on the spin triplet PES is already well under way. Steric hindrance at long Mo—ligand distances, on the other hand, is found to be of little importance. The 2¹A' state drops in energy throughout addition and the accompanying LT curve crosses the curve for the 3³A'' state at a Mo—ligand distance slightly below 3 Å (2.8—2.9 Å) for both of the ligands N₂ and CO. For N₂, the TS of the endothermic addition on the diabatic triplet PES is located much later on the reaction coordinate (at a distance MO—N ≈ 2.2 Å for R = H) and at significantly higher energies, thus making spin inversion before reaching this TS the preferred alternative. For CO on the other hand, the TS of the exothermic addition on the triplet PES is located only shortly after and at slightly higher energies than the point of crossing of the two LT curves and the balance between a classical barrier as caused by the TS and a spin-inversion related barrier turns out to be of a more delicate nature. Our current computational approach is in favor of the former alternative, thus indicating that the preferred route of CO addition is for the system to remain a spin triplet until after the TS. Finally, our mechanistic findings are supported

by excellent agreement between the calculated activation and reaction enthalpies and those experimentally available for addition of N₂ and CO to Cp*MoCl(PMe₃)₂.

Acknowledgments

We thank the Conseil Régional de Bourgogne for funding to upgrade our computing facility and CINES for a grant of CPU time. VRJ thanks the CNRS for a research fellowship. We also thank Jeremy N. Harvey for providing us with his MECP location program and for helpful discussions.

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