A Quantum-Chemical Study of Dinitrogen Reduction at Mononuclear Iron–Sulfur Complexes with Hints to the Mechanism of Nitrogenase

Markus Reiher* and Bernd Artur Hess[a]

Abstract: The mechanism of biological dinitrogen reduction is still unsolved, and the structure of the biological reaction center, the FeMo cofactor with its seven iron atoms bridged by sulfur atoms, is too complicated for direct attack by current sophisticated quantum chemical methods. Therefore, iron–sulfur complexes with biologically compatible ligands are utilized as models for studying particular features of the reduction process: coordination energetics, thermodynamic stability of intermediates, relative stability of isomers of N_2H_2, end-on versus side-on binding of N_2, and the role of states of different multiplicity at a single iron center. From the thermodynamical point of view, the crucial steps are dinitrogen binding and reduction to diazene, while especially the reduction of hydrazine to ammonia is not affected by the transition metal complex, because the complex-free reduction reaction is equally favored. Moreover, the abstraction of coordinated ammonia can be easily achieved and the complex is recovered for the next reduction cycle. Our results are discussed in the light of studies on various model systems in order to identify common features and to arrive at conclusions which are of importance for the biological mechanism.

Keywords: density functional calculations · iron · nitrogen fixation · S ligands

1. Introduction

The mild, nitrogenase-catalyzed reduction of molecular nitrogen to ammonia is one of the fundamental syntheses for life. Its detailed reaction mechanism is still not known. All mechanisms suggested so far remain largely speculative. [1–4] Hints for solving the problem may be deduced from quantum-chemical calculations on model compounds, which answer questions on the energetic contribution of certain structural features of these complexes that are not easily amenable to experiment. An additional challenge for chemical research is to find a model complex in which all structurally essential parts of the enzyme are incorporated so that it catalyzes the reduction of molecular nitrogen under ambient conditions.

From the structural viewpoint, the active site, namely, the FeMo cofactor (FeMoco) in the MoFe protein, is highly complex, and so chemically very different complex types can be designed and utilized to model certain aspects of the biological nitrogen reduction process. All these different types of model complexes are important in arriving at a better understanding of the whole system. For instance, the occurence of one molybdenum atom in the active center of the MoFe protein in nitrogenase led to the development of model molybdenum complexes (see the extensive experimental work, also supplemented by theoretical investigations, on iron–sulfur-based Mo clusters of high nuclearity by Coucouvanis et al.[5–11]). In view of the iron and vanadium nitrogenases it is evident that this is not sufficient to understand the whole active center, which comprises seven additional iron atoms.

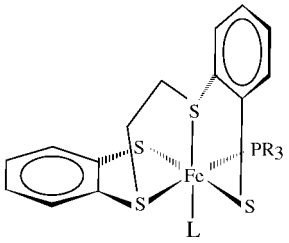
We focus here on the extensive work on mononuclear and dinuclear iron and ruthenium complexes with sulfur ligands by Sellmann et al. (see refs. [4, 12, 13] for reviews). The basic hypotheses discussed in connection with the Sellmann-type complexes are that 1) iron atoms of FeMoco are involved in binding the N_xH_y species; 2) the reduction occurs in two-proton, two-electron reduction steps, as suggested by experiments (see the references cited above); and 3) FeMoco opens to allow pseudooctahedral coordination of N_2 to two iron atoms. Coucouvanis et al. recently also argued for a comparable opening mechanism with particular emphasis on breaking of the Fe–Fe contact upon two-electron reduction.[14] For this study we chose the mononuclear complexes **1**-L depicted in Scheme 1, which were experimentally investigated with various metal centers such as Fe, Ni, Mo,[15–17] and mainly with Ru.[17–20]

While ammonia and hydrazine complexes are comparatively easy to obtain, the most unstable complexes to be

[a] Dr. M. Reiher, Prof. Dr. B. A. Hess
Lehrstuhl für Theoretische Chemie
Universität Erlangen-Nürnberg, Egerlandstrasse 3
91058 Erlangen (Germany)
Fax: (049) 9131-85-27736
E-mail: markus.reiher@chemie.uni-erlangen.de,
hess@chemie.uni-erlangen.de

Supporting information for this article is available on the WWW under http://www.chemeurj.org/ or from the author.

0947-6539/02/0823-5332 $ 20.00+.50/0 *Chem. Eur. J.* **2002**, *8*, No. 23



L = N_xH_y, R = Mc
$[Fe(S_4)PR_3(N_xH_y)]$
1-L

Scheme 1. Model compounds for key intermediates in the biological nitrogen fixation process.

considered are the diazene and particularly the dinitrogen complex. For this reason, the **1**-N_2 complex is not known, and the diazene complex is dinuclear ($[\mathbf{1}]_2N_2H_2$).[22, 23] It is likely that a potential N_2 complex would also be dinuclear. However, we concentrate on mononuclear complexes to analyze the binding modes and energetics of the nitrogen species on a single iron center. This is the first step towards an understanding of the binding energetics in the corresponding dinuclear complexes.

Apart from the particular structure of model complexes, the presence and transfer of protons during reduction is essential. Protons may be bound by ligands of the metal centers or by the metal centers themselves before they are transferred to coordinated N_2 to give N_2H_x species. These unstable N_2H_x molecules are stabilized by coordination to the metal centers and also through hydrogen bonds to acceptor atoms in the ligand sphere. We have already investigated the role of such hydrogen bonds in detail for Sellmann-type complexes.[24, 25] Here, our focus is on the reaction energetics of dinitrogen reduction assisted by the Sellmann-type complex **1**-L. We aim at the stable structures in the process rather than considering transition states of the reduction, which are only worth studying when the characteristics of the stable intermediates are well understood.

After a description of the computational methodology in Section 2, Section 3 presents exploratory studies on states of different multiplicity, end-on versus side-on binding of N_2, different isomers of diazene, and ligand coordination energies. Then we discuss the reaction energetics of all two-proton, two-electron reduction intermediates and compare them to the reaction without assistance of the complex (Section 4). In a final discussion (Section 5), which compares our results to those for other model systems, we try to identify the vital questions for the role of the metal complex and the biological reduction process. We emphasize that these studies on other model systems, which also utilized DFT methods, were barely aware of unrecognized complications found for various density functionals when calculating states of different spin multiplicity (see Sections 2 and 3).

2. Methods of Calculation

For all calculations we used the density functional programs provided by the TURBOMOLE 5.1 suite.[28] All results are obtained from all-electron Kohn–Sham calculations. We employed the Becke–Perdew functional BP86[29, 30] and the hybrid functional B3LYP[31, 32] as implemented in TURBOMOLE. In connection with the BP86 functional we always used the resolution of the identity (RI) technique.[33, 34]

These two functionals were chosen since they are well-established representatives of pure and hybrid density functionals yielding reasonable reaction energetics in many cases. However, the situation is different for iron compounds, and highly unreliable energetics were obtained for complexes of the type under study.[35] A systematic study has shown that these iron complexes are critical cases when high-spin/low-spin energy splittings are small and differ widely when calculated with pure and hybrid density functionals.[25] To avoid these uncertainties we used, in addition to BP86 and B3LYP, our reparametrized B3LYP, dubbed B3LYP*, which was developed particularly for these complexes[25] but is of general applicability.[34]

The influence of basis-set size was studied with three basis sets. The first, denoted SV(P), is Ahlrichs' split-valence basis set[37] with polarization functions on heavy atoms, but not on hydrogen atoms. Moreover, we used Ahlrichs' TZVP basis set[38] featuring a valence triple-zeta basis set with polarization functions on all atoms and the even larger TZVPP basis with additional polarization functions (taken from Dunning's cc-pVTZ basis set) as implemented in TURBOMOLE. The TZVPP calculations took considerably more computer time than the TZVP calculations. For a sufficiently large number of test calculations the TZVP and TZVPP reaction energies differed by only about 5 kJ mol^{-1} without correction for the basis-set superposition error (BSSE). If a counterpoise correction is added, our test calculations on coordination energies have shown that results obtained with the TZVP and the TZVPP basis sets differ by less than 1 kJ mol^{-1}. We thus concluded that the TZVP basis set in combination with the counterpoise correction[39, 40] is sufficiently accurate for our purposes. Only in combination with the counterpoise correction is the SV(P) basis set able to give results which might be comparable with TZVP results. We therefore refrain from reporting here the results from calculations with the SV(P) and TZVPP basis sets.

All structures were optimized with the corresponding density functional and basis set. For the calculation of reaction enthalpies and entropies we performed vibrational analyses in a harmonic force field by calculating the second derivatives of the total electronic energy, computed as numerical first derivatives[41, 42] of analytic energy gradients obtained from TURBOMOLE. Since the BP86 functional turned out to be the most reliable functional for structure parameters and vibrational frequencies[25, 35, 43] we report only bond lengths from BP86/RI structure optimizations and take the zero-point vibrational energy (ZPE) and the temperature corrections to reaction energies from the BP86/RI vibrational analyses. This procedure is appropriate because it represents the optimum choice of computational effort and accuracy of the zero-point and finite temperature corrections. While the vibrational frequencies of the partition function were calculated within the harmonic approximation, the rotational and translational contributions to the enthalpy were estimated by the classical partitioning scheme ($1/2kT$ per degree of freedom). Furthermore, we only discuss the electronic effect on the reaction energies and add the ZPE correction at 0 K. The enthalpies calculated for a given temperature are almost equal to the ZPE, since they only contain an additional temperature (Boltzmann) weighted term for the vibrational contribution plus $3kT$. We refrain from discussing entropic effects or Gibbs free enthalpies in terms of this quantum-chemical, semi-classical model, because in every coordination or reduction step one free molecule (the ligand or H_2) is bound such that its translational and rotational degrees of freedom are transformed into vibrational degrees of freedom to give an almost constant free energy contribution of about 60 kJ mol^{-1} at 298.15 K and 1013.25 mbar (compare the nuclear contribution to the free enthalpy ΔG_{nuc} in Tables 2 and 3). Obviously, this effect would blur the system-inherent electronic energetics at 0 K. The program Molden[44] was used for the visualization of structures.

3. Exploratory Studies

Before we discuss the essentials of the catalytic potential of the complex, we analyze the ground-state multiplicities of the complexes, end-on and side-on binding of dinitrogen, diazene

isomers, and ligand-binding energies, all of which can be determined from the outset.

Multiplicities of the ground states: For reasonable reaction energetics of any kind of mechanism involving first-row transition metal atoms, it is mandatory to find the correct multiplicity of the ground state. Closed-shell systems, of which the complex fragment under study is an example, tempt one to use the fast-converging restricted Kohn–Sham method to obtain the all-singlet energetics for the reduction. However, spin polarization and states of different multiplicities must be considered for weak ligand fields. Spin polarization of the singlet states of our **1**-L complex does not occur, since unrestricted Kohn–Sham calculations on possible open-shell singlets give the same results as closed-shell singlet restricted Kohn–Sham calculations. Moreover, the singlet structures are also "triplet-stable", which was checked by a stability test as implemented in TURBOMOLE. For the coordination energy of diazene in dinuclear Sellmann-type iron–sulfur complexes, we found that neither the standard pure density functional BP86/RI nor the standard hybrid density functional B3LYP can predict reliably the ground-state multiplicity, and hence reliable coordination energies could not be calculated.[35] It was possible to overcome these problems[25] by reducing the exact exchange admixture in B3LYP to 15% (B3LYP*). This was possible because the deviations between BP86/RI and B3LYP were systematic for various Sellmann-type complexes. It turned out that the low-spin/high-spin energy splitting depends linearly on the exact exchange admixture, and the slope for a given multiplicity difference is almost the same for different Sellmann-type complexes.[25]

The relative energies for the stable intermediates in their singlet, triplet and quintet states are given for BP86/RI, B3LYP and B3LYP* in Table 1. It is clear from reference [25] that the B3LYP* results are to be preferred for the complexes under consideration. The BP86/RI and B3LYP results are mainly given for comparison, since these functionals are widely used, and some experience has been gained with results from these calculations (Table 1).

As found for six-coordinate Sellmann-type complexes,[25, 35] the BP86/RI ordering of states is singlet, triplet and quintet, while B3LYP gives quintet as the ground state multiplicity, followed by singlet and triplet. Only in the case of the *trans*-N_2H_2 complex are the singlet and quintet states so close that B3LYP is not able to clearly prefer one over the other. The most reliable B3LYP* functional gives singlet ground states for all six-coordinate complexes. However, in case of σ donors without π-acceptor character (i.e., hydrazine and ammonia), the quintet and singlet states of the corresponding complexes lie very close to one another, and DFT is not sufficiently reliable to answer the question of ground-state multiplicity with certainty. On the other hand, the final answer of DFT to this question is not important for the reaction energetics if an accuracy of the order of 10 kJ mol^{-1} is sought for. In case of the five-coordinate fragment, which has a distorted trigonal-bipyramidal structure, the singlet state is the highest energy state with all functionals. While BP86/RI and B3LYP* predict the triplet state to be the ground state, B3LYP favors the quintet state, as one would expect in view of the discussion in reference [25].

End-on versus side-on binding of N_2: Even in the case of so-called weak activation of dinitrogen, in which the N–N distance is very similar to the bond length in the free diatomic molecule, side-on binding must also be considered as a possible coordination mode[45, 46] (if "strong activation" occurs, side-on binding becomes more important). Side-on binding has been studied for the four-atom system Fe_2N_2 by Siegbahn,[47] who found that the N–N bond length of 128 pm is much longer than in isolated dinitrogen and indicates strong activation of N_2 by two bare iron atoms. The Fe–Fe distance of 395 pm indicates that the iron–iron interaction can be neglected. It is also interesting that Siegbahn found, on the basis of the Hartree–Fock harmonic force field, a N–N stretching mode of 1581 cm^{-1}, which he compares with N_2 activation on a Fe(111) surface, for which an average value of 1555 cm^{-1} was measured. While Fe_2 may serve as a model for the activation of dinitrogen on an iron surface, it is unlikely that these results can be transferred to the case of model complexes in which iron atoms are surrounded by a ligand sphere that modulates their reactivity to a large extent. For the monometallic complex **1**-N_2 we find that the dinitrogen molecule binds end-on, while N_2 dissociates from the complex when forced to bind side-on. The N–N bond length of 112.8 pm and the harmonic vibrational wavenumber of 2134 cm^{-1} indicate only very weak activation by the metal complex fragment (BP86/RI/TZVP; cf. 110.4 pm and 2361 cm^{-1} for free N_2). From these results we safely conclude that the side-on binding mode will not occur in the dinuclear Sellmann-type complexes.

Table 1. Relative energies [kJ mol^{-1}] of lowest-lying singlet ($S=0$), triplet ($S=1$), and quintet ($S=2$) spin states of **1**-L at 0 K (TZVP basis set). The RKS singlet states are chosen as the zero level of energy. The values in parentheses are $\langle S^2\rangle$ expectation values measuring the amount of spin contamination in the UKS wavefunction.

		BP86/RI		B3LYP		B3LYP*	
Complex	$S(S+1)$	$E_{LS/HS}$	$\langle S^2\rangle$	$E_{LS/HS}$	$\langle S^2\rangle$	$E_{LS/HS}$	$\langle S^2\rangle$
1-N_2	2	85.8	(2.049)	36.3	(2.054)	49.4	(2.056)
	6	125.8	(6.057)	−15.1	(6.017)	23.4	(6.019)
1-*t*N_2H_2	2	82.8	(2.102)	32.3	(2.110)	45.1	(2.129)
	6	120.0	(6.161)	1.8	(6.059)	33.9	(6.094)
1-N_2H_4	2	57.9	(2.041)	11.0	(2.043)	22.6	(2.043)
	6	91.7	(6.024)	−26.8	(6.016)	3.3	(6.017)
1-NH_3	2	55.7	(2.042)	10.5	(2.044)	21.8	(2.044)
	6	89.1	(6.024)	−27.7	(6.015)	2.2	(6.017)
1 without 6th ligand	2	−2.2	(2.036)	−47.6	(2.045)	−36.4	(2.043)
	6	53.0	(6.025)	−60.8	(6.018)	−31.9	(6.019)

0947-6539/02/0823-5334 $ 20.00+.50/0 *Chem. Eur. J.* **2002**, *8*, No. 23

Diazene isomers: Since diazene is the least stable of the stable intermediates under consideration here, and is thus the key intermediate in the reduction process, we analyzed how different isomers of N_2H_2 are stabilized by the five-coordinate metal fragment **1**. For mononuclear molybdenum and tungsten complexes, an important role has been attributed to asymmetric reduction products such as NNH_2.[48, 49] This view is based on earlier suggestions[50] that considered generation of a single NH_3 molecule to be an important step in the reduction process. A nitrido complex remains, and the second NH_3 molecules is released by its protonation and reduction. Such nitrido complexes are well known for molybdenum.[51, 52]

Isomerization mechanisms of isolated *trans*- to *cis*-diazene were studied, and transition states for two possible interconversion routes were more than 200 kJ mol^{-1} less stable than *trans*-diazene.[53] The stability of *trans*- relative to *cis*-diazene was calculated to be 21–29 kJ mol^{-1} with different quantum-chemical methods and basis sets (see ref. [53] and references therein). This is in good agreement with the value of 26–28 kJ mol^{-1} which we obtained with the three density functionals. Regardless of the functional chosen the NNH_2 isomer is ca. 87 kJ mol^{-1} higher in energy than *trans*-diazene, that is, this isomer is not important as a possible reduction intermediate in the noncatalytic process.

The energy difference between coordinated *cis*- and *trans*-diazene is almost the same as for the free molecules. This has already been resolved in terms of cancellation of stronger coordination of *cis*-diazene by lone pair–lone pair repulsion.[24] The picture changes for NNH_2 upon coordination to metal fragment **1**, and **1**-NNH_2 is 43.4 kJ mol^{-1} (B3LYP*) higher in energy than **1**-*t*N_2H_2 and thus more than 40 kJ mol^{-1} more stable than *trans*-diazene upon coordination.

While *cis*-diazene and NNH_2 need not to be considered for symmetry reasons in dinuclear Sellmann-type complexes, they both can become important intermediates for open structures of FeMoco.

Ligand binding energies: The ligand binding energies in Table 2 refer to reaction (LB). They allow us to draw in conclusions on the role of the single iron center during ligand reduction. For the discussion of energetics (see Methods of Calculation) we prefer the $\Delta D_0 = \Delta E_{CP,B3LYP*} + \Delta ZPE$ values with counterpoise-corrected electronic energies from B3LYP* calculations and ZPEs from BP86/RI vibrational analyses; all other data are given for comparison.

$$[Fe] + L \rightarrow [Fe]L \qquad (LB)$$

N_2 is stabilized by only 11.9 kJ mol^{-1} upon coordination to the metal fragment. This electronic stabilization effect is quenched by the zero-point vibrational levels of 10.8 kJ mol^{-1} and becomes unfavorable in view of the reverse entropic effect. Note that BP86/RI overestimates binding of N_2 by about 50 kJ mol^{-1}, which would lead to completely erroneous conclusions. B3LYP gives too-small coordination energies for the σ/π ligands N_2 and N_2H_2, while both B3LYP and B3LYP* yield similar results for the σ-donor ligands NH_3 and N_2H_4. *trans*-Diazene ex periences the largest stabilization (by −60.3 kJ mol^{-1}), while the σ-donor ligands are loosely bound.

Complex **1** thus fulfills two important criteria of a nitrogenase model complex: 1) the unstable diazene ligand is significantly stabilized electronically by −73.1 kJ mol^{-1} (−60.3 kJ mol^{-1} upon inclusion of the ZPE) and 2) the ammonia ligand can easily dissociate to regenerate the "catalyst". However, binding of N_2 is too weak, even if the first two-proton, two-electron reduction step is considered to be very fast. Thus, strategies are required to increase the absolute value of the N_2 coordination energy by variation of the chelate ligand.

We can now answer the open question in reference [35] to which extent the hydrogen-bond stabilization contributes to the coordination of diazene. Since we were only interested in the pure electronic effect, we compared the total coordination energy of −73.1 kJ mol^{-1} with the estimated total hydrogen-bond energy of 20 kJ mol^{-1} for the mononuclear complex **1**-*t*N_2H_2.[24] Thus, the stabilization of the unstable diazene ligand by hydrogen bonds amounts to 27 % of the total coordination energy in the case of **1**-*t*N_2H_2.

The coordination energies of diazene and hydrazine to strong-ligand-field $[Fe(CO)_4]$ fragments are large and comparable in magnitude.[54] In these carbonyl complexes, stabilization of diazene by hydrogen bonding to the ligands of the metal fragment is not possible, and the stabilization of the ligands has its origin in the direct metal–ligand interaction. Together with our our weak-ligand-field metal fragment **1**, this is an example of how the coordination energy of the ligand can be controlled by the strength of the ligand field and the properties of the first-shell ligand atoms, that is, by their hydrogen-bond acceptor character in this case.

4. Analysis of the Catalytic Potential

The hypothetical catalytic cycle is depicted in Figure 1.

Table 2. Ligand stabilization energies [kJ mol^{-1}] for reaction LB for **1**-L (TZVP basis set). $\Delta D_0 = \Delta E_{CP,B3LYP*} + \Delta ZPE$. The total electronic energies were all taken from the ground states obtained with the particular density functional. The vibrational contributions were calculated from singlet structures with BP86/RI for the six-coordinate complexes, while the five-coordinate fragment is taken in its triplet ground state, which possesses a 1.5 kJ mol^{-1} larger ZPE than its singlet state and an additional contribution of 2.7 kJ mol^{-1} for ΔG_{nuc} from the entropic contribution of the degenerate spin state. BP86/RI-freq denotes the pure vibrational, rotational and translational contribution to the reaction energetics. (ΔH_{nuc} and ΔG_{nuc} at 298.15 K and 1013.25 mbar.)

	BP86/RI		B3LYP		B3LYP*		BP86/RI-freq			
complex	ΔE	ΔE_{cp}	ΔE	ΔE_{cp}	ΔE	ΔE_{cp}	ΔZPE	ΔH_{nuc}	ΔG_{nuc}	ΔD_0
1-N_2	−72.4	−64.1	−0.3	6.8	−19.5	−11.9	10.8	9.1	61.3	−1.1
1-*t*N_2H_2	−136.9	−125.0	−50.3	−39.5	−84.6	−73.1	12.9	11.1	67.3	−60.3
1-N_2H_4	−74.8	−62.4	−45.2	−33.7	−44.9	−32.7	10.5	9.6	68.0	−22.2
1-NH_3	−72.1	−60.0	−46.8	−35.4	−44.6	−32.7	14.0	11.0	66.1	−18.7

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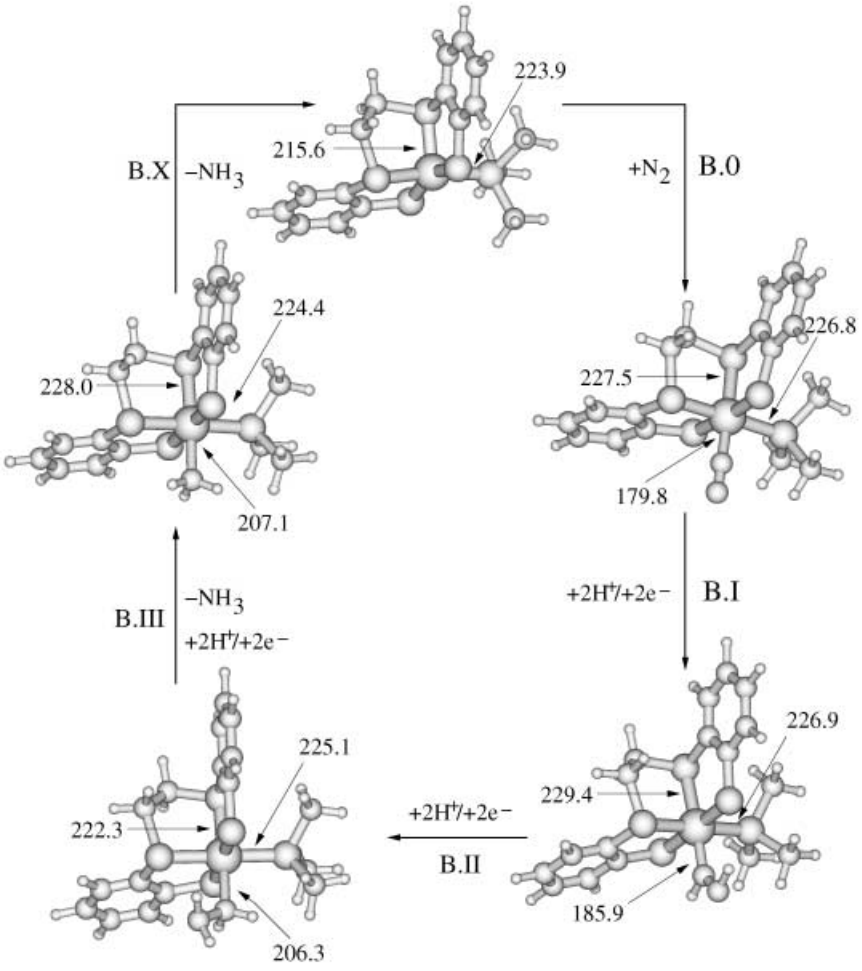

Figure 1. Hypothetical reaction cycle for reduction of N_2 assisted by the model complex. Three important bond lengths are shown: distance between the nitrogen species and the metal center, the distance of the corresponding *trans* ligand to the metal center and the P–Fe distance as an example of a bond length in the equatorial positions (for all other structural parameters, see the Supporting Information). Bond lengths are given for BP86/RI with the TZVP basis in picometers.

Structural changes: We restrict our discussion to the most important structural parameters, which are the bonding distances of the N_yH_x species to the iron center, the distances of the corresponding *trans* ligand and the P–Fe distances as an example for a metal–ligand bond length in the equatorial plane. These bond lengths are shown in Figure 1. For more information on the structure of the model complexes, see the Cartesian coordinates in the Supporting Information.

The distance of 179.8 pm between the coordinating nitrogen atom of N_2 and the Fe center is considerably smaller than that of 185.9 pm for the strongly bound diazene ligand. Therefore, this N–Fe distance cannot be regarded as an indicator of coordination strength but originates rather from the different hybridisations of the nitrogen atoms. The sp nitrogen atom in N_2 yields shorter bond lengths than the sp^2 nitrogen atom in diazene. This view is also confirmed by considering sp^3 nitrogen atoms: the N–Fe distances of the σ-donor ligands NH_3 and N_2H_4 of 207.1 and 206.3 pm, respectively, reflect the similar coordination strength already mentioned for the coordination energetics. The Fe–N distance of 185.9 pm in **1**-*t*N_2H_2 compares very well with the experimental distance of 187.5 pm in the dinuclear analogue, which contains PEt_3 ligands and *tert*-butyl substituents in the phenyl rings.[22] The distance of the central metal atom to the thioether sulfur atom in the *trans* position increases on coordination of the sixth ligand, from 215.6 pm in the five-coordinate metal fragment to 222.3–229.4 pm. However, this enlargement is rather unspecific for the coordination strength of the sixth ligand, as the strongly bound *trans*-diazene ligand yields 229.4 pm, but the weakly bound N_2 gives 227.5 pm. The P–Fe distance of the phosphane ligand changes only little during the reduction process.

Reaction energetics: Since our aim is an energy scheme that shows whether the monometallic model compound is able to function as a catalyst, we compared the energetics for the uncoordinated ligands with those at the iron center of the metal fragment **1**. For the metal-free reaction three reduction steps A.I–A.III can be defined in which one hydrogen molecule is added at a time to model the two-proton, two-electron reductions.

$$N_2 + H_2 \rightarrow N_2H_2 \quad \text{(A.I)}$$

$$N_2H_2 + H_2 \rightarrow N_2H_4 \quad \text{(A.II)}$$

$$N_2H_4 + H_2 \rightarrow NH_3 + NH_3 \quad \text{(A.III)}$$

The energetics of these three reactions were studied in detail by Sekusak and Frenking.[55] We list their recommended values for the heat of formation and our results in Table 3. As can be seen, our methodology to calculate the electronic structure with the reparametrized density functional B3LYP* and to add the vibrational contribution using harmonic force fields from BP86/RI calculations yields heats of formation which are in good agreement with the recommended values. We find the largest deviation of 13.3 kJ mol^{-1} for reaction A.I, which is still satisfactory in view of the large reaction enthalpy of about 200 kJ mol^{-1}. Possible errors in the reaction enthalpies come from the fact that the reactions are not isodesmic and thus give rise to basis set superposition errors. Calculations with the TZVPP basis set show that electronic energies ΔE change in general by 5 kJ mol^{-1}, but we refrain from discussing these small effects here, since we wish to make comparisons with calculations on the metal complexes using the sufficiently large TZVP basis.

The overall reduction energy $\Delta D_{0,\mathrm{tot}} = \sum_i \Delta D_{0,i}$ is -79.5 kJ mol^{-1} at 0 K ($i \in \{\text{A.I–A.III}\}$). While the energies

0947-6539/02/0823-5336 $ 20.00+.50/0 *Chem. Eur. J.* **2002**, *8*, No. 23

Table 3. Catalytic and noncatalytic dinitrogen reduction. All reactants were taken in their ground state with the corresponding spin state as predicted by each individual density functional. Those complexes (e.g., **1**-NH_3 in the case of B3LYP) which do not have a singlet ground state can be identified from Table 1. BP86/RI-freq denotes the pure vibrational, rotational and translational contributions to the reaction energetics (ΔH_{nuc} and ΔG_{nuc} at 298.15 K and 1013.25 mbar). $\Delta D_0 = \Delta E_{CP,B3LYP^*} + \Delta ZPE$. $\Delta H_0 = \Delta E_{B3LYP^*} + \Delta H_{nuc}$ denotes the standard free enthalpy of formation at 298.15 K and 1013.25 mbar. The reference enthalpies of formation were obtained on the basis of experimental measurements in combination with correlated ab initio methods.[55]

	BP86/RI		B3LYP		B3LYP*		BP86/RI-freq					
Reaction	ΔE	ΔE_{cp}	ΔE	ΔE_{cp}	ΔE	ΔE_{cp}	ΔZPE	ΔH_{nuc}	ΔG_{nuc}	ΔD_0	ΔH^0	$\Delta H^{0[55]}$
A.I	150.9		165.8		161.8		31.6	26.7	59.3	192.4	188.5	205.7
A.II	−129.1		−131.0		−131.5		38.6	33.5	67.0	−92.9	−98.0	−96.6
A.III	−187.7		−194.2		−192.6		13.6	14.0	3.0	−179.0	−178.6	−186.8
B.I	86.5	90.1	100.7	104.4	96.8	100.6	33.7	28.7	65.3	134.3		
B.II	−67.0	−66.5	−125.9	−125.2	−91.8	−91.1	36.2	32.0	67.7	−54.9		
B.III	−185.0	−185.3	−221.5	−221.6	−192.3	−192.6	17.1	15.4	1.1	−175.5		

in Table 3 are given for the actual reduction step, it is instructive to give all energies with respect to a common energy reference level. This is done in Figure 2, where the

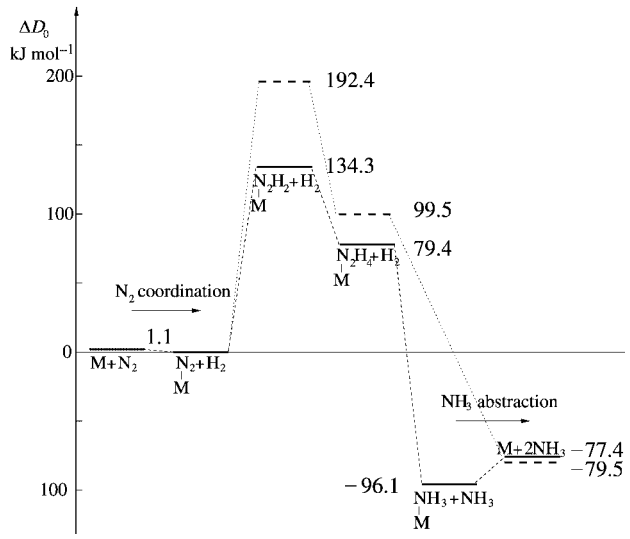

Figure 2. Energetics of dinitrogen reduction with the mononuclear catalyst **1** (solid lines). The energy D_0 of N_2 bound to **1** and three unbound H_2 molecules was chosen as the energy reference point $\Delta D_0 = \Delta E_{CP,B3LYP^*} + \Delta ZPE$. Note that the nonreacting H_2 molecules (e.g., two H_2 molecules in the $N_2 + H_2$ step) are not mentioned explicitly. The energetics of dinitrogen reduction without a catalyst are depicted for comparison (dotted lines). Here, the D_0 energy of one N_2 and three H_2 molecules was chosen as the reference energy.

energy of one dinitrogen and three hydrogen molecules is taken as the reference point. Figure 2 shows that the first reduction step is thermodynamically the most difficult, while the following reductions to hydrazine and ammonia can be easily achieved once diazene is produced. We are now well prepared to analyze the effect of the metal fragment on the reduction reactions A.I – A.III. Here, we have to consider two additional reactions, namely, the coordination of N_2 and the abstraction of NH_3, which are denoted as B.0 and B.X.

$$[Fe] + N_2 \rightarrow [Fe]N_2 \quad \text{(B.0)}$$

$$[Fe]N_2 + H_2 \rightarrow [Fe]N_2H_2 \quad \text{(B.I)}$$

$$[Fe]N_2H_2 + H_2 \rightarrow [Fe]N_2H_4 \quad \text{(B.II)}$$

$$[Fe]N_2H_4 + H_2 \rightarrow [Fe]NH_3 + NH_3 \quad \text{(B.III)}$$

$$[Fe]NH_3 \rightarrow [Fe] + NH_3 \quad \text{(B.X)}$$

The energies for this scheme are given in Table 3. Note that reaction B.0 is identical to the coordination of N_2 already discussed and that B.X is the reverse of NH_3 coordination (see Table 2).

The B3LYP* results lie in between those from BP86/RI and B3LYP. Note that the B3LYP* and B3LYP energeties are almost equal if singlet states for all complexes are assumed for B3LYP. The energy differences originate from the rigorous choice of the minimum-energy structure without taking care of the corresponding spin state. Since we give the results with the more familiar functionals BP86/RI and B3LYP only for reasons of comparison, we concentrate on the recommended B3LYP* data.

Apart from the weak coordination of N_2, discussed above, we find a remarkable energy drop for the most important first endothermic reduction step, from 192.4 kJ mol^{-1} to 134.3 kJ mol^{-1}. If N_2 can be bound and transformed into N_2H_2, which is considerably stabilized by the mononuclear complex **1**, the reduction process is straightforward. The production of hydrazine and ammonia is exothermic by 54.9 and 175.5 kJ mol^{-1}, respectively. Note that the reduction step B.II is less favored by 38 kJ mol^{-1} if the iron center is present, and this has its origin in the better stabilization of diazene relative to hydrazine, while reaction A.III and B.III are equal in energy. This energetical equivalence of the third reduction steps, which involves the formation of two N–H bonds and breaking of the H–H and N–N bonds, indicates that the Fe center, whose primary role is the fixation of the hydrazine reactant, does not affect N–N bond breaking. Frenking et al. found similar energetics for the same reduction process mediated by $[Fe(CO)_4]$ fragments.[54] For our discussion here, it is important to note that reaction energies are similar while the ligands are much more strongly bound. The overall energy change $\Delta D_{0,tot} = \Sigma_i \ \Delta D_{0,i}$ is -77.4 kJ mol^{-1} ($i \in$ {B.0,B.I–III,B.X}, which is, of course, equal to that of the metal-free reduction process (the small difference of 3.2 kJ mol^{-1} comes mainly from numerical errors in the vibrational analyses).

As before we give the reaction energetics of the complex reaction from the viewpoint of a single energy as the center of reference. To obtain the corresponding plot to the metal-free reaction we choose the energy of the five-coordinate metal fragment with bound dinitrogen and three hydrogen molecules as the reference energy level (see Figure 2).

Figure 2 shows that the barriers of the stable intermediates are lowered to a certain degree, while ammonia coordination

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is still not too strong. An optimum catalyst would lower all transition state barriers, which are not taken into account here, and all energies of intermediates to give a flat potential energy surface. At the same time, the product (ammonia) must not be bound too strongly, so that the catalyst can be regenerated. Apart from the very weak coordination of N_2, the complex fragment **1** facilitates dinitrogen reduction. Furthermore it also has features which are important for low transition-state barriers, namely, the possibility to protonate sulfur atoms, which brings protons close to the N_2 moiety.

5. General Discussion and Conclusion

The final step is now to extract those features of the model system which are most likely of importance for the nitrogenase system. Obviously, the main characteristics of the biological system, that is, a protein environment with the Fe protein and the P cluster in the MoFe protein, which are far beyond the scope of the present study, cannot be considered. Our general conclusions are for a single iron center surrounded by sulfur atoms, as occurs in FeMoco.

As was found earlier (see, for instance, the discussion in reference [56]) N_2 is bound too weakly. It may be unlikely that end-on coordination to one or two iron centers can lead to sufficiently strong coordination of dinitrogen. Since side-on binding of triply bonded N_2 is also unfavorable, we are left with three ways out, provided that the mononuclear iron–sulfur complex **1** is a suitable model for a single Fe center in FeMoco: 1) the first reduction step is so fast that dinitrogen need not be strongly bound, 2) up to four (maybe six) iron atoms can activate N_2 to give μ^4-N_2 with a N–N single bond (as suggested on the basis of semiempirical calculations[57–60]), or 3) the molybdenum atom may play a central role. The second possibility was proposed on the basis of restricted frozen-core Kohn–Sham calculations on an FeMoco model by Dance,[61, 62] who found an binding mode intermediate between μ^4,η^1 and μ^4,η^2 to be most stable. However, these propositions are not necessarily the final answer, since open-shell states are most likely to become important, and exact exchange was not present in the density functional chosen to cure the singlet preference of the pure density functional. Machado and Davidson found for largely simplified models using ab initio methods (MP2 and CI) that a dimeric Fe^{III} site of low coordination number could be useful for N_2 binding.[63]

Siegbahn et al. obtained the important result from B3LYP calculations on polynuclear Fe–S complexes that a hydrogen atom attached to a bridging sulfur atom can dramatically change the affinity of the cluster for N_2.[21] From the work of Frenking et al.[54] we can conclude that the coordination energy of N_2 can be increased up to 96 kJ mol^{-1} in strong ligand fields at the cost of increased binding energies for NH_3. Modifications of the chelate ligand to give stronger ligand fields, protonation of sulfur atoms, and/or reduced coordination numbers are thus a promising way for solving the problem of weak coordination of N_2. The three diazene isomers are all stabilized significantly on coordination to Fe by the direct coordination energy and by hydrogen bonding. They should all be taken into account as possible stable intermediates in the FeMoco mechanism. Different open FeMoco structures could favor different isomers; while *trans*-diazene needs a larger Fe–Fe distance than *cis*-diazene, *cis*-diazene and especially NNH_2 will become important if FeMoco opens only a little. The last two reduction steps to hydrazine and ammonia appear to be straightforward once the diazene intermediate has been generated. Extensive periodic DFT studies have been undertaken by Rod, Nørskov, and co-workers,[56, 64, 65] who investigated FeMoco models from the point of view of heterogeneous catalysis. Two of their most important results are that FeMoco does not dissociate N_2 (N–N bond breaking occurs in the final reduction step), and the reduction takes place at the Fe atoms. Interestingly, end-on binding to a single Fe center is found rather than bonding to an Fe_4 face of the cluster. These results confirm that the study of mononuclear iron–sulfur complexes is indeed a promising approach to the problems of biological and biomimetic nitrogen fixation.

All findings in this work and those obtained by other groups must be regarded as possible binding and reaction modes, instead of established facts immediately transferrable to the biomolecule, and serve as a stimulus to examine other possibilities. This clearly shows that more reliable data must be obtained from the study of model complexes, which allow one to reduce the complexity of FeMoco in order to investigate particular features of a possible mechanism and to carefully elucidate the accuracy of the quantum chemical method.

Acknowledgements

We are grateful to Prof. D. Sellmann for numerous fruitful and stimulating discussions on the compounds synthesized in his group. Financial support through SFB 583 "Redoxaktive Metallkomplexe" of the DFG and by the Fonds der Chemischen Industrie are gratefully acknowledged.

[1] G. J. Leigh, *Eur. J. Biochem.* **1995**, *229*, 14–20.
[2] D. Coucouvanis, *J. Biol. Inorg. Chem.* **1996**, *1*, 594–600.
[3] C. J. Pickett, *J. Biol. Inorg. Chem.* **1996**, *1*, 601–606.
[4] D. Sellmann, J. Sutter, *J. Biol. Inorg. Chem.* **1996**, *1*, 587–593.
[5] K. D. Demadis, S. M. Malinak, D. Coucouvanis, *Inorg. Chem.* **1996**, *35*, 4038–4046.
[6] M. A. Tyson, D. Coucouvanis, *Inorg. Chem.* **1997**, *36*, 3808–3809.
[7] S. M. Malinak, A. M. Simeonov, P. E. Mosier, C. E. McKenna, D. Coucouvanis, *J. Am. Chem. Soc.* **1997**, *119*, 1662–1667.
[8] J. Han, K. Beck, N. Ockwig, D. Coucouvanis, *J. Am. Chem. Soc.* **1999**, *121*, 10448–10449.
[9] J. Han, D. Coucouvanis, *J. Am. Chem. Soc.* **2001**, *123*, 11304–11305.
[10] J. Han, M. Koutmos, S. Al Ahmad, D. Coucouvanis. *Inorg. Chem.* **2001**, *40*, 5985–5999.
[11] K. K. Stavrev, S. Urahata, T. Herz, J. Han, D. Coucouvanis, *Int. J. Quantum Chem.* **2001**, *85*, 469–474.
[12] D. Sellmann, J. Sutter in *Perspectives in Coordination Chemistry, Vol. 5 of Education in Advanced Chemistry*, University of Wroclaw, Poland, **2000**, pp. 49–65.
[13] D. Sellmann, J. Utz, N. Blum, F. W. Heinemann, *Coord. Chem. Rev.* **1999**, *190–192*, 607–627.
[14] D. Coucouvanis, J. Han, N. Moon, *J. Am. Chem. Soc.* **2002**, *124*, 216–224.
[15] D. Sellmann, H. Friedrich, F. Knoch, *Z. Naturforsch. B* **1993**, *48*, 1675–1680.
[16] D. Sellmann, G. Mahr, F. Knoch, M. Moll, *Inorg. Chim. Acta* **1994**, *224*, 45–59.

[17] D. Sellmann, P. Bail, F. Knoch, M. Moll, *Chem. Ber.* **1995**, *128*, 653–663.
[18] D. Sellmann, P. Lechner, F. Knoch, M. Moll, *Angew. Chem.* **1991**, *103*, 599–601; *Angew. Chem. Int. Ed. Engl.* **1991**, *30*, 552–553.
[19] D. Sellmann, P. Lechner, F. Knoch, M. Moll, *J. Am. Chem. Soc.* **1992**, *114*, 922–930.
[20] D. Sellmann, J. Käppler, M. Moll, Falk Knoch, *Inorg. Chem.* **1993**, *32*, 960–964.
[21] P. E. M. Siegbahn, J. Westerberg, M. Svensson, R. H. Crabtree, *J. Phys. Chem.* **1998**, *102*, 1615–1623.
[22] D. Sellmann, H. Friedrich, F. Knoch, M. Moll, *Z. Naturforsch. B* **1993**, *48*, 76–88.
[23] D. Sellmann, A. Hennige, F. W. Heinemann. *Inorg. Chim. Acta* **1998**, *280*, 39–49.
[24] M. Reiher, D. Sellmann, B. A. Hess, *Theor. Chem. Acc.* **2001**, *106*, 379–392.
[25] M. Reiher, O. Salomon, B. A. Hess, *Theor. Chem. Acc.* **2001**, *107*, 48–55.
[26] J. Kim, D. C. Rees, *Science* **1992**, *257*, 1677.
[27] J. Kim, D. C. Rees, *Nature* **1992**, *360*, 553.
[28] R. Ahlrichs, M. Bär, M. Häser, H. Horn, C. Kölmel, *Chem. Phys. Lett.* **1989**, *162*, 165–169.
[29] A. D. Becke. *Phys. Rev. A* **1988**, *38*, 3098–3100.
[30] J. P. Perdew. *Phys. Rev. B* **1986**, 33, 8822–8824.
[31] A. D. Becke, *J. Chem. Phys.* **1993**, *98*, 5648–5652.
[32] P. J. Stephens, F. J. Devlin, C. F. Chabalowski, M. J. Frisch, *J. Phys. Chem.* **1994**, *98*, 11623–11627.
[33] K. Eichkorn, O. Treutler, H. Öhm, M. Häser, R. Ahlrichs, *Chem. Phys. Lett.* **1995**, *240*, 283–290.
[34] K. Eichkorn, F. Weigend, O. Treutler, R. Ahlrichs, *Theor. Chem. Acc.* **1997**, *97*, 119–124.
[35] M. Reiher, O. Salomon, D. Sellmann, B. A. Hess, *Chem. Eur. J.* **2001**, *7*, 5195–5202.
[36] O. Salomon, M. Reiher, B. A. Hess, *J. Chem. Phys.* **2002**, *117*, 4729–4737.
[37] A. Schäfer, H. Horn, R. Ahlrichs, *J. Chem. Phys.* **1992**, *97*, 2571–2577.
[38] A. Schäfer, C. Huber, R. Ahlrichs, *J. Chem. Phys.* **1994**, *100*, 5829–5835.
[39] S. F. Boys, F. Bernardi, *Mol. Phys.* **1970**, *19*, 553–566.
[40] F. B. van Duijneveldt, J. G. C. M. van Duijenveldt-van de Rijdt, J. H. van Lenthe, *Chem. Rev.* **1994**, *94*, 1873–1885.
[41] C. Kind, M. Reiher, J. Neugebauer, B. A. Hess. Snf, University of Erlangen-Nürnberg, **1999–2001**.
[42] J. Neugebauer, M. Reiher, C. Kind, B. A. Hess, *J. Comp. Chem.* **2002**, *23*, 895–910.
[43] M. Reiher, J. Neugebauer, B. A. Hess, *Z. Physik. Chem.*, in press.
[44] G. Schaftenaar, J. H. Noordik, *J. Comput.-Aided Mol. Design* **2000**, *14*, 123–134.
[45] F. Tuczek, N. Lehnert, *Angew. Chem.* **1998**, *110*, 2780–2782; *Angew. Chem. Int. Ed.* **1998**, *37*, 2636–2638.
[46] M. D. Fryzuk, S. A. Johnson, *Coord. Chem. Rev.* **2000**, *200–202*, 379–409.
[47] P. E. M. Siegbahn, *J. Chem. Phys.* **1991**, *95*(1), 364–372.
[48] N. Lehnert, F. Tuczek, *Inorg. Chem.* **1999**, *38*, 1659–1670.
[49] N. Lehnert, F. Tuczek, *Inorg. Chem.* **1999**, *38*, 1671–1682.
[50] R. N. F. Thorneley, D. J. Lowe in *Molybdenum Enzymes*, *Vol. 4*, Wiley, New York, **1985**, p. 221.
[51] K. Dehnicke, J. Strähle, *Angew. Chem.* **1981**, *93*, 451–464; *Angew. Chem. Int. Ed. Engl.* **1981**, *20*, 413–426.
[52] K. Dehnicke, J. Strähle, *Angew. Chem.* **1992**, *104*, 978–1000; *Angew. Chem. Int. Ed. Engl.* **1992**, *31*, 955–978.
[53] C. Angeli, R. Cimiraglia, H.-J. Hofmann, *Chem. Phys. Lett.* **1996**, *259*, 276–282.
[54] Y. Chen, M. Hartmann, G. Frenking, *Eur. J. Inorg. Chem.* **2001**, 1441–1448.
[55] S. Sekusak, G. Frenking, *J. Molec. Struct.* (*THEOCHEM*), **2001**, *541*, 17–29.
[56] T. H. Rod, J. K. Nørskov, *J. Am. Chem. Soc.* **2000**, *122*, 12751–12763.
[57] K. K. Stavrev, M. C. Zerner, *Chem. Eur. J.* **1996**, *2*, 83–87.
[58] K. K. Stavrev, M. C. Zerner, *Int. J. Quantum Chem.* **1997**, *96*, 141–145.
[59] K. K. Stavrev, M. C. Zerner, *Int. J. Quantum Chem.* **1998**, *70*, 1159–1168.
[60] S.-J. Zhong, C.-W. Liu, *Polyhedron*, **1997**, *16*, 653–661.
[61] I. G. Dance, *Aust. J. Chem.* **1994**, *47*, 979–990.
[62] I. Dance, *Chem. Commun.* **1997**, 165–166.
[63] F. B. C. Machado, E. R. Davidson, *Theor. Chem. Acc.* **1995**, *92*, 315–326.
[64] T. H. Rod, B. Hammer, J. K. Nørskov, *Phys. Rev. Lett.* **1999**, *82*, 4054–4057.
[65] T. H. Rod, A. Logadottir, J. K. Nørskov, *J. Chem. Phys.* **2000**, *112*, 5343–5347.

Received: April 18, 2002 [F4027]

  0947-6539/02/0823-5339 $ 20.00+.50/0