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Ammonia synthesis at low temperatures

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Density functional theory (DFT) calculations of reaction paths and energies for the industrial and the biological catalytic ammonia synthesis processes are compared. The industrial catalyst is modeled by a ruthenium surface, while the active part of the enzyme is modeled by a MoFe$_7$S$_9$ complex. In contrast to the biological processes, the industrial process requires high temperatures and pressures to proceed, and an explanation of this important difference is discussed. The possibility of a metal surface catalyzed process running at low temperatures and pressures has been carried out to evaluate its feasibility. The calculations suggest that it might be possible to catalytically produce ammonia from molecular nitrogen at low temperatures and pressures, in particular if energy is fed into the process electrochemically. © 2000 American Institute of Physics.

I. INTRODUCTION

The conversion of N$_2$ from the atmosphere into a biologically accessible form of nitrogen is a very difficult process. The formation of, e.g., NH$_3$, requires the N–N bond to be broken, and this bond is extremely strong, the bond energy being about 1000 kJ/mole. The process, therefore, requires either extreme temperatures, like in an arc, or the participation of an effective catalyst. Ammonia is synthesized industrially from N$_2$ by two very different catalytic processes. Industrially, it takes place by passing N$_2$ and H$_2$ over Fe or Ru surfaces at quite high temperatures and pressures, about 400 °C and 100 atm. In nature, on the other hand, the enzyme nitrogenase catalyzes the synthesis of ammonia from N$_2$, electrons, and protons at room temperature and atmospheric pressure.

In the present paper, we discuss why the two processes require such different reaction conditions, and whether a process similar to the biological one can be envisaged at a metal surface. We base the discussion on new insight into the molecular mechanisms of the two processes from experiments and from density functional calculations of the reaction energetics. The calculations suggest that a low temperature, low pressure process might be possible on a metal surface under certain conditions.

II. THE SURFACE PROCESS

The ammonia synthesis reaction,

$$\text{N}_2 + 3\text{H}_2 \rightarrow 2\text{NH}_3,$$

on Fe and Ru surfaces has been the subject of a large number of experimental and theoretical studies and a detailed, molecular picture of the process has been developed. The reaction proceeds via dissociation of N$_2$ and H$_2$ on the surface with subsequent hydrogenation of the adsorbed N atoms. Our density functional theory (DFT) calculations of the reaction energetics on Ru surfaces illustrate the reaction mechanism, see Fig. 1. The dissociation of N$_2$ is the rate limiting step in this reaction. The barrier for dissociation is rather low; experiments find a dissociation barrier close to zero on Fe surfaces and as low as 40 kJ/mole on stepped Ru. Both values are consistent with the temperature dependence of the synthesis rate measured on an industrial catalyst. They are also in excellent agreement with reaction barriers calculated using DFT. The high temperatures and pressures are, therefore, not needed for N$_2$ dissociation to take place. H$_2$ dissociation is even more facile. The problem in the surface process is that the bonding of the N and H atoms to the metal surfaces is so strong (cf. Fig. 1) that high temperatures are needed to have enough clean, reactive surface available for dissociation and reaction. The high temperature has the side effect that the equilibrium in Eq. (1) is shifted to the left. This is not desirable, since no catalyst can produce more ammonia than the equilibrium amount. The high pressures are chosen to alleviate this problem, since that shifts the equilibrium back towards the products again.

A low temperature process based on N$_2$ and H$_2$ dissociation on the catalyst surface would, therefore, require a surface which does not bind the N and H atoms too strongly while keeping the barrier for N$_2$ dissociation low. Ru may be a slightly better catalyst than Fe because it does that to some extent, but a really good, low temperature catalyst based on the reaction Eq. (1) may be hard to find because the N–surface bond strength and the barrier for N$_2$ dissociation tends to be strongly coupled so that a weaker N–surface bond also results in a higher dissociation barrier.

III. THE ENZYME PROCESS

The enzyme nitrogenase represents an alternative catalyst for the ammonia synthesis. The active part in the enzyme is believed to be the FeMo cofactor (FeMoco) which has the stoichiometric formula MoFe$_7$S$_9$ (homo-citrate). The overall process can be written.

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where the obligatory simultaneous \( H_2 \) evolution has been left out. The electrons are provided by reduced ferredoxin. Large amounts of energy is used in the process, both in the form of a high chemical potential of the electrons and in the form of hydrolysis of at least 16 molecules adenosinetriphosphate (ATP) per turn over of Eq. (2).^{3,4}

![Energy diagram for ammonia synthesis on Ru(0001)](image1)

\[
\text{N}_2 + 6e^- + 6H^+ = 2\text{NH}_3, \tag{2}
\]

where the obligatory simultaneous \( H_2 \) evolution has been left out. The electrons are provided by reduced ferredoxin. Large amounts of energy is used in the process, both in the form of a high chemical potential of the electrons and in the form of hydrolysis of at least 16 molecules adenosinetriphosphate (ATP) per turn over of Eq. (2).^{3,4}

The active site of the enzyme is very well characterized,^{20–32} but the detailed molecular mechanism is not as well established as for the metal surface process. It is generally believed that the biological process does not involve initial breaking of the \( \text{N}^-\text{N} \) bond,^{33} and recent DFT calculations on different Mo, Fe sulfide complexes modeling the FeMoco^{34–36} support this picture. These are the same type of calculations,^{9,16} describing in detail the experimentally very well characterized surface process. It is, therefore, likely that the approach can be used to describe the enzyme process as well. Here the main approximation is that only a small fraction of the enzyme can be included. DFT calculations using a MoFe\(_{6}\)S\(_9\) complex to model the FeMoco suggest that \( \text{N}_2 \) is adsorbed on the FeMoco without dissociating, and when electrons and protons are added to the \( \text{N}_2 \) molecule one by one, first one and then the second \( \text{NH}_3 \) molecule (or \( \text{NH}_4^+ \) ion) leaves the catalytic site.^{35} Figure 2 compares the energetics of adding \( H \) atoms (from \( H_2 \)) to an \( \text{N}_2 \) molecule in the gas phase and adsorbed on the MoFe\(_{6}\)S\(_9\) complex. The effect of the MoFe\(_{6}\)S\(_9\) complex is very significant, in particular in stabilizing the least stable NNH intermediate by 110 kJ/mole.

The calculated energetics, Fig. 2, suggests that if the hydrogen entering the process comes directly from \( H_2 \), the model enzyme still has a sizeable “barrier” associated with the NNH intermediate. In the biological process \( H_2 \) is not the

![Energy diagram for the hydrogenation of \( \text{N}_2 \) in the gas phase and on the MoFe\(_{6}\)S\(_9\) complex modeling the FeMoco](image2)
source of hydrogen atoms, and the energy of the (‘‘H’’
$=\text{H}^+ + e^-$) entering Eq. (2) is different from that of hydrogen
in H$_2$. It may be$^{56}$ that the reaction is able to proceed at
room temperature because the enzyme feeds hydrogens with
a higher chemical potential than in H$_2$ into the reaction in the
form of electrons with a high electrochemical potential and/or
through the hydrolysis of ATP.$^{37–39}$ If this is the case, it might be possible to produce ammonia by electrolysis
of the isolated FeMoco. So far no one has been able to do
that, but a first step in this direction has been taken by Pickett
et al.$^{25}$ who have reported that for large enough negative
bias, H$_2$ can be produced, showing that the chemical
potential of (H$_2$ + e$^-$) in the active site of the enzyme can be
raised electrochemically above that of hydrogen in H$_2$.
Shilov et al.$^{40}$ have catalytically reduced acetylene by means
of the FeMoco and various amalgams as reductants. In this
connection it is also relevant to note that there has been
several reports on the protolysis of N$_2$ containing transition
metal complexes under strongly reducing conditions.$^{41–43}$

The possibility that we will discuss in the following is
whether a process like the one shown in Fig. 2 is possible
directly on a metal surface in particular if extra energy is fed
into the reaction electrochemically. We are using the DFT
calculations to study the question whether the FeMoco
model system we consider is unique in letting the process in
Fig. 2 go so relatively easily, or whether a similarly facile
process is possible at a metal surface. If that is the case, it
might be possible to form NH$_3$ at a metal surface, by using it
as the cathode in a proton containing electrolyte in the pres-
ence of molecular nitrogen.

IV. CALCULATIONAL DETAILS

The DFT calculations behind the results in Figs. 1 and 2
and the further results to follow are based on a plane-wave
expansion of the wave functions, a GGA description of ex-
change and correlation effects,$^{44,45}$ and ultra soft
pseudopotentials$^{46}$ except for S where a nonlocal soft
pseudopotential$^{37}$ is used. Plane waves with kinetic energies
up to 25 Ry are used. The self-consistent electron density is
determined by iterative diagonalization of the Kohn–Sham
Hamiltonian, Fermi-population of the Kohn–Sham states
($k_B T = 0.1$ eV), and Pulay mixing of the resulting electronic
density.$^{48}$ All total energies have been extrapolated to $k_B T$
= 0 eV.

In the DFT calculations, the MoFe$_6$S$_9$ complex is re-
peated periodically in one direction to give all Fe and Mo
atoms the same coordination number as in the real FeMoco.
In the other two directions the system is also repeated peri-
dodically but with vacuum in between to avoid interaction
effects. A complete structural relaxation to the lowest energy
state is performed for each configuration studied. It turns out
that the model MoFe$_6$S$_9$ complex has bond lengths and
angles closely resembling those found experimentally for the
FeMoco.$^{27–32}$ For further details of the calculations on the
model of the active part of the enzyme, see Ref. 36. The only
difference is that in the present paper the obtained densities
are used as input for a total energy calculations using the
slightly more accurate RPBE functional to describe exchange
correlation effects.$^{45}$

The metal surface chosen to study the question of a mo-
olecular N$_2$ hydrogenation process is the Ru(0001) surface
modeled by a periodic array of two layer slabs separated by
the equivalent of five layers of vacuum. An unit cell giving
(2 × 2) periodicity along the surface is used and the corre-
spending Brillouin zone is sampled by 18 special k-points.
The two layer slab gives results for N and N$_2$ adsorption
that are within 0.2 eV of the results using 3–6 layers. The re-
mainding computational details are exactly as for the model
enzyme.$^{36}$ The adsorbed species were allowed to fully relax,
but the substrate atoms were kept fixed at their ideal bulk
positions.

V. GENTLE N$_2$ HYDROGENATION

In Fig. 3 we investigate the possibility of hydrogenating
N$_2$ directly when it is adsorbed on the Ru(0001) surface. As
for the MoFe$_6$S$_9$ complex the calculations for the surface
have been performed by first adsorbing N$_2$ and then adding

![Figure 3](image-url)
H atoms one by one. Each time a new H atom is added, several bindings sites on N₂ have been tried in order to find the most stable intermediate. In Fig. 3 we include the structures of the most stable intermediates.

It is clear from Fig. 3 that the most stable intermediates on the Ru surface are very similar to those found for the model enzyme. In both cases the first hydrogenation step is endothermic. After that the reaction proceeds exothermically until the first ammonia splits off after addition of the fifth hydrogen, Fig. 3(g). Addition of the sixth hydrogen forms adsorbed ammonia Fig. 3(h), which desorbs endothermically, Fig. 3(i).

In agreement with other evidence, our calculations indicate that the transfer of protons to the adsorbed N₂ is not associated with significant energy barriers. If we assume this to be the case, the rate limiting step is associated with reaching the state Fig. 2(c) or Fig. 3(c). The small adsorption energy, \( E(b) \), gives rise to a low coverage of N₂ at the temperatures and pressures of interest here (300 K and 1 atm). It is simple to show that due to the low coverage, the rate for the total reaction depends only on \( E(c) \) and not on \( E(c) - E(b) \). The overall activation energy for the total reaction is, therefore, equal to \( E(c) \). We find \( E(c) \approx 90 \text{kJ/mol} \) for the MoFe₆S₉ complex and \( E(c) \approx 80 \text{kJ/mol} \) for Ru(0001). As discussed above, when the hydrogen atoms are added in the form of electrons and protons, the barrier may be decreased by changing the electrochemical potential of the electrons.

The calculations do not have an accuracy to predict accurately activation energies, but they strongly indicate that for a sufficiently negative bias the metal surface should in principle allow ammonia production at room temperature and atmospheric pressure. There are of course a number of potential problems in achieving this, the most serious of which may be the competition of the ammonia synthesis with hydrogen evolution. The same is seen in the enzyme process where \( \text{H}_2 \) production also competes with \( \text{NH}_3 \) formation. On the Ru surface the problem is worse because H atoms bind stronger than N₂ to the surface, while the opposite is true at the active site of the MoFe₆S₉ complex, where H bound to Fe is unstable relative to H on S or \( \text{H}_2 \). Perhaps steps which bind N₂ significantly stronger than terraces and does not bind H atoms quite as strongly can act as active sites for this reaction. This may, however, introduce N₂ dissociation which would immediately destroy the reactive sites. Alternatively, the Ru surface or other metal surfaces may have to be poisoned by, e.g., sulfur adsorption which both prevents H adsorption and N₂ dissociation. In fact, one may view the FeMoco as a Fe cluster passivated by S. In this connection it may be important that the cluster can distort to accommodate the N₂, see Fig. 2(a) and 2(b), as pointed out by Somorjai and Borodko. Yet another possibility is to use a noble metal or a surface alloy adsorbing H atoms less strongly.

Apart from a negative bias, the requirement for a low temperature ammonia synthesis reaction from N₂ is that protons are readily available. This may be accomplished in solution, or by using a proton conductor as the electrolyte. It cannot be excluded that the enzyme has a structure that facilitates the proton transfer particularly well, and that it is difficult to obtain equally good conditions at a metal surface. On the other hand, it is known that even the isolated cofactor can produce \( \text{H}_2 \) and can protonate acetylene, and binds CO in much the same way as in the enzyme.

Recently it has been reported that ammonia was produced electrochemically by a Pd catalyst on a proton conducting oxide. We suggest that this might have happened by the mechanism discussed here. We note that a reasonably low temperature reaction using \( \text{H}_2 \) as the H source might even be possible at the surface if N₂ dissociation and H poisoning can be avoided.

VI. SUMMARY

In summary, we have calculated the most stable intermediates along a reaction path where adsorbed N₂ on Ru(0001) is hydrogenated, and compared the results with the corresponding reaction mechanism previously published for the enzyme nitrogenase. The comparison shows many similarities between the mechanism on these two catalysts. In particular, we find that both reaction mechanism may proceed at low temperature if hydrogen is fed into the reaction in the form of electrons and protons with a higher chemical potential than hydrogen in the form of \( \text{H}_2 \).

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The rate at low ammonia pressures is given by

\[ r \sim 2 k \theta_{N_2}^2, \]

where the rate constant, \( k \), for \( b \rightarrow c \) is proportional to \( \exp(-E(c)-E(b)/k_B T) \). \( \theta_{N_2} \) is the degree of N\(_2\) coverage, given by a Langmuir isotherm. For low coverage the Langmuir isotherm gives that \( r \sim \exp(-E(b)/k_B T) \). We find, therefore, that \( r \) is proportional to \( \exp(-E(c)/k_B T) \) for low coverage.