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The Heck Olefination Reaction; A DFT Study of the Elimination Pathway

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Abstract : Theoretical studies of the pathway in the Heck reaction between ethene and a methyl electrophile at $[Pd(H_2ACH_2AH_2)(CH_3)(H_2C{=}CH_2)]^+$ (A = P, N) reveal intermediates with an agostic H which is the one preferentially transferred to base. © 1998 Elsevier Science Ltd. All rights reserved.

Organopalladium chemistry continues to make a substantial contribution to organic synthesis. Among the procedures providing most current interest, the Heck reaction is prominent.[1] Recent mechanistic studies provide some insights into the reaction pathway, but are constrained by the transient nature of key reactive intermediates which have eluded characterisation.[2] An overview of the accepted catalytic cycle is presented in Figure 1, which indicates the four basic steps. Oxidative addition of an unsaturated halide or triflate to a formally Pd[0] species (step (a)) is followed by alkene coordination and C-C bond formation through *cis*-ligand migration in step (b). The product is released by further reaction to form initially a palladium hydride in step (c), followed by reaction with a proton base, which causes elimination of the product and reversion to the PdL_2 species in step (d). Intermediates may either be cationic or neutral depending on the conditions and constraints. For realistic catalytic systems, only the reactant and product of step (b) are well characterised, although the structure of the Pd[0] species can be inferred from elsewhere; related η^2-alkene complexes have been characterised at low temperature in Brookhart's work on palladium-catalysed alkene polymerisations.[3]

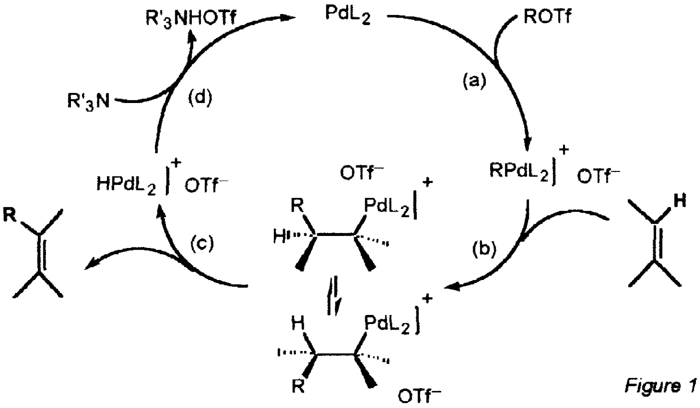

Figure 1

Much remains to be learnt about the mechanism, and more complete characterisation of intermediates is needed. Theoretical studies are a valuable adjunct and we have begun a study using high level Density Functional Theory (DFT) methodologies.[4] Our work on the oxidative addition step (a) in Figure 1 and the C-C coupling step (b) will be reported separately. Stages (b) and (c) have been modelled in related cases by Ziegler's and Morokuma's groups in the context of C_2H_4 polymerisation and copolymerisation, while aspects of the C-C coupling reaction have been examined by Siegbahn *et al.*[5] Hence this paper concentrates mainly on

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the base-promoted elimination stage, which could occur sequentially as (c), (d) in Figure 1 but also by direct deprotonation of the insertion product as in (e), Figure 2.

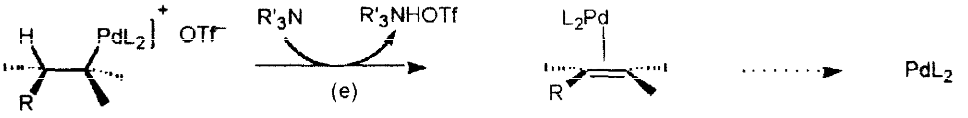
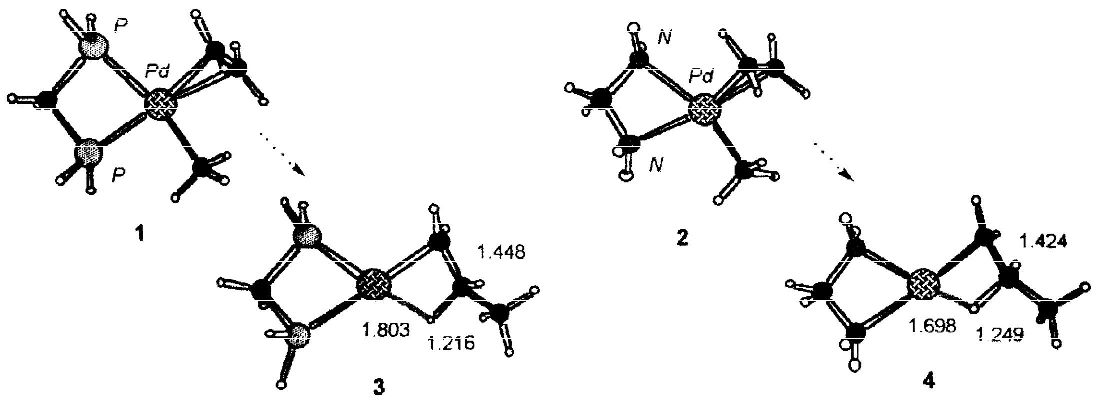


Figure 2

We first established that two catalytic cycles of immediate interest employing N- and P-ligands were computationally viable. Accordingly, energy minima were located for the model cationic complexes $[Pd(CH_3)\text{-}\eta^2\text{-}(C_2H_4)L]^+$ with L = $H_2PCH_2PH_2$ in **1** and L = $H_2NCH_2NH_2$ in **2**. The products of the ethene insertion step (b) were also examined, and it was demonstrated for both the diphosphine complex **3** and the diamine complex **4** that the minimum energy structure was one where the fourth site in the square plane is occupied by an agostic H, in accord with earlier calculations (ref 5). The length of the C1-C2 bond in both complexes **3** and **4** is shorter than an isolated single bond, in accord with X-ray structural data on agostic ethyl compounds where related bond lengths of 0.142 to 0.148 nm have been recorded.[6] In exploring the energy surface of these intermediates other significant minima were observed which will be fully described in a later full paper.[7] However, we note here that the isomeric palladium hydride is *not* an energy minimum in these specific cases. Geometry optimisation of a hydride complex results in spontaneous reversion to the β-agostic form.[8]



Surprisingly little work has been carried out on the alkyl elimination step in the Heck reaction, for which there are several conceivable mechanisms. A central, and apparently unanswered question is whether this step occurs by β-elimination as in Figure 1 (b), (c) or by base-catalysed proton-transfer from the alkyl as in Figure 2, (e). Since the calculations show that hydride complexes are not local minima, β-elimination is not a viable option. Turning to base-catalysed proton-transfer, the modelling shows that a solvent water molecule disrupts the β-agostic interaction yielding an aqua species some 20 kJ mol^{-1} lower in energy. This difference is sustained with NH_3 in the vicinity. However, the subsequent barrier to deprotonation is over 60 kJ mol^{-1} higher than for deprotonation from the corresponding agostic complex (*vide infra*). Displacing the solvent prior to deprotonation is energetically favoured.

Hence the theoretical analysis focuses on the proton transfer step from species **3** and **4**, which are defined energy minima. This raises an interesting question - is the alkene more easily formed by loss of the agostic proton or the non-agostic proton of the propyl group? Employing NH_3 as a base, a linear transit[9] was generated, shortening the reacting $H_3N\cdots H\text{-}C$ distance in steps of 0.01 to 0.018 nm. For the diphosphine ligated species **3**, the resulting energy profile is shown in Figure 3(i) while the profile for the diamine **4** is given in Figure 3(ii). In each case, rather different trajectories are described by the two relevant proton transfers, but the conclusions are clear :

i) the agostic hydrogen is kinetically the more acidic one and hence preferentially deprotonated[10] and,

ii) the alkene remains coordinated after deprotonation.

The TS **5** for transfer of agostic hydrogen indicates longer C-H and N-H distances for the transferring proton than in the non-agostic TS **6**; the Pd-H bond is more attenuated in the latter while there is more hydride-like character for the former. Solvation corrections[11] do not alter the energy profiles significantly except for the notional end-points where the ammonium ion has completely moved away from the complex, but correcting the DFT energies for solvation of the isolated species results in the overall reactions being exothermic. In the presence of a polar solvent, the Michaelis complexes with weakly associated NH_4^+ ions would probably no longer be local minima.

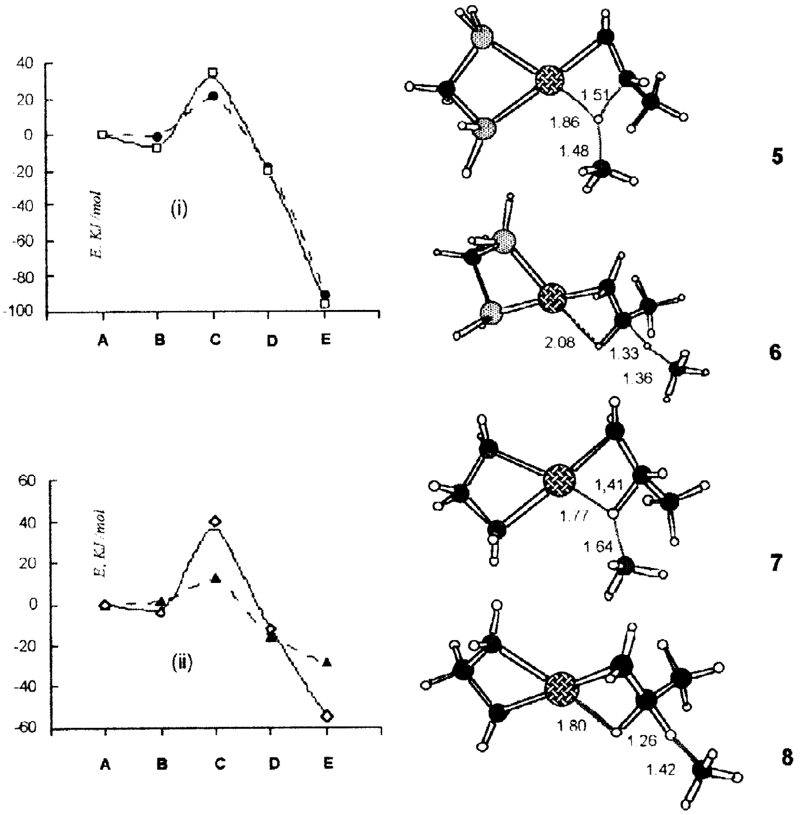


Figure 3 (i) Proton transfer from the diphosphine complex 3 to NH_3. ● *agostic,* ☐ *non-agostic. The transition state for proton transfer from the agostic H is shown as 5, that for the non-agostic H as 6. (ii) As (i);* ▲ *agostic,* ◇ *non-agostic, for the diamine complex 4, with 7 as the agostic TS and 8 as the non-agostic TS.* **A**, *isolated reactants;* **B** *reactant complex;* **C** *transition state;* **D** *product complex;* **E** *isolated products.*

Comparison of the P-P and N-N ligation reveals the same qualitative result, in that deprotonation of the agostic hydrogen is favoured over deprotonation of its geminal partner in complex **4**. The barrier is somewhat lower for the diamine, and the agostic transition-state 7 occurs earlier than for the diphosphine complex represented in **5**. The energy difference between 7 and **8** is more marked than in the diphosphine case. A stronger agostic interaction is evidenced by the longer C-H distance and shorter Pd-H contact for the N-N system as it traverses the energy surface. This behaviour stems from the greater ionic character of the diamine complex which results in less charge donation to Pd so that the metal is a better acceptor of charge from the agostic hydrogen. Finally, for the model systems examined here, the calculations support the mechanism outlined in Figure 2. A revised catalytic cycle is displayed in Figure 4. The first two steps shown

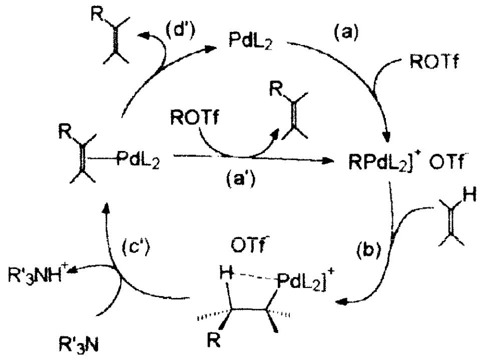


Figure 4

in Figure 1 are unchanged while steps (c) and (d) are swapped with the added proviso that the alkene remains coordinated after deprotonation (c'). A *distinct* palladium-hydride species does not appear to play a role in this step. Subsequent product loss could then occur via displacement by solvent (d'), although the aqua complex [$PdL_2(OH_2)$] is actually at higher energy than [PdL_2(alkene)], or as part of the next oxidative addition step (a').

Acknowledgments

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7. Complete energy profiles have been computed for all steps in the proposed cycle of Figs 1,2.
8. In the unconstrained $Pd(NH_3)_2^+$ series the hydrido(η^2-propene) complex is indeed an energy minimum, but still 28 $kJmol^{-1}$ higher in energy than its isomer, the analogue of species **4**.
9. The linear transit procedure optimises all other degrees of freedom at a series of fixed N-H distances between the incoming ammonia base and the target hydrogen. The initial and final N-H contacts correspond to those values found for unconstrained optimisations of Michaelis-type species with respectively NH_3 and NH_4^+ loosely associated with the relevant Pd complex.
10. c.f. Kremer, T.; Junge, M.; Schleyer, P. von R. *Organometallics*, **1996**, *15*, 3345-3359.
11. Energy corrections for aqueous solvation were computed as described in Deeth, R. J.; Elding, L. I. *Inorg. Chem.*, **1996**, *35*, 5019-5026.