C–N coupling in the gas-phase reactions of ammonia and [M(CH)]⁺ (M = Ni, Pd, Pt): a combined experimental/computational exercise

Robert Kretschmer,a,b Maria Schlangena and Helmut Schwarz*a,c

Electrospray ionization (ESI) of methanolic solutions of monomeric nickel(II) acetate, [Ni(CH₃COO)₂], and tetrameric platinum(II) acetate, [Pt₄(CH₃COO)₈], leads to the formation of the corresponding methylidyne complexes [M(CH)]⁺ (M = Ni, Pt), which react with ammonia under C–N coupling. While the product couples M/[CH₄N]⁺ and [M(CH₂N)]⁺/H₂ are observed for both metals, hydrogen-atom expulsion to generate [M(CHNH₂)]⁺/H is only observed in the case of the nickel-containing system, and the proton transfer leading to M/[NH₄]⁺ is limited to platinum. Attempts to conduct related experiments with [Pd(CH)]⁺/NH₃ failed. The mechanisms that explain the experimentally observed reaction channels have been investigated computationally using the B3LYP functional for all metals of the nickel group (M = Ni, Pd, Pt). In line with labeling experiments using the reaction pairs [M(CD)]⁺/NH₃ and [M(CH)]⁺/ND₃ (M = Ni, Pt), two different mechanistic scenarios of the dehydrogenation process are operative for the Ni and Pt systems, respectively.

Introduction

The formation of carbon–nitrogen bonds constitutes an important step in the preparation of several products ranging from chemical feedstocks to pharmaceuticals, and over the last few decades, intensive research has been devoted to this topic.¹ The use of ammonia as an inexpensive reagent for C–N coupling reactions is highly desired.² Ammonia is consumed on a large scale in industry, and C–N bond coupling reactions are e.g. accomplished in the synthesis of urea and in the Degussa process; in the latter, HCN is generated from CH₄ and NH₃ at high temperatures. However, the specific, metal-mediated formation of nitrogen-containing molecules generated directly from NH₃ in homogeneous catalytic reactions under ambient conditions is still rather limited due to the unwanted deactivation of the catalyst by the formation of Werner amine complexes. The improvement of existing and the development of new catalysts can ideally be achieved based on the knowledge of the intrinsic properties of the active metal center and of the underlying reaction mechanism, derived at a molecular level.

One way to gain such insight is studying model systems in the gas phase. Mass-spectrometry-based experiments³ have for example aided in the identification of CH₂NH as a crucial intermediate in the Degussa process,⁴ and its existence has been confirmed later by in situ photoionization experiments.⁵ In the gas-phase model of the [Pt]⁺-mediated coupling of ammonia and methane,⁴,⁶ the generation of [Pt(CH₂)]⁺ from [Pt]⁺ and methane constitutes the first step (eqn (1)).

\[
[Pt]^+ + CH_4 \rightarrow [Pt(CH_2)]^+ + H_2 \quad (1)
\]

[Pt(CH₂)]⁺ can then react with NH₃ to afford three different product couples (eqn (2)–(4)).⁶,⁷

\[
\begin{align*}
[Pt(CH_2)]^+ + NH_3 & \rightarrow [Pt(CHNH_2)]^+ + PtH \quad 70\% \quad (2) \\
[Pt(CH_2)]^+ + NH_3 & \rightarrow [Pt(CHNH_2)]^+ + H_2 \quad 25\% \quad (3) \\
[Pt(CH_2)]^+ + NH_3 & \rightarrow [PtCH]^+ + NH_3 \quad 5\% \quad (4)
\end{align*}
\]

Also [PtC]⁺ and [Pt(CH)]⁺ bring about C–N coupling in the reaction with ammonia,⁶,⁷ the complex [Pt(CH)]⁺ can be generated by electrospray ionization of the tetrameric platinum(II) acetate, [Pt₄(CH₃COO)₈], dissolved in methanol⁷ or by collision-induced dissociation of [Pt(CH₂)]⁺.⁶ As demonstrated earlier,⁶,⁷ the nature of the metal center crucially influences reaction efficiencies, branching ratios, and the generated product species in C–N coupling reactions.⁹ In order to uncover similarities and differences, and to explore trends within group 10 of the periodic table, we envisaged expanding the investigation to the [Ni(CH)]⁺/NH₃ and [Pd(CH)]⁺/NH₃...
couples. The focus is particularly on the capability of C–N bond formation, and the mass-spectrometric experiments are complemented by kinetic and labeling studies as well as by computational investigation. However, while [Pt(CH)]⁺ and [Ni(CH)]⁺ complexes can easily be generated by electrospray ionization, [Pd(CH)]⁺ is not accessible by this method; thus, the potential reactivity of this ion can, for the time being, only be probed by computational studies.

**Experimental**

**Reagents**

Acetic acid, acetic acid-D₄, nickel(II) acetate, nickel(II) carbonate hydrate, palladium(II) acetate, silver acetate and methanol were purchased from Sigma-Aldrich and were used without further purification. [Pt₄(CH₃COO)₈] was prepared from platinum(II) chloride and silver acetate in acetic acid, as described in detail previously.¹⁰ [Pt₄(CD₃COO)₈] was synthesized analogously by using [Ag(CH₃COO)] and CD₃COOD in a molar ratio of about 1 : 100. [Ni(CD₃COO)₂] was prepared by treating basic nickel(II) carbonate hydrate with CD₃COOD. Dry ammonia (99.98%) was obtained from Air Liquide and ND₃ (99.0 atom-% D) was purchased from Sigma-Aldrich.

**Mass spectrometry and ion/molecule reactions**

The experiments were performed with a VG Bio-Q mass spectrometer of QHQ configuration (Q: quadrupole; H: hexapole) equipped with an electrospray-ionization (ESI) source, as described in detail elsewhere.¹¹ Millimolar solutions of [Ni(CH₃COO)] and [Cd₂COOD] in a molar ratio of about 1 : 100. [Ni(CD₃COO)₂] was prepared by treating basic nickel(II) carbonate hydrate with CD₃COOD. Dry ammonia (99.98%) was obtained from Air Liquide and ND₃ (99.0 atom-% D) was purchased from Sigma-Aldrich.

**DFT calculations**

In the computational studies we employed the Gaussian 09 program package¹⁴ using the B3LYP functional.¹⁵ For C, H, and N we used the triple-ξ plus polarization (TZVP) basis sets of Ahlrichs and co-workers.¹⁶ For Ni, Pd, and Pt, the Stuttgart–Dresden scalar relativistic pseudopotentials in conjunction with the corresponding basis sets were employed.¹⁷ The validity of this protocol has already been proven by comparing the experimental and theoretical value of BDE(Pt–CH).¹⁸ For [Ni(CH)]⁺ the calculated BDE value of 311.0 kJ mol⁻¹ is within the uncertainty of the experimental value (301.0 ± 11.6 kJ mol⁻¹);¹⁹ BDE(Pd–CH) has, to the best of our knowledge, not been reported in the literature. All energies (given in kJ mol⁻¹) are corrected for (unscaled) zero-point vibrational energy contributions.

**Results and discussion**

**Experimental results**

Fig. 1 shows the mass spectra for the thermal reactions of mass-selected [Ni(CH)]⁺ and [Pt(CH)]⁺ with ammonia, with the reaction products given in eqn (5)–(10).

![Mass spectra](image)

**Experimental results**

Fig. 1 shows the mass spectra for the thermal reactions of mass-selected [Ni(CH)]⁺ and [Pt(CH)]⁺ with ammonia, with the reaction products given in eqn (5)–(10).

![Experimental results](image)

In accordance with previous results,¹⁰ three product couples are observed when [Pt(CH)]⁺ is reacted with ammonia. The
reaction mechanisms are operative in the dehydrogenation activation of ammonia. In contrast, for both $M = \text{Ni}$ and $\text{Pt}$, $\text{Dalton Transactions}$ Paper

is slightly less e

as $[\text{CH}_2\text{NH}_2]^+$ are known as product ions for the $[\text{Pt-} (\text{CH})^+]/\text{NH}_3$ couple. $6$ The reaction of $[\text{Ni}(\text{CH})^+]$ with ammonia $\text{Ni}$, $\text{Pd}$, and $\text{Pt}$, respectively) indicate a specific N

assignment is based on the fact that the direct formation of this ion $\text{via}$ a ligand exchange $[\text{Ni}(\text{CH})^+] + \text{NH}_3 \rightarrow [\text{Ni}(\text{NH}_3)^+] + \text{CH}$ is calculated to be endothermic by 63 kJ mol$^{-1}$; thus, this process is not accessible under thermal or quasi-thermal conditions.$19,22$

$$[\text{Ni}(\text{CH})^+] + 2\text{NH}_3 \rightarrow [\text{Ni}(\text{NH}_3)^+] + \text{CH}_2\text{N}_2 \quad (11)$$

The assignments of the reaction channels given in eqn (5)–(11) are in keeping with labeling experiments employing the couples $[\text{M}(\text{CD})^+] / \text{NH}_3$ and $[\text{M}(\text{CH})^+] / \text{ND}_3$ $(M = \text{Ni}, \text{Pt})$. These experiments provide further insight into the origin of the neutral products $\text{H}_2$ and $\text{H}$ of the reactions 6, 7, and 9. The exclusive deuterium and hydrogen atom losses according to eqn (7a) and (7b), respectively, indicate a specific N–H bond activation of ammonia. In contrast, for both $M = \text{Ni}$ and $\text{Pt}$, hydrogen/deuterium scrambling processes and/or coexisting reaction mechanisms are operative in the dehydrogenation according to eqn (6a/9a) and (6b/9b). While for the $[\text{Ni}(\text{CH})^+] / \text{ND}_3$ couple the loss of $D_2$ (eqn (6a)) is preferred compared to that of HD elimination (eqn (9a)), the opposite is observed for $[\text{Pt}(\text{CH})^+] / \text{ND}_3$; analogous results are obtained for the corresponding $[\text{M}(\text{CD})^+] / \text{NH}_3$. $23$ In the case of random $D_2$/HD or $H_2$/HD losses from the couples $[\text{M}(\text{CH})^+] / \text{ND}_3$ or $[\text{M}(\text{CH})^+] / \text{ND}_3$, respectively, 50:50 ratios would have been expected; consequently, different reaction mechanisms must apply for the two metals.

$$[\text{Ni}(\text{CH})^+] + \text{ND}_3 \rightarrow [\text{Ni}(\text{CHND}_2)^+] + \text{D} \quad (7a)$$

$$[\text{Ni}(\text{CD})^+] + \text{NH}_3 \rightarrow [\text{Ni}(\text{CDNH}_2)^+] + \text{H} \quad (7b)$$

$$[\text{M}(\text{CH})^+] + \text{ND}_3 \rightarrow [\text{M}(\text{CHD}_2\text{N})^+] + \text{D}_2 \quad (6a/9a)$$

This journal is © The Royal Society of Chemistry 2013

Dalton Trans., 2013, 42, 4153–4162 | 4155

Computational results

DFT calculations were performed to obtain mechanistic insights concerning the different pathways observed in the reactions of $[\text{M}(\text{CH})^+]$ $(M = \text{Ni}, \text{Pt})$ with ammonia; the analogous reaction pathways have also been calculated for $M = \text{Pd}$. For $[\text{M}(\text{CH})^+]$ two isomers were located on the potential-energy surfaces (PESs), i.e. the carbyne $[\text{M}(\text{CH})^+]$ as well as the hydrido carbide $[\text{HMC}]$; however, the latter isomer is much higher in energy for all three metals (by 421 kJ mol$^{-1}$, 160 kJ mol$^{-1}$, and 90 kJ mol$^{-1}$ for $M = \text{Ni}, \text{Pd}$, and $\text{Pt}$, respectively) and thus does not play a role in thermal reactions. For all three metals, the singlet state of $[\text{M}(\text{CH})^+]$ corresponds to the electronic ground state, and the singlet–triplet splitting increases in the series $\text{Ni}$, $\text{Pd}$, $\text{Pt}$ ($\Delta E_{\text{sing–trip}} = 14.9, 53.1$, and 162.3 kJ mol$^{-1}$ for $M = \text{Ni}$, $\text{Pd}$, and $\text{Pt}$, respectively).

Fig. 2 summarizes the PESs associated with the formations of the $M/[\text{CH}_2\text{NH}_2]^+$ pairs for $M = \text{Ni}$, $\text{Pd}$, $\text{Pt}$; the relative energies are given in Table 1. Starting from $[\text{M}(\text{CH})^+]$, ammonia can coordinate either to the metal center leading to the Werner complex 1 or to the carbon center to give 2 directly under the formation of a C–N bond. 1 and 2 can isomerize via $\text{TS}_{1/2}$, which is located energetically below the entrance channel for all three metals. Starting from complex 2, a hydrogen shift from nitrogen to carbon occurs to produce a $\text{CH}_2\text{NH}_2$ moiety; two different pathways exist: (i) in metal-mediated processes via transition structures $\text{TS}_{2/3}$ and $\text{TS}_{2/4}$ or (ii) directly via $\text{TS}_{2/4}$ as an intra-ligand shift without the participation of the metal center. Despite several efforts, it was not possible to locate $\text{TS}_{2/3}$ for $M = \text{Ni}$ and $\text{TS}_{2/4}$ for $M = \text{Pd}$ and $\text{Pt}$. After the formation of the $[\text{M}(\text{CH}_2\text{NH}_2)]^+$ complex 4, dissociation leads to the observed product couples $M/[\text{CH}_2\text{NH}_2]^+$. The exothermicity of the whole process increases from platinum to nickel to palladium, reflecting the strong Pt–C bond in $[\text{Pt}(\text{CH})^+]$ due to relativistic effects.$24$ The charge-reversed, alternative product pairs $[\text{M}/\text{CH}_2\text{NH}_3]$ in their ground states are with $162.1$ kJ mol$^{-1}$ for $\text{Ni}$, $223.0$ kJ mol$^{-1}$ for $\text{Pd}$, and $276.2$ kJ mol$^{-1}$ for $\text{Pt}$ higher in energy relative to the formation of the ground state neutral metals, respectively, in line with the higher ionization energies of the metals, i.e. $[\text{IE}(\text{Pt}) = 868.4$ kJ mol$^{-1}, 25 \text{IE}(\text{Pd}) = 804.4$ kJ mol$^{-1}, 26 \text{IE}(\text{Ni}) = 733.7$ kJ mol$^{-1}, 27$ compared to $\text{IE}([\text{CH}_2\text{NH}_3]) = 606.9$ kJ mol$^{-1}$. $23c$ However, the $[\text{Ni}]^+ / \text{CH}_2\text{NH}_2$ couple in the high spin and low spin states as well as the $[\text{Pd}]^+ / \text{CH}_2\text{NH}_2$ product pair are located energetically below the entrance channel and should therefore be accessible under thermal conditions; yet, the non-occurrence of these product ions reflects the much more favoured formation of the neutral metal atoms together with $[\text{CH}_2\text{NH}_3]^+$. As shown in Fig. 2 and Table 1, a two-state reactivity (TSR) scenario,$28$ which is crucial in numerous reactions of cationic nickel complexes in the gas phase,$29$ is not necessarily involved.
in these reactions because all intermediates and transition structures in their low-spin ground state are lower in energy compared to the entrance channel. Thus, the possible involvement of a TSR scenario is largely controlled by the efficiency of the spin–orbit coupling which is the highest for platinum. For the latter system, however, the high spin and low spin surfaces do not cross in the course of the reaction. Here, the triplet state is the ground state only of the exit channel; thus, a spin

Fig. 2  Schematic potential-energy surfaces for the formations of $M[\text{CH}_2\text{NH}_2]^+$ from $[M(\text{CH})]^+\text{NH}_3$ for (a) Ni, (b) Pd, and (c) Pt. The structures of the corresponding minima and transition states are given in (d). The energies are given relative to the singlet ground states of the educts; for details, see Table 1. For the sake of clarity, charges are omitted. C: H: N: metal.
crossing might take place in the last step of the formation of the products \([\text{CH}_3\text{NH}_2]^+\) and neutral Pt. With the triplet ground state of neutral Ni, a crossing from the singlet ground state of the educts to the triplet surface would also render the reaction more exothermic for the nickel system. Only neutral Pd possesses a singlet ground state, i.e. no spin crossing is necessary in this case to form the products in their singlet ground state.

As already mentioned, the ammonium ion \([\text{NH}_4]^+\) is only observed in the reactions of the \([\text{Pt}(\text{CH})]^+/\text{NH}_3\) couple, eqn (10). This is in good agreement with the calculated proton affinities (PAs) of the metal carbides; while PA(NiC) = 915.1 kJ mol\(^{-1}\) and PA(PdC) = 879.5 kJ mol\(^{-1}\) exceed PA(NH\(_3\)) = 852.1 kJ mol\(^{-1}\), platinum carbide possesses a lower proton affinity (PA (PtC) = 780.1 kJ mol\(^{-1}\)), and is thus able to act as a Brønsted acid.

Besides the formation of \([\text{M}(\text{CHNH})]^+\), we also observe the product ions \([\text{M},\text{C},\text{H}_3,\text{N}]^+\) (\(\text{M} = \text{Ni}, \text{Pt}\)) and \([\text{Ni},\text{C},\text{H}_3,\text{N}]^+\). The associated reaction pathways have also been investigated by means of DFT calculations; the latter indicate that C-N coupling is involved also in these reactions. A schematic potential-energy surface is shown in Fig. 3 and the corresponding energies are given in Table 2. As demonstrated by Diefenbach \textit{et al.},

\[\text{[M(CH)]}^+ + \text{NH}_3\]

\[\text{1} \quad -243.6 \quad -229.3 \quad -209.0 \quad -145.6 \quad -260.4 \quad -105.1\]

\[\text{TS}_{1/2} \quad -93.5 \quad -112.2 \quad -95.3 \quad -63.6 \quad -63.2 \quad -7.9\]

\[\text{2} \quad -214.4 \quad -260.5 \quad -221.3 \quad -233.1 \quad -207.8 \quad -148.6\]

\[\text{TS}_{2/3} \quad -84.2 \quad -132.9 \quad -62.5 \quad -117.2 \quad -20.0 \quad -45.7\]

\[\text{3} \quad -324.4 \quad -339.9 \quad -362.7 \quad -214.8 \quad -363.8 \quad -187.6\]

\[\text{TS}_{3/4} \quad -305.7 \quad -252.6 \quad -347.5 \quad -163.0 \quad -233.0 \quad -95.0\]

\[\text{TS}_{2/4} \quad -120.3 \quad -123.6 \quad -86.6 \quad -5.7\]

\[\text{4} \quad -394.7 \quad -369.8 \quad -428.0 \quad -277.0 \quad -308.8 \quad -209.7\]

\[\text{M} + \text{[CH}_3\text{NH}_2]^+ \quad -184.1 \quad -249.5 \quad -268.3 \quad -189.5 \quad -79.2 \quad -117.2\]

\[\text{[M] + CH}_3\text{NH}_2 \quad -87.4 \quad -9.0 \quad -45.3 \quad 233.7 \quad 159.0 \quad 236.0\]

\[\text{MC} + \text{[NH}_4]^+ \quad 63.0 \quad 91.8 \quad 27.4 \quad 33.4 \quad -72.0 \quad 56.2\]

\(^a\) No stable geometry could be obtained.

Table 1 Relative energies (given in kJ mol\(^{-1}\)) of all ground (singlet) and first-excited (triplet) state species shown in Fig. 2.
Fig. 3  Schematic potential-energy surfaces for the formations of \([\text{M}(\text{CHNH}_2)]^+, \text{[M}(\text{CHNH})]^+ (7\text{a}, \text{ path I}), \text{ and } \text{[M}(\text{CNH}_2)]^+ (7\text{b}, \text{ path II}), \text{ respectively, for (a) } \text{nickel, (b) palladium, and (c) platinum. The structures of the corresponding minima and transition states are given in (d). The energies are given relative to the singlet ground states of the educts (Fig. 2); for details, also see Table 2. For the sake of clarity, charges are omitted. C \text{, H } \text{, N } \text{, metal}.\)
degenerated reactions of the \([\text{M(CH}_3]\text{]}^+\)/\(\text{CH}_4\) pairs (\(\text{M} = \text{Fe, Co, Ni, Ru, Rh, Pd, Os, Ir, Pt}\)).\(^{35}\) OA/RE scenarios are especially observed in electron-rich, late 4d and 5d transition metal complexes,\(^{36}\) while the \(\sigma\)-bond metathesis mechanism is typically operative for early transition metals and for those of the first row thus preventing high formal oxidation states.\(^{37}\) In the present case, the platinum dihydride complexes 5a and 5b are formed in a first step, and the subsequent generation of the \(\sigma\)-hydrogen complexes 6a and 6b proceeds smoothly and more or less barrier-free (1.0 \(\text{kJ mol}^{-1}\) and 1.1 \(\text{kJ mol}^{-1}\) relative to the reactants).

<table>
<thead>
<tr>
<th>Species</th>
<th>Ni</th>
<th>Pd</th>
<th>Pt</th>
</tr>
</thead>
<tbody>
<tr>
<td>([\text{M(CH}_3]\text{]}^+ + \text{NH}_3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3)</td>
<td>0.0</td>
<td>14.9</td>
<td></td>
</tr>
<tr>
<td>([\text{M(CHNH}_3]\text{]}^+ + \text{H})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\text{TS}_1/2)</td>
<td>-324.4</td>
<td>-339.9</td>
<td></td>
</tr>
<tr>
<td>(2)</td>
<td>-156.1</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>(\text{TS}_1/3)</td>
<td>-127.5</td>
<td>-193.9</td>
<td></td>
</tr>
<tr>
<td>(6a)</td>
<td>-293.2</td>
<td>-262.0</td>
<td></td>
</tr>
<tr>
<td>([\text{M(CHNH}_3]\text{]}^+ + \text{H}_2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\text{TS}_2/6a)</td>
<td>-234.2</td>
<td>-208.7</td>
<td></td>
</tr>
<tr>
<td>(\text{TS}_2/6b)</td>
<td>-254.3</td>
<td>-113.2</td>
<td></td>
</tr>
<tr>
<td>6b</td>
<td>-258.5</td>
<td>-270.0</td>
<td></td>
</tr>
<tr>
<td>([\text{MC(NH}_2]\text{]}^+ + \text{H}_2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\text{TS}_3/6a)</td>
<td>-205.1</td>
<td>-202.9</td>
<td></td>
</tr>
<tr>
<td>(\text{TS}_3/6b)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Species</th>
<th>Ni</th>
<th>Pd</th>
<th>Pt</th>
</tr>
</thead>
<tbody>
<tr>
<td>([\text{M(CH}\text{]}^+\text{NH}_2\text{]}^+ + \text{H})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\text{TS}_3/6a)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\text{TS}_3/6b)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Relative energies (given in \(\text{kJ mol}^{-1}\)) of all ground (singlet) and first-excited (triplet) state species shown in Fig. 3

<table>
<thead>
<tr>
<th>Species</th>
<th>Ni</th>
<th>Pd</th>
<th>Pt</th>
</tr>
</thead>
<tbody>
<tr>
<td>([\text{M(CH}_3]\text{]}^+ + \text{NH}_3)</td>
<td>0.0</td>
<td>14.9</td>
<td></td>
</tr>
<tr>
<td>(3)</td>
<td>-324.4</td>
<td>-339.9</td>
<td></td>
</tr>
<tr>
<td>([\text{M(CHNH}_3]\text{]}^+ + \text{H})</td>
<td>-156.1</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>(\text{TS}_1/2)</td>
<td>-127.5</td>
<td>-193.9</td>
<td></td>
</tr>
<tr>
<td>(2)</td>
<td>-293.2</td>
<td>-262.0</td>
<td></td>
</tr>
<tr>
<td>([\text{M(CHNH}_3]\text{]}^+ + \text{H}_2)</td>
<td>-234.2</td>
<td>-208.7</td>
<td></td>
</tr>
<tr>
<td>(\text{TS}_2/6a)</td>
<td>-254.3</td>
<td>-113.2</td>
<td></td>
</tr>
<tr>
<td>(6a)</td>
<td>-258.5</td>
<td>-270.0</td>
<td></td>
</tr>
<tr>
<td>([\text{MC(NH}_2]\text{]}^+ + \text{H}_2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\text{TS}_3/6a)</td>
<td>-205.1</td>
<td>-202.9</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 Selected bond lengths (\(r\), given in Å) of the singlet species shown in Fig. 2 and 3, the bond lengths of the triplet state species are given in parentheses

<table>
<thead>
<tr>
<th>Species</th>
<th>Ni</th>
<th>Pd</th>
<th>Pt</th>
</tr>
</thead>
<tbody>
<tr>
<td>([\text{M(CH}\text{]}^+\text{NH}_2\text{]}^+ + \text{H})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\text{TS}_3/6a)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4 Schematic potential-energy surfaces for the formations of the two isomers \(\text{[Pt(CHNH)_2]}^+\) and \(\text{[Pt(CNH}_2]\text{]}^+\) by a sequence of oxidative addition and reductive elimination. The energies are given relative to the singlet ground state of the educts \(\text{[Pt(CH)]}^+\) and \(\text{NH}_3\) (Fig. 2). For the sake of clarity, charges are omitted. C, H, N, Pt.
to 5a and 5b, respectively). Similar pathways could not be located for nickel and palladium; here, the initial structures converge to the corresponding intermediates shown in Fig. 3 or they are much higher in energy.

Starting from 2, an alternative reaction path for the formation of [M(CNH3)]+ is also conceivable, in which the hydrogen of the CH group is transferred in a first step to the metal center and H2 is formed subsequently from the hydride ligand and one hydrogen of the NH3 group. While the formation of [HM(CN)H3]+ is possible from a kinetic as well as thermodynamic point of view, the reaction is kinetically hindered by the barrier associated with the second step, i.e. the formation of [(H2)M(CN)H3]+; the latter is higher in energy compared to the entrance channel (4Ni: 53.2 kJ mol⁻¹; 4Pd: 28.2 kJ mol⁻¹; 4Pt: 9.9 kJ mol⁻¹).

The data for r(M–C) in 3 correspond to the data obtained by the single and the double bond radii approach.³¹,³² Depending on the metal, the formations of [M(CNHN)]+ (7a, path I) and [M(CNHN)]+ (7b, path II) starting from 3 are associated with different changes in the bond lengths. While the metal-dependent deviations in the M–C bond length in 7a are more or less minor (0.02 Å−0.05 Å), the values of the M–N bond of this structure are quite different for the Ni, Pd, and Pt systems. For nickel, r(Ni–N) = 1.83 Å corresponds to a single bond; in contrast, the values for palladium and platinum (2.20 Å and 2.06 Å) exceed those obtained by the single bond radii approach by 0.18 Å and 0.12 Å, respectively.³¹,³³ Compared to the formation of 7a, the changes in the bond lengths accompanied by the formation of [M(CNHN)]+ (7b) are much more pronounced. Starting from 3, the M–C bond in 7b is shortened by 0.13 Å to 0.17 Å and also the C–N bond length gets reduced.

With respect to the labeling experiments employing the [M(CD)]+/NH3 and [M(CH)]+/ND3 couples, the double N–H bond activation of path I (Fig. 3) results in the loss of H2 and D2, respectively, while the C–H and N–H bond formation of path II leads to HD elimination for both isotopolog pairs. However, the losses of H2 and D2 from [M(CD)]+/NH3 and [M(CH)]+/ND3, respectively, can also be explained by path II if scrambling processes are taken into account, i.e. if the system has time enough to pass TSv,shb back and forth before the elimination of molecular hydrogen occurs; in contrast, the multiple traverse of TSb,shb does not change the isotopic product pattern. Because TSv,shb is in the case of nickel energetically more demanding compared to the exit channel, molecular hydrogen is expected to be instantly eliminated after its formation. Based on the calculations, scrambling processes in the [Ni–(CD)]+/NH3 and [Ni(CH)]+/ND3 pairs can thus be excluded, and the eliminations of H2/HD and D2/HD observed in the experiments, respectively, are most likely caused exclusively by the two different reaction pathways of dehydrogenation (Fig. 3). Thus, while ⁴TSv,shb and ³TSv,shb are similar in energy, respectively, ³TSv,shb is by 72.5 kJ mol⁻¹ lower in energy compared to ⁴TSv,shb, i.e. double N–H bond activation according to a TSR scenario is kinetically more favourable, in line with the preferred losses of D2 and H2 in the labeling experiments using ND3 and NH3, respectively. In contrast, the predominant loss of HD obtained for both the [Pt(CD)]+/NH3 and [Pt(CH)]+/ND3 couples points to the preferred formation of [Pt(CNHN)]+ relative to [Pt(CHNH)]+. Here, the calculated thermochemistry for the formations of both ions agrees with the experimental findings. While ⁴TSv,shb is 20.1 kJ mol⁻¹ lower in energy compared to ³TSv,shb (Fig. 4), the former transition structure results in the more energy demanding formation of [Pt(CHNH)]+ which is 52.2 kJ mol⁻¹ higher in energy compared to [Pt(CNHN)]+ and 9.2 kJ mol⁻¹ higher compared to ³TSv,shb, respectively; however, both isomers [Pt(CNHN)]+ and [Pt(CHNH)]+ are accessible under thermal conditions. In the formation of the latter, ⁴TSv,shb is located energetically below the exit channel; however, back reactions to 3 do not affect the isotopic pattern of the product ion and scrambling processes have thus not to be taken into account, indicating that both isomers [Pt(CNHN)]+ and [Pt(CHNH)]+ are formed in the experiments.

Conclusions

The methyldyne complexes [M(CH)]+ (M = Ni, Pt) have been generated by electrospray ionization (ESI) of solutions of monomeric nickel(i) acetate, [Ni(CH2COO)2], and tetrmeric platinum(ii) acetate, [Pt4(CH3COO)8], in methanol. The so formed ions were allowed to react with ammonia, yielding common as well as different product pairs: while the M(CH2NH3)2+ and [M,C,H2,N]+/H2 are formed in the experiments.

The formations of both ions agrees with the experimental findings, different reaction pathways are involved in the formation of [CH2NH3]+ which is accomplished either by a metal-mediated or intra-ligand hydrogen shift. The product ion of H elimination corresponds to [M(CHNH)2]+; the fact that this complex can only be observed for nickel is a result of an increasing M–H bond strength in the intermediate [HM(CHNH)2] which leads also to [M(CHNH)2]+ and [M(CHNH)+]. The formations of the latter product ions proceed again via different reaction pathways; while for nickel and palladium a σ-bond metathesis is operative, for platinum a sequence of oxidative addition and reductive elimination is involved thus demonstrating metal-depending reaction mechanisms for the same type of reaction.

Acknowledgements

This work is dedicated to Professor Rainer Beckert on the occasion of his 60th birthday. Financial support by the Fonds der Chemischen Industrie and the Cluster of Excellence “Unifying Concepts in Catalysis” (EXC 314/1) funded by the Deutsche Forschungsgemeinschaft and administered by the Technische Universität Berlin is gratefully acknowledged. We appreciate helpful discussions with Dr. Burkhard Butschke and thank the North-German Supercomputing Alliance (HLRN) for allocating resources.
computer time. R.K. acknowledges the Stiftung Stipendien-Fonds des Verbandes der Chemischen Industrie for a Kekulé scholarship and the Alexander von Humboldt Stiftung for a Feodor Lynen Research Fellowship.

Notes and references


Due to relatively low signal-to-noise ratios, the isotopic pattern of the product ions in the dehydrogenation process is associated with rather large error bars; thus, we refrain from modeling the experimental data to a kinetic scheme aimed at specifying the kinetic isotope effects of this reaction.