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Selective Synthesis of Cis- and Trans-[(NHC\textsubscript{Me})\textsubscript{2}PtCl\textsubscript{2}] and [NHC\textsubscript{Me}Pt(cod)Cl][NHC\textsubscript{Me}PtCl\textsubscript{3}] using NHC\textsubscript{Me}SiCl\textsubscript{4}

Lesley C. Lewis-Alleyne,\textsuperscript{a,b} Bassem S. Bassil,\textsuperscript{b} Tobias Böttcher\textsuperscript{c} and Gerd-Volker Röschenthaler\textsuperscript{a,b}

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NHC\textsubscript{Me}SiCl\textsubscript{4}, (NHC\textsubscript{Me} = 1,3-dimethylimidazolidin-2-ylidene), was used to synthesise novel NHC\textsubscript{Me}-Pt(II) complexes. An atypical trans-cis isomerisation process has also been achieved for [(NHC\textsubscript{Me})\textsubscript{2}PtCl\textsubscript{2}], while the synthesis of the unique double-complex salt, [(NHC\textsubscript{Me})Pt(cod)Cl][ (NHC\textsubscript{Me})PtCl\textsubscript{3}], (cod = 1,5-cyclooctadiene), revealed the first-ever N-heterocyclic carbene analogue of the Cossa’s salt anion.

Metal complexes of N-heterocyclic carbenes (NHCs) have been established in organometallic chemistry and catalysis.\textsuperscript{1-4} Another burgeoning field for such complexes is in medicine, where NHC complexes are finding valuable applications as antibiotic and anti-cancer agents.\textsuperscript{5,11} The rational design, and synthesis, of metal-carbene complexes have benefited from several approaches.\textsuperscript{12, 13} Among these, the use of NHC\textsubscript{Me}SiCl\textsubscript{4} shows huge efficacy for providing a low-cost, high-yielding, synthetic route to NHC-metal complexes when a saturated, non-bulky NHC is desired.\textsuperscript{14} Our interest in NHC\textsubscript{Me}-Pt(II) complexes seeks primarily to provide promising candidates for testing in anti-cancer studies.

The facile reaction of PtCl\textsubscript{2} with 2 equivalents of NHC\textsubscript{Me}SiCl\textsubscript{4} (Scheme 1) gave exclusively trans-[(NHC\textsubscript{Me})\textsubscript{2}PtCl\textsubscript{2}] (1) (Fig. 1)

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\begin{align*}
\text{Scheme 1 Reactions of of NHC\textsubscript{Me}SiCl\textsubscript{4} with PtCl\textsubscript{2} and [Pt(cod)Cl].}
\end{align*}
\]

Table 1 Selected bond lengths and angles

<table>
<thead>
<tr>
<th>Bond Lengths for 1Å</th>
<th>Selected Angles for 1°</th>
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<tbody>
<tr>
<td>Pt\textsubscript{1}-C\textsubscript{1} 2.027(2)</td>
<td>C\textsubscript{1}-Pt\textsubscript{1}-C\textsubscript{1} 180.0</td>
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<tr>
<td>Pt\textsubscript{1}-Cl\textsubscript{1} 2.3087(7)</td>
<td>Cl\textsubscript{1}-Pt\textsubscript{1}-Cl\textsubscript{1} 180.0</td>
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</table>

<table>
<thead>
<tr>
<th>Bond Lengths for 2Å</th>
<th>Selected Angles for 2°</th>
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</thead>
<tbody>
<tr>
<td>Pt\textsubscript{1A}-C\textsubscript{1A} 1.967(3)</td>
<td>C\textsubscript{1A}-Pt\textsubscript{1A}-C\textsubscript{1A} 178.49(8)</td>
</tr>
<tr>
<td>Pt\textsubscript{1A}-C\textsubscript{6A} 1.971(3)</td>
<td>C\textsubscript{6A}-Pt\textsubscript{1A}-C\textsubscript{1A} 177.32(8)</td>
</tr>
<tr>
<td>Pt\textsubscript{1A}-Cl\textsubscript{1A} 2.3770(7)</td>
<td>Cl\textsubscript{1A}-Pt\textsubscript{1A}-Cl\textsubscript{1A} 91.75(2)</td>
</tr>
<tr>
<td>Pt\textsubscript{1A}-Cl\textsubscript{6A} 2.3734(7)</td>
<td>Cl\textsubscript{6A}-Pt\textsubscript{1A}-Cl\textsubscript{6A} 90.51(11)</td>
</tr>
</tbody>
</table>

as a pale yellow crystalline solid. This was in contrast to the product from the corresponding PdCl\textsubscript{2} reaction,\textsuperscript{14} where the cis complex product was reported. Cis-complexes of platinum, in particular those with minimal steric hindrance,\textsuperscript{7, 8} are regarded as the preferred configuration for the purpose of testing for anti-tumour properties. Considering that substitution reactions on a square-planar platinum(II) complex may preserve the original
geometry, the reaction of [Pt(cod)Cl₂] with 2 equivalents of NHC₅MeSiCl₄ (Scheme 1) was carried out, and this successfully yielded cis-[NHC₅Me]₂PtCl₂ (2) (Fig. 1) as the sole product. From NMR analysis, complexes 1 and 2 are distinguishable, in particular from¹⁹⁵Pt NMR, which showed a significant upfield shift at -3730.20 ppm for the cis complex, 2, compared to that for the trans-complex, 1, at -3271.09 ppm. Both signals are in agreement with¹⁹⁵Pt NMR reported for other Pt(II)-NHC₅Me.⁷, ¹⁵, ¹⁶

Thermogravimetric Analysis (TGA) with Differential Scanning Calorimetry (DSC) was carried out for the two isomers of [(NHC₅Me)₂PtCl₂] (Figure 2). The initial weight loss at decomposition, for both complexes, corresponds to the loss of the NHC ligands. In the TGA/DSC spectrum for 1 (Figure 2b), an exothermic process occurs before any significant loss of mass, and the final decomposition process at 320 °C. An irreversible trans-cis isomerisation was suspected, and confirmed when the trans complex was heated to 300 °C (i.e. after the exothermic transition without loss of mass) and NMR spectra of the resulting material obtained. The 'H and ¹⁹⁵Pt NMR signals corresponded solely to the cis-complex. In addition, the TGA/DSC spectrum of the material obtained after an initial cycle of heating to 300 °C and cooling to room temperature (Figure 2c) showed the identical spectrum to that for 2 (Figure 2a). This is the first reported thermally induced trans-cis isomerisation for a bis-NHC platinum complex, which is in direct contrast to the cis-trans isomerisation reported for similar bis-NHC-platinum(II) species.¹⁷ Such non-typical trans-cis isomerisations of platinum coordination compounds were first reported for amino⁻⁻ and bis-pentamethylsulfide⁻⁻ platinum(II) derivatives, where it was suggested that increased stability may be related to crystal structure effects. The NHC-platinum complex shows greater thermodynamic stability when the (sufficiently small)¹⁹ NHC is in a trans position to the halide ligand. Such observations can also be made from earlier work on platinum-NHC coordination compounds by Lappert,²⁰⁻²² and even more recent reports.²³, ²⁴ From the crystal structures, the conformation of the NHC ligands is oriented to minimise any steric hindrance.²⁵ Still, under appropriate conditions, 1 shows greater kinetic stability, similar to the complexes also reported by Lappert.²⁰

During initial attempts to synthesise 2, when NHC₅MeSiCl₄ was utilised as the limiting reagent, a second, easily-crystallisable, and visually distinguishable complex product was isolated. The bright yellow crystals were characterised by X-Ray crystallography (Figure 3) and shown to be a double complex salt, [(NHC₅Me)₂Pt(cod)Cl][(NHC₅Me)₂PtCl₂] (3). Subsequently, when the reaction of [Pt(cod)Cl₂] with NHC₅MeSiCl₄ was carried out in a 1:1 ratio in a highly polar solvent (to enhance the formation of an ionic salt), and prolonged heating, 3 was selectively obtained (Scheme 1). The complex salt was further characterised by multi-nuclear and 2D NMR techniques.¹ The ¹⁹⁵Pt NMR spectrum showed two signals; one at an upfield shift of -3542.34 ppm, thought to be the cationic complex component of 3, and the other at -2930.61 ppm, for the anionic complex component. While similar cationic platinum(II) complexes are known,²⁶-²⁸ to the best of our knowledge, [Pt(NHC₅Me)Cl₂]⁻, is the first-reported N-heterocyclic carbene analogue of the Cossa’s salt anion.²⁹ The cis and trans effects of ligands in [PtLCl₂]⁻
analouges can be easily compared, particularly with respect to the chloride ligands, which have significance for anti-tumour agents.

Multi-nuclear platinum complexes offer further interest for potential electrochemical properties. The double-complex salt, 3, poses a unique candidate, since both the cation and anion complexes contain an NHC ligand.

Conclusions

Diverse forms of platinum(II)-NHC complexes have been readily prepared by the use of an inexpensive and efficient carbene transfer reagent, NHCSiCl3. In the literature, anti-tumour activity has been considered for neutral cis- and trans-platinum(II) complexes, as well as for cod-substituted platinum(II) complexes, and even trichloro-platinum(II) complexes. We expect our findings to contribute promising candidates for anti-tumour studies, as well as to improve the rational design of complexes that are supported by a non-bulky NHC. While platinum(II)-NHC complexes are also useful in catalyst design, herein has also been shown the potential for NHC double-complex salts to be considered for materials with electrochemical properties.

Notes and references

Selective Synthesis of *Cis*- and *Trans*-[(NHC<sup>Me</sup>)<sub>2</sub>PtCl<sub>2</sub>] and [NHC<sup>Me</sup>Pt(cod)Cl][NHC<sup>Me</sup>PtCl<sub>3</sub>] using NHC<sup>Me</sup>SiCl<sub>4</sub>

Lesley C. Lewis-Alleyne,* Bassem S. Bassil, Tobias Böttcher and Gerd-Volker Röschenthaler*

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NHC<sup>Me</sup>SiCl<sub>4</sub> was used to selectively synthesise *cis* and *trans*-[NHC<sup>Me</sup>]<sub>2</sub>PtCl<sub>2</sub>], as well as [NHC<sup>Me</sup>Pt(cod)Cl][NHC<sup>Me</sup>PtCl<sub>3</sub>], which revealed the first ever N-heterocyclic carbene analogue of the Cossa’s salt anion.