SET processes in Lewis acid–base reactions: the tritylation of N-heterocyclic carbenes†

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Reactions between N-heterocyclic carbenes (NHCs) and the trityl cation, [Ph3C]+, give covalent adducts of type [NHC–CPh3]+ and/or [NHC–C6H5–CPh2]+. EPR spectroscopy, UV-Vis analyses, and trapping experiments imply that adduct formation involves carbene radical cations and the trityl radical. The results demonstrate that single electron transfer (SET) processes should be considered for reaction of NHCs with oxidizing Lewis acids.

Below, we provide experimental evidence for the relevance of SET processes in reactions of NHCs with the Lewis acid [Ph3C][B(C6F5)4]. In particular, we show that adduct formation involves the formation of a carbene radical cation and the trityl radical.

Results and discussion

N-heterocyclic carbenes are not only important ligands in transition metal chemistry, but they are also used extensively as Lewis bases in main group chemistry. For the present study, we have investigated the reaction of NHCs with the Lewis acid [Ph3C][B(C6F5)4]. When 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene (IDipp, 1a) was allowed to react with the trityl salt in toluene at –40 °C, we observed the clean formation of adduct 2a.

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The structure of 2a was established by NMR spectroscopy and by single crystal X-ray diffraction (XRD) analysis (see the ESI†). The formation of 2a was expected, since a structurally related compound was reported by the group of Stephan for the reaction of 1,3-di-tert-butylimidazol-2-ylidene (IrBu, 1b) and [Ph3C][B(C6F5)4]†.‡

When the reaction between 1a and the trityl salt was performed in toluene at room temperature, side products were formed, as revealed by NMR spectroscopic analysis of the reaction mixture. Adduct 2a was still the main product (76%), but the imidazolium salt [IDipp-H]+[B(C6F5)4] (3a) was formed in 24% yield, along with a small amount of triphenylmethane, Ph3CH (~5%).

During our investigations, we were intrigued by the following observation: when 1a was added to a solution of the trityl salt (either RT or ~40 °C), the color of the solution turned from yellow to purple. The purple color quickly faded away, and at the end of the reaction, a nearly colorless solution was observed (Fig. 1a).

When the beginning of the reaction was followed by UV-vis spectroscopy at room temperature, one could observe a gradual decrease of the band at 438 nm, which can be attributed to the trityl cation. Simultaneously, a band 343 nm and a weaker band at 591 nm started to grow (Fig. 1c). The latter disappearance with time, and a band at 343 and 591 nm disappeared nearly instantaneously (ESI, Fig. S8†).

The results imply that adduct formation proceeds via one (or more) short-lived intermediate(s). In order to examine if radicals are involved, we investigated mixtures of 1a and [Ph3C][B(C6F5)4] by EPR spectroscopy. We were able to detect a signal with a complex hyperfine coupling, which can be attributed to the trityl radical (Fig. 1b). The formation of [Ph3C]+ provides an explanation for the absorption at 343 nm, because the trityl radical is known to have a band in that region. We propose that the purple color (broad band at 591 nm), which we observed at the beginning of the reaction, is due to [1a]+. This assumption is substantiated by the following control experiment: when IDipp was deliberately oxidized with [NO][SbF6] in toluene at room temperature, a short-lived purple color was also observed (for details, see ESI†). The main product of this reaction was the imidazolium salt [IDipp-H][SbF6], which is presumably formed by reaction of the intermediate [1a]+ with the solvent (see Fig. S14†). Taken together, the experimental data suggest that the reaction between 1a and [Ph3C][B(C6F5)4] proceeds via single electron transfer to give [Ph3C]+ and [1a]+ (Scheme 3). At ~40 °C, selective cross-coupling results in formation of adduct 2a, whereas hydrogen atoms abstraction becomes a competing pathway for reactions performed at room temperature. The carbene radical cation [1a]+ is more reactive than the persistent [Ph3C]+, which provides an explanation that we were not able to detect the former by EPR spectroscopy.

It is worth noting that NHC-based radical cations have been suggested as intermediates of reactions between NHCs and oxidants such as tetracyanoethylene, ferrocenium salts, and Ph[OTf]2. The products of these reactions are either imidazolium salts (formed via H atom abstraction from the solvent) or dicaticonic dimers (formed by homo-coupling of the NHC radical cations). In our case, cross-coupling of [Ph3C]+ and [1a]+ is

![Image](https://via.placeholder.com/150)

Scheme 2 Reaction of IDipp (1a) with [Ph3C][B(C6F5)4] in toluene.

![Image](https://via.placeholder.com/150)

Scheme 3 Formation of the Lewis acid–base adduct 2a proceeds via the radicals [Ph3C]+ and [1a]+.†
strongly favored over homo-coupling reactions. We have analyzed reaction mixtures by mass spectroscopy, and we were able to detect peaks for the coupling adduct 2a and the imidazolium salt 3a, but not for a dicationic dimer 

Further evidence for the formation of radicals was obtained by trapping experiments with the hydrogen atom donors THF or Ph3SnH (Table 1). When the reaction between 1a and the trityl salt was performed in the presence of 25 vol% THF, adduct formation was impeded, and the imidazolium salt 3a was formed in 73% yield, along with equimolar amounts of Ph3CH. Similar results were observed for reactions with Ph3SnH. When a solution of Ph3SnH in toluene was added to an equimolar mixture of 1a and [Ph3C][B(C6F5)4], the dominant imidazolium-based product was 3a (42%). Furthermore, we were able to detect Ph3SnSnPh3 by 119Sn NMR spectroscopy (\(\delta^{119}\text{Sn} = 131.1\), ESI, Fig. S16f). The formation of the distannane is further evidence for the involvement of radicals.\(^6,22\) We noted that the starting materials (1a and the trityl salt) do also react with Ph3SnH. However, these reactions gave alternative products, and Ph3SnSnPh3 was not observed.

Next, we re-examined the addition of iPrBu (1b) to [Ph3C][B(C6F5)4]. When the reaction was performed in toluene at \(-40^\circ\text{C}\), the known coupling product 2b\(^15\) was obtained in nearly quantitative yield. In contrast, only a small amount of 2b was formed when the reaction was carried out at room temperature in the presence of 25 vol% THF (Table 1 and ESI†). Under these conditions, the main products were the imidazolium salt [IBuH][B(C6F5)4] (3b, characterized also by X-ray crystallography) and Ph3CH (both 79%). Using Ph3SnH as radical scavenger, the yield of the imidazolium salt was even higher (87%). As in the case of reactions with IDipp, the dimer Ph3SnSnPh3 was detected by \(\delta_{119}\text{Sn} NMR spectroscopy.

Similar results were obtained for reactions of IMes (1c) with [Ph3C][B(C6F5)4] in the presence of the radical scavenger THF: the main products were the imidazolium salt 3c and Ph3CH (Table 1), indicating an initial SET process between the carbene and the trityl salt.\(^22\) However, reactions performed in toluene at \(-40^\circ\text{C}\) gave a surprising result. The expected adduct 2c was only formed in 18% yield. The main product (71%) was the isomeric coupling product 4, with a C–C bond to the central carbon atom of the trityl group (Scheme 4). The formation of 4 can be explained by the reduced steric demand of the mesityl wingtip groups.\(^24\)

### Conclusions

To conclude, we have investigated the formation of adducts between N-heterocyclic carbenes and the trityl cation, a mildly oxidizing Lewis acid.\(^23\) EPR spectroscopy, UV-vis analyses, and trapping experiments indicate that the reactions proceed via an initial SET step, giving highly reactive carbene radical cations and the trityl radical. The adducts are then formed by selective cross-coupling. So far, there is scarce experimental evidence for the involvement of radical processes in Lewis acid–base reactions, in particular for systems which form stable acid–base adducts.\(^5,6,10\) The results demonstrate that SET chemistry is a viable option for reactions of NHC Lewis bases with oxidizing Lewis acids. For the present study, we have focused on the trityl cation, but our findings should be considered for reactions of NHCs with oxidizing metal ions/complexes.\(^25\)

### Conflicts of interest

There are no conflicts to declare.

### Acknowledgements

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### References


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**Table 1** Reactions of NHCs 1 with [Ph3C][B(C6F5)4] in the presence of the radical scavengers THF and Ph3SnH

<table>
<thead>
<tr>
<th>Radical scavenger</th>
<th>Yield of 3a</th>
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<tbody>
<tr>
<td>1a (R = Dipp)</td>
<td>THF (25 vol%)</td>
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<tr>
<td>1a (R = Dipp)</td>
<td>Ph3SnH (2 equiv.)</td>
</tr>
<tr>
<td>1b (R = iPrBu)</td>
<td>THF (25 vol%)</td>
</tr>
<tr>
<td>1b (R = iPrBu)</td>
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</tr>
<tr>
<td>1c (R = Mes)</td>
<td>THF (25 vol%)</td>
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* Yields were determined by \(^1\text{H} NMR spectroscopy.*
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