Introduction

Over the past 25 years, the hydroamination of olefins, and in particular the intramolecular hydroamination/cyclization (IHC) of aminoolefins and aminoalkynes, has developed into a most prominent catalytic reaction in (organo)rare-earth metal chemistry.\(^1-5\) The IHC affords direct and atom-efficient access to natural products like alkaloids and other functionalized mono- and polyazacycles.\(^1-5\) The ground breaking discovery by Marks et al. in 1989 revealed that rare-earth metalloocene-based catalysts of the type \([\text{C}_2\text{Me}_3]_2\text{LnH}_2\) or \([\text{C}_2\text{Me}_3]_2\text{LnCH(SiMe}_3)_2\) convert 2,2-dimethyl-4-penten-1-amine (herein denoted as product \(\text{P1}\)) with the catalytic activity being metal-size-dependent (maximum turnover frequencies \(N_t\) for lanthanum: 125 and 95 h\(^{-1}\) (25 °C), respectively).\(^6\) Later on, catalyst design put main emphasis on chelating diamido- and diaryloxo ancillary ligands \(\text{L}^{2-}\) as well as on readily exchangeable monoanionic amido ligands \(\text{NR}_2\) (= actor ligand) targeting well-defined discrete complexes \(\text{LLn}^{m\text{H}}\text{NR}_2\).\(^4,7-13\) Many of these non-metallocene complexes have been accessed \textit{via} protonolysis reactions – often generated \textit{in situ} – using silylamide complexes \(\text{Ln}[\text{SiMe}_3]_2\) or \(\text{Ln}[\text{SiHMe}_2]_3\)(THF).\(^7,8\)

More recently, the implementation of chiral variants for asymmetric hydroamination has been demonstrated at elevated temperatures.\(^4,14\) \(\text{Ln}[\text{si}]\) precatalysts of the type \(\text{LLn}^{m\text{H}}\text{NR}_2\),\(^7,9\) \(\text{Ln}^{\text{mH}}\text{NR}_2\),\(^8,15\) and \(\text{Ln}^{\text{mH}}\text{NR}_2\) bearing two, three or four exchangeable monoanionic amido ligands \(\text{NR}_2\), respectively, did receive much less attention. Lack of a rigid stabilizing ancillary backbone, ligand redistribution, and multiple active sites have to be considered potential drawbacks. Nevertheless, the \(\text{C}_2\)-symmetric bis(oxazolinato) bis(amido) complex \(\text{[4R(5S)-Ph}_3\text{Box}\text{La}[\text{SiMe}_3]_2\text{]}\) exhibited good rates (e.g., \(\text{S1}: N_t = 25 \text{ h}^{-1}; 23 \text{ °C}\))\(^9\) and homoleptic \(\text{Y}[\text{SiMe}_3]_2\) was advertised as a commercially available comparatively inexpensive precatalyst (e.g., \(\text{S1}: N_t = 11.6 \text{ h}^{-1}; 25 \text{ °C}\)).\(^15\) Moreover, surface grafting of the latter homoleptic derivative on large-pore mesoporous silica afforded hybrid
Scheme 1  Protonolysis of the precatalyst as initiating step of the IHC catalytic cycle: scope of routinely employed actor ligands X and relevant examples of disisopropylamido complexes.

Results and discussion

IHC activity of bimetallic ate complexes LiLn[N(iPr)₂]₄ (THF)

Because of their easy accessibility for the entire rare-earth metal series, we examined in detail the performance of the bimetallic ate complexes LiLn[N(iPr)₂]₄(THF) (Ln = Sc (1a), Y (1b), La (1c)) in the hydroamination/cyclization of terminal aminokanes (Scheme 2).

1 It has been shown that LDA22 or treatment of lithiated aminoalkene with diisopropylamine (DPA) can efficiently catalyze IHC of non-activated olefins.
It has been previously shown that the substrates amino-2,2-dimethyl-4-pentene (S1), 1-amino-2,2-diphenyl-4-pentene (S2), and 1-amino-2,2-diphenyl-5-hexene (S3) give the cyclized products 2,4,4-trimethylpyrrolidine (P1), 2-methyl-1,4,4-diphenylpyrrolidine (P2), and 2-methyl-5,5-diphenylpyrrolidine (P3), respectively. The scope of substrates, products and well-defined catalysts under study are illustrated in Scheme 2.

The catalytic reactions have been monitored by $^1$H NMR spectroscopy using C$_6$D$_6$ as a solvent, and 2 or 4 mol% of precatalyst at 26 °C or 60 °C (Table 1). For phenyl-substituted aminoalkenes S2 and S3, the color of the reaction mixtures changed from colourless to yellow at the beginning of the catalytic transformations. The progress of ring closure was determined by the integral ratios of the $^1$H NMR specific peaks of the substrates and products relative to the signal of free HNPr$_2$.

Generally, complexes LiLn(N(iPr)$_2$)$_3$(THF) (Ln = Sc (1a), Y (1b), La (1c)) follow the prevailing rules for IHC observed for rare-earth-metal catalysts. Comparison of entries 1, 5, and 12 (Table 1) shows that the ring closing for the investigated aminoalkenes S1, S2, and S3 catalyzed by the same precatalyst proceeds according to the Thorpe-Ingold-effect. The rates of cyclization revealed the trends consistent with the Baldwin’s guidelines for ring closure, meaning that aminoalkene S1 is the least reactive, while S2 is easily converted. Furthermore, as previously observed the catalytic activity increased with increasing ionic radius of the rare-earth metal centre (e.g., Table 1, entries 1, 2, and 4). Quantitative conversion of aminoalkenes S2 and S3 with precatalysts 1b (Y; Table 1, entries 7 and 13) and 1c (La; Table 1, entry 10) was observed after 0.15 h at 60 °C with the highest $N_i = 164$ h$^{-1}$. Therefore, the cyclization of S2 was additionally monitored at 26 °C. La-catalyst 1c with the largest rare-earth metal centre is the most efficient displaying 99% conversion after 0.6 h at 26 °C (Table 1, entry 11), followed by Y-catalyst 1b (Table 1, entry 9) with 88% conversion after 1.5 h. After ca. 5 h, the respective Sc-catalyst 1a had converted only 26% of S2 (Table 1, entry 6). This latter effect of the rare-earth metal onto the IHC of aminoalkene S2 is depicted in Fig. 1. The experimental conversion/time data plots for all three aminoalkenes and LiY(NiPr)$_3$(THF) (1b) as the precatalyst are shown in Fig. 2. Significant transformation of substrate S1 occurred only at 60 °C. Surprisingly, La complex 1c did not convert aminoalkene S3 as efficiently as anticipated and the reactions seemed not completed even after several days (Table 1, entries 17 and 18). Careful analysis of the $^1$H NMR spectroscopic data, however, revealed the co-formation of isomerized byproduct 1-amino-2,2-diphenyl-4-hexene (P4, Fig. 3). The formation of P4 started parallel to that of the main cyclized product P3 and reached ca. 20% conversion (relative to the concentration of the substrate), independent of the reaction temperature (60 °C or 26 °C). The experimental conversion/time data plots using 4 mol% LiLa(N(iPr)$_2$)$_3$(THF) (1c; Table 1, entry 17) are shown in Fig. 4, corroborating that the competitive isomerization reaction for S3 slowed down markedly the formation of the major cyclized product P3. Such concomitant aminoalkene isomerizations were observed previously in IHC reactions employing alkali metal bases such as NaK alloy or n-BuLi, and alkaline-earth metal complexes. While the use of NaK gave the isomerized aminoalkene as the major product, treatment of amino-2,2-dimethyl-4-pentene

<table>
<thead>
<tr>
<th>Entry</th>
<th>Aminoalkene</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S1</td>
<td>1a [Sc]</td>
</tr>
<tr>
<td>2</td>
<td>S1</td>
<td>1b [Y]</td>
</tr>
<tr>
<td>3</td>
<td>S1</td>
<td>1c [La]</td>
</tr>
<tr>
<td>4</td>
<td>S1</td>
<td>1a [Sc]</td>
</tr>
<tr>
<td>5</td>
<td>S2</td>
<td>1b [Y]</td>
</tr>
<tr>
<td>6</td>
<td>S2</td>
<td>1a [Sc]</td>
</tr>
<tr>
<td>7</td>
<td>S2</td>
<td>1b [Y]</td>
</tr>
<tr>
<td>8</td>
<td>S2</td>
<td>1c [La]</td>
</tr>
<tr>
<td>9</td>
<td>S3</td>
<td>1b [Y]</td>
</tr>
<tr>
<td>10</td>
<td>S3</td>
<td>1a [Sc]</td>
</tr>
<tr>
<td>11</td>
<td>S3</td>
<td>1c [La]</td>
</tr>
</tbody>
</table>

*4 mol% 1 in C$_6$D$_6$. All conversion data were derived from $^1$H NMR spectra referring to the corresponding duration of reaction. Initial $N_i$ versus overall $N_i$ (taken at 80% conversion, unless otherwise stated). $^2$2 mol% 1b in C$_6$D$_6$. $^3$Ratio cyclized product P3: isomerized aminoalkene P4 $\approx$ 4 : 1. $^4$Conversion completed after <9 min. $^5$At 99% conversion. $^6$Initial $N_i = N_i$ at 80%. $^7$N_i at time t given in this table.
with n-butyllithium in THF led to cyclization. Later, Markó et al. treated 1-amino-4-pentene with 16 mol% n-BuLi which led to the cyclization product, but the isomerized alkene formed to different extents. A detailed investigation and discussion of the formation of isomerized aminoalkene in the course of IHC was performed by Hill et al. for the cyclization of 1-amino-2,2-dimethyl-5-hexene and 1-amino-2,2-diphenyl-5-hexene \((S_3)\) in the presence of the \(\beta\)-diketiminate-supported calcium complex \([\text{ArNC(Me)CHC(Me)NAr}]\text{Ca}[\text{N(SiMe}_3\text{)}_2]\text{(THF)}\). For the \(S_3\)-reaction, the ca. 10% yield of the isomerized byproduct (which was not observed for the magnesium precatalyst \([\text{ArNC(Me)CHC(Me)NAr}]\text{MgMe(THF)}\)) were ascribed to stereoelectronic effects: formation of a boat-like six-membered ring transition state might lead to an allyl species via intramolecular proton transfer and subsequently to the isomerized product \(P_4\) (or regenerated \(S_3\)) via protonolysis. To the best of our knowledge such competitive isomerization/IHC reactions have not been observed yet for rare-earth metal catalysts. Any competing effect of the lithium cation might be ruled out on the basis of a VT NMR study since the Li(THF)\(^+\) fragment shows approximately the same mobility in the respective yttrium (1b) and lanthanum complexes (1c). As in the case of the aforementioned Mg/Ca transformations, the occurrence of the isomerization reaction in the presence of LiLa(N\(\text{NiPr}_2\))\(_4\text{(THF)}\) (1c) can be rationalized on the basis of the large size of La(\(\text{III}\)). In this sense the scandium (1a) and yttrium (1b) catalysts did not yield any detectable amount of \(P_4\). Similar to the study by Hill et al. the isomerized byproduct does not undergo subsequent cyclization. Overall, the distinct reactivity of 1c toward \(S_3\), which is comparable to that of \([\text{ArNC(Me)CHC(Me)NAr}]\text{Ca}[\text{N(SiMe}_3\text{)}_2]\text{(THF)}\) seems to originate from similarities of the calcium(\(\text{II}\)) and lanthanum(\(\text{III}\)) cations e.g., Lewis acidity and comparable size of the effective ionic radii (Ca\(^{2+}\) 1.00–1.34 Å and La\(^{3+}\) 1.03–1.36 Å, depending on the coordination number). Precatalyst 1c did not promote the isomerization of aminoalkene S1 and S2.

**IHC catalytic activity of LDA**

Early research on the generation of carbon–nitrogen bonds involved the alkali metal-catalyzed amination of olefins in
The Li/Y diisopropylamide catalyst system

The IHC activity of complex LiY[NiPr2]4(THF) (1b) was further elaborated at a concentration of 2 mol% (cf., Table 1).

1957\(^{40}\) and 1985.\(^{41}\) The application of LDA supported by irradiation (150 W tungsten bulb) was described by Trost et al. as a viable protocol in alkaloid synthesis.\(^{42}\) Moreover, Markó et al. reported on the addition of diisopropylamine to the lithiated substrate 1-amino-4-pentene or treatment with either catalytic quantities or with 1 equiv. of LDA to afford the cyclized product 2-methylpyrrolidine.\(^{24}\) Furthermore, mixtures of n-BuLi/HN(SiMe3)\(_2\) and Li[N(SiMe3)\(_2\)]\(_2\)/TMEDA\(^{44}\) as well as a chiral lithium amides\(^{45}\) were successfully utilized in base-catalyzed IHC reactions. In order to exclude any significant effect of LDA, the separation of which might occur in ate complex (1)/substrate (S) reaction mixtures, we probed the IHC catalytic activity of LDA for the aminoalkenes under study.

Putative cyclization of S2, which benefits most from the Thorpe-Ingold effect, did not occur in the presence of 4 mol% LDA even after 96 h at 60 °C (Table 2, entry 1). The formation of a significant amount of cyclized product P2 (ca. 18%) could be observed after 5 h, using 12 mol% LDA at 26 °C (Table 2, entry 2). Further increase of both the reaction temperature (60 °C) and concentration of LDA (21 mol%) led to full conversion of substrate S2 after 4 h (Table 2, entry 3).

As mentioned in the introduction, the only known rare-earth metal ate complexes, which have been investigated in detail for the catalytic IHC, are bimetallic lanthanide-binaphthylamide complexes of the A and B-type (Chart 1).\(^{27–29,46,47}\) While addition of LiCl to [(R)-C\(_2\)H\(_3\)]\(_2\)N(R)\(_2\) Y(CH\(_3\))SiMe\(_3\)](THF)\(_2\) and [(R)-C\(_2\)H\(_3\)]\(_2\)N(R)\(_2\)](Y[NiPr\(_2\)](THF))\(_2\) (R = c-C\(_5\)H\(_9\), SiMe\(_3\), SiMe\(_2\)Bu) mainly produced higher enantioselectivities,\(^{29}\) lithium-ate complexes [Li(THF)]\(_3\)Ln[(R)-C\(_2\)H\(_3\)]\(_2\)N(R)\(_2\)]\(_2\) displayed higher catalytic activity than the potassium analogues [K(THF)]\(_3\)Ln[(R)-C\(_2\)H\(_3\)]\(_2\)N(R)\(_2\)]\(_2\) (Ln = Y, Yb; R = c-C\(_5\)H\(_9\), CH\(_2\)Bu).\(^{28}\) It is noteworthy that such bimetallic rare-earth metal binaphthylamide complexes were employed to some extent generated in situ\(^{48}\) and required higher concentrations of the catalysts and longer reaction times\(^{28}\) compared to our ate complexes LiLn[NiPr\(_2\)](THF). Diethylamide ate complexes of type C (Chart 1) were described as efficient catalysts for asymmetric IHC reactions.\(^{12a}\)

**Table 2** IHC of aminoalkene S2 and S3 promoted by LDA at variable concentrations and temperatures in C\(_6\)D\(_6\).

<table>
<thead>
<tr>
<th>Entry</th>
<th>Aminoalkene</th>
<th>Product</th>
<th>Conc./mol%</th>
<th>T/°C</th>
<th>t/h</th>
<th>Conv./%(^a)</th>
<th>(N_i) (\hbar/h)(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S2</td>
<td>P2</td>
<td>4</td>
<td>60</td>
<td>96</td>
<td>&lt;1</td>
<td>&lt;1(^c)</td>
</tr>
<tr>
<td>2</td>
<td>S2</td>
<td>P2</td>
<td>12</td>
<td>26</td>
<td>4.84</td>
<td>18</td>
<td>1.9/0.3(^c)</td>
</tr>
<tr>
<td>3</td>
<td>S3</td>
<td>P3</td>
<td>21</td>
<td>60</td>
<td>96</td>
<td>43</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>4</td>
<td>S3</td>
<td>P3</td>
<td>4</td>
<td>26</td>
<td>4.84</td>
<td>&lt;1</td>
<td>&lt;1(^c)</td>
</tr>
</tbody>
</table>

\(^a\) All conversion data were derived from \(^1\)H NMR spectra referring to the corresponding duration of reaction. \(^b\) Initial \(N_i\) versus overall \(N_i\) (taken at 80% conversion, unless otherwise stated). \(^c\) \(N_i\) at time \(t\) given in this table.

Compared to the 4 mol%-reaction, which gave 24% conversion of S1 after 4.84 h at 60 °C (Table 1, entry 2), use of half of the amount of 1b did not produce any detectable P1 even after 9.7 h (Table 1, entry 3). In contrast, under the same conditions 98% of aminoalkene S2 were converted after 0.6 h (Table 1, entry 8) and, similarly, aminoalkene S3 could be cyclized after 0.9 h (Table 1, entry 14). At 26 °C, cyclization of S3 in the presence of 2 mol% 1b was noted at 36% after 4.84 h (Table 1, entry 16). These results underline the high catalytic activity of the investigated amide complexes, the impact of the Thorpe-Ingold effect, as well as the different rates of the formation of five- and six-membered rings. The experimental conversion/time data plots for the IHC of aminoalkenes S2 and S3 using 2 mol% 1b as the precatalyst are depicted in Fig. 5.

In our preceding work on rare-earth metal diisopropylamide complexes, the diversity of molecular compositions, solution behaviours and solid-state structures depending on the ratio MNiPr\(_2\)/LnCl\(_3\) (M = Li, Na) and presence of donor solvent was emphasized.\(^{21}\) In the following experiments we assessed the catalytic performance of (a) [Li(NiPr\(_2\))]\(_2\) (2), that is, in the absence of donor solvent THF (Table 3, entry 3), (b) in situ generated bimetallic catalysts using LiNiPr\(_2\)/LnCl\(_3\) ratios of 4 (aiming at 1b; Table 3, entry 4) and 2.5 (aiming at Y[NiPr\(_2\)](THF))\(_2\); Table 3, entry 5), (c) in situ generated...
Li[N(SiHMe₂)₂]₄(THF) (from YCl₃(THF)₃.₃ + 4 LiN(SiHMe₂)₂) (Table 3, entry 6), and (d) crystalline NaY(NiPr₂)₄(THF) (3b) to probe any alkali metal effect, compared to pure crystalline complex 1b (Table 1, entry 9 and LDA (Table 2, entry 2). (a) Indeed, the THF-free polymeric complex [LiY(NiPr₂)₄]ₙ (2), which is soluble in aliphatics and aromatics, revealed the highest catalytic activity of all isopropylamide complexes under study (Fig. 6). Using 4 mol% of 2 the conversion of S₂ was completed after 1.1 h even at ambient temperature (Table 3, entry 3 and Fig. 6). The superior reactivity of 2 compared to the THF-coordinate congener 1b (Table 1, entry 9 and Fig. 6) can be rationalized on the basis of their distinct dynamic behaviours in solution as revealed by VT NMR spectroscopic studies, suggesting distinct Li–N bonding in 2. This might affect the initial protonolysis reaction (NiPr₂/substrate exchange, Scheme 1). Moreover, upon elimination of a bulky NiPr₂ ligand the Lewis base THF present in 1b could switch from Li to Y coordination and thus compete with any vacant coordination site of the catalyst, the availability of which is essential for the subsequent insertion/cyclization step of the catalytic cycle. The IHC reaction of S₂ catalyzed by 2 was repeated under the same conditions using 5.09 µmol of tetrakis(p-tolyl)silane as an internal standard revealing the same conversion and NMR yield >99% after 1.1 h (initial Nᵢ = 62.4 h⁻¹ and overall Nᵢ = 45.92 h⁻¹ at 80% conversion (Fig. S2†)). The negative effect of THF on IHC reactions was early observed by Marks et al.⁶ (b) More interestingly, isolation and crystallization of complexes 1b or 2 seem not be a prerequisite for efficiently catalyzing the IHC reaction. Although crystalline complex 1b afforded 78% conversion of S₂ after 0.5 h, the reaction decelerated drastically afterwards (Table 1, entry 9 and Fig. 6). The corresponding reaction employing the respective in situ generated catalyst, preformed from YCl₃(THF)₃.₃ and 4 equivalents of LiNiPr₂ in C₆D₆ (preformation time 5 min), was at the beginning slower, but afforded 97% conversion of the substrate already after 1 h (Table 3, entry 4 and Fig. 6). It is noteworthy that for both reactions ca. 80% cyclization was accomplished.

Table 3 IHC of aminoalkene S₂ catalyzed by various amide complexes in C₆D₆ at 26 °C

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst</th>
<th>Conc./mol%</th>
<th>t/h</th>
<th>Conv./%</th>
<th>Nᵢ⁻¹/h⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1⁴</td>
<td>Li[NiPr₂]₄(THF) (1b)</td>
<td>4</td>
<td>1.5</td>
<td>&gt;88</td>
<td>67.3/34.1</td>
</tr>
<tr>
<td>2⁵</td>
<td>LDA</td>
<td>12</td>
<td>4.84</td>
<td>100</td>
<td>4.1/0.3⁶</td>
</tr>
<tr>
<td>3/⁶</td>
<td>[LiY(NiPr₂)₄]ₙ (2)</td>
<td>4</td>
<td>1.1</td>
<td>&gt;99</td>
<td>60.5/45.8⁶</td>
</tr>
<tr>
<td>4</td>
<td>In situ 1b (YCl₃(THF)₃.₃ + 4 LDA)</td>
<td>4</td>
<td>1.7</td>
<td>&gt;99</td>
<td>30.6/28.7⁶</td>
</tr>
<tr>
<td>5</td>
<td>In situ Y[NiPr₂]₄(THF)₂ [YCl₃(THF)₃.₃ + 2.5 LDA]</td>
<td>4</td>
<td>4.84</td>
<td>100</td>
<td>0.2⁶</td>
</tr>
<tr>
<td>6</td>
<td>In situ Y[Ni(SiHMe₂)₂]₄(THF) [YCl₃(THF)₃.₃ + 4 LiN(SiHMe₂)₂]</td>
<td>4</td>
<td>392</td>
<td>100</td>
<td>&lt;0.1⁶</td>
</tr>
<tr>
<td>7</td>
<td>Sc[NiPr₂]₄(THF) (4)</td>
<td>4</td>
<td>4.84</td>
<td>100</td>
<td>4.5/0.9⁶</td>
</tr>
<tr>
<td>8</td>
<td>Ce[NiPr₂]₄ (5)</td>
<td>4</td>
<td>2.0</td>
<td>100</td>
<td>17.7/5.6⁶</td>
</tr>
</tbody>
</table>

All conversion data were derived from ¹H NMR spectra referring to the corresponding duration of reaction. Initial Nᵢ versus overall Nᵢ (taken at 80% conversion, unless otherwise stated). cf. Table 1, entry 9. cf. Table 2, entry 2. *Nᵢ at time t given in this table. †The presence of 10 equivalents of HNiPr₂ did not affect the catalytic transformation.
after 0.75 h (see Fig. 6). In contrast, in situ generated Y(NiPr3)2(THF), obtained from YCl3(THF)3, and 2.5 equivalents of LiNiPr2 in C6D6 exhibited only minor catalytic activity (Table 2, entry 5 and Fig. 6). Applying 4 mol% of the catalyst, only 4% conversion of S2 was detected after 3 h followed by a stagnation of the IHC reaction. As importantly for assessing the role of LDA is the fact that pure LDA promotes the IHC of substrate S2 not until a concentration of 12 mol% (Table 2). Moreover, crystallized mixed NiPr2/Cl complexes such as choro-bridged [Ln(NiPr3)2(µ-Cl)(THF)]2 achieved generally lower IHC catalytic activity for aminoalkane S2. For example, [Sc(NiPr3)2(µ-Cl)(THF)]2 converted 31% of the substrate after 48 h (not displayed in Table 3), accounting for a smaller catalytic efficiency per metal centre, compared to catalysts 1a and 4 (vide supra).

(c) Yttrium complexes featuring the less basic but similarly sized bis(dimethylsilyl)amido ligand have been employed previously for catalytic IHC reactions. For direct comparison, {Li[Ni(SiHMe2)2]4(THF)}59 was generated in situ from YCl3(THF)3, and four equivalents of Li[Ni(SiHMe2)2] in C6D6 (preformation time 5 minutes) (Table 3, entry 6). Not unexpectedly, cyclization of S2 proceeded very slowly at ambient temperature, affording 34% conversion after 8 d and 47% after another 4 d.

(d) Having synthesized the sodium congeners NaLn(NiPr3)2(THF) (Ln = Sc (3a), Y (3b)) as well,24 we were also interested in elucidating the effect of the alkali metal ion on the IHC reactions (Table S1†). We found that the Y–Na catalyst 3b exhibits markedly lower activity than the Y–Li catalyst 1b, converting 37% of S2 after a reaction time of 3 h at 60 °C and achieving full conversion only after 24 h (Table S1, entry 2) (1b: complete conversion after 9 minutes) (Table 1, entry 7). The decreased catalytic activity of the Y–Na derivative 3b was further supported by the outcome of the cyclization of substrate S3 (Table S1†), which gave 15% and complete cyclization after 3 h and 48 h at 60 °C, respectively (Table S1, entry 4), 1b: complete conversion after 9 minutes (Table 1, entry 13). The decreased reactivity of the sodium ate complexes might originate from their changed dynamic behaviour in solution and decreased thermal stability. AVIT NMR spectroscopic study revealed that complex 3b is highly fluxional even at ca. –70 °C (1b: above ca. 0 °C), which was attributed to a weaker (ionic) bonding of the Na(THF) fragment with the amido ligands compared to the Li(THF) fragment.21 The comparatively weaker bonding of the Na(THF) fragment might exert a destabilizing effect on the LnNiPr34- counterion as revealed by accelerated decomposition (formation of HNPNiPr2; see also ref. 28: Li† versus K†). As observed for complexes Li[NiPr3]4(THF) (1), the Sc–Na derivative 3a was far less active than the Y–Na complex 3b. Complex 3a converted only traces of the substrates S2 and S3 after 24 h reaction time and reached full conversion after 3 and 12 d, respectively (Table S1, entries 1 and 3). Although the catalytic role and influence of the alkali metals in such bimetallic complexes is not clarified until now, their presence and type clearly affects the catalytic performance of amide complexes. Similar observations were made by Schulz et al. when probing bimetallic rare-earth metal binaphthylamide complexes of the type [M(THF)4]Ln[(R)-C20H12(NR)2]2 (M = Li, K) as catalysts for IHC.28

IHC catalytic activity of complexes Sc(NiPr3)2(THF) (4) and Ce(NiPr3)4 (5)

Crystalline alkali-metal free tris(amido) complex Sc(NiPr3)2(THF) (4) can be readily obtained.21 Although it is routinely observed that scandium catalysts are less active than their yttrium counterparts, complex 4 had converted 18% of S2 after 5 h (Table 3, entry 7) thus kind of outperforming in situ formed Y(NiPr3)2(THF), which cyclicized 4% during the same time period (Table 3, entry 5). The inefficiency of the latter yttrium-reaction, however, might be also a result of the in situ protocol applied for the synthesis of Y(NiPr3)2(THF),56 allowing a preformation time of 5 min only. Matching the present results, complex 4 is significantly less active than lithium ate complex LiSc(NiPr3)4(THF) (1a) (Table 1, entry 6). Next, we initially probed the IHC catalytic activity of the alkali-metal-free homoleptic tetravalent complex Ce(NiPr3)4 (5).21 Like complexes LiLn(NiPr3)4(THF) (1), the cerium complex 5 adopts a tetrahedral coordination geometry, but features a more Lewis-acide rare-earth metal center and shorter Ln–N(amido) bonds as a consequence of the tetravalent oxidation state. Generally, there exist only a few reports on molecular organo-Ce(IV) catalysis.52 Complex 5 achieved 44% conversion of substrate S2 after 2 h, displaying an Nt = 5.6 h–1 (Table 3, entry 8). By then the color of the reaction mixture changed from blue to brown and the cyclization came to an halt, probably due to decomposition of the catalyst.

IHC catalytic activity of rare-earth metal diisopropylamide complexes compared to bis(trimethylsilyl)amides Ln[N(SiMe3)2]4

The final part of this study compares the catalytic activities of the investigated rare-earth metal diisopropylamide complexes with those of the ubiquitous rare-earth metal bis(trimethylsilyl)amides Ln[N(SiMe3)2]4 (Ln = Sc (6a), Y (6b), and La (6c)). Complexes 6 were previously found to efficiently catalyze the IHC of aminoolfinens and aminoalkynes.6,15 For direct comparison the reactions with precatalysts 6, which were sublimed prior to use, were carried out using exactly the same conditions as for LiLn(NiPr3)4(THF) (Ln = Sc (1a), Y (1b), and La (1c)) described above. The obtained results as listed in Table 4 are compared in the following with entries 1, 2, 4, 5, 7, 10, 12, 13, and 17 of Table 1. The majority of the reactions revealed that the rare-earth metal bis(trimethylsilyl)amide complexes 6 exhibit overall higher cyclization rates independent of the substrate. In the case of substrate S3, an activity increase from 6a (Sc) to La (6c) could be observed as expected (Table 4, entries 7–9) but 6a afforded almost the same Nt as scandium ate complex 1a (Table 1, entry 12). It also occurred for S3, that the yttrium diisopropylamide complex outperformed the silyl-amide one (1b: Nt = 164 h–1 (Table 1, entry 13); 6b: Nt = 13.9 h–1 (Table 4, entry 8)). Moreover, the competitive isomerization reaction of S3 to give P4 (Fig. 3 and 4) detected for LiLa(NiPr3)4(THF) (1c) could not be observed for La[N(SiMe3)2]4.
Easily available rare-earth metal diisopropylamide complexes LiLn(\textit{N}(\textit{SiMe}_{3})_{2})_{3}(\textit{THF}) (\textit{Ln} = \textit{Y}, \textit{La})\textsuperscript{44} display high catalytic activity for regio-selective intramolecular hydroamination/cyclization reactions of terminal aminoalkenes depending on the substrate and the rare-earth metal centre at mild temperatures and low catalyst concentrations. The catalysts can be conveniently obtained in situ combining YCl\textsubscript{3}(\textit{THF})\textsubscript{3},\textit{3} and four equivalents of LiN\textit{P}_{\textit{r}}\textsubscript{2} (LDA), briefly before addition of aminoalkene. Although the largest rare-earth metal centre exhibits the highest IHC activity, it is prone to side reactions as shown for a competitive isomerization reaction in case of 1-amino-2,2-diphenyl-5-hexene (formation of 1-amino-2,2-diphenyl-4-hexene versus the 6-membered heterocycle 2-methyl-4,4-diphenylpiperidine). The occurrence of such isomerization reactions in tandem with hydroamination was previously reported for alkali and alkaline-earth metal-promoted catalysis but not in the case of rare-earth metal catalysis. Moreover, the present diisopropylamide case study clearly revealed the effect of donor solvent (THF), halo co-ligands and alkali metals on the catalytic performance of the rare-earth metal complex. It is shown that the presence of THF slows down drastically substrate conversion \((\text{LiLn(\textit{N}(\textit{Pr})_{2})_{3}(\textit{THF}) versus \text{LiLn(N(Pri)})_{2}\text{THF})})\), most likely by competing with substrate coordination/cyclization at the catalytically active centre. Similarly, the presence of highly mobile AM(THF)\textsuperscript{+} fragments decelerates the conversion rates \((\text{AM = alkali metal; LiLn(\textit{N}(\textit{Pr})_{2})_{3}(\textit{THF}) \Rightarrow \text{NaLn(N(Pr)})_{2}(\textit{THF}))}). The presence of chelating ligands seems to counteract an efficient catalytic process as well shown for heteroleptic complex \([\text{Sc(N(Pr)}_{2})_{3}(\mu-\text{Cl})(\text{THF})])\). Compared to the ubiquitous rare-earth metal bis\text{(trimethylsilyl)amides} \text{Ln}(\textit{N}(\textit{SiMe}_{3})_{2})_{3} (\textit{Ln} = \textit{Sc, Y}, \textit{La}), which require sublimation prior to use, the investigated rare-earth metal diisopropylamide complexes show significantly lower catalytic activity. Exceptionally, 4-coordinate complex LiY(\textit{N}(\textit{Pr})_{2})_{3}(\textit{THF}) outperformed three-coordinate \text{Ln}(\textit{N}(\textit{SiMe}_{3})_{2})_{3} for the IHC of 1-amino-2,2-diphenyl-5-pentene. We assume that the enhanced steric saturation of the rare earth-metal centre in ate complexes AMLn(\textit{N}(\textit{Pr})_{2})_{3}(\textit{THF}), and enhanced thermal instability compared to \text{Ln}(\textit{N}(\textit{SiMe}_{3})_{2})_{3} overcompensate the comparatively higher reactivity of the Ln–N\textit{P}_{\textit{r}} bond \((\text{versus} \text{Ln–N(\textit{SiMe}_{3})}_{2})\). Nevertheless, ate complexes AMLn(\textit{N}(\textit{Pr})_{2})_{3}(\textit{THF}) display an overall higher IHC efficiency than the previously reported rare-earth metal diamidobinaphthyl ate complexes.\textsuperscript{27–29,47,48} Finally, our preliminary observations that tetravalent cerium complex Ce(\textit{N}(\textit{Pr})_{2})_{3} revealed higher conversion rates than Sc(\textit{N}(\textit{Pr})_{2})_{3}(\textit{THF}) might significantly broaden the scope of cerium(iv) catalysis.

### Conclusions

Easily available rare-earth metal diisopropylamide complexes LiLn(\textit{N}(\textit{Pr})_{2})_{3}(\textit{THF}) (\textit{Ln} = Y, La)\textsuperscript{44} display high catalytic activity for regio-selective intramolecular hydroamination/cyclization reactions of terminal aminoalkenes depending on the substrate and the rare-earth metal centre at mild temperatures and low catalyst concentrations. The catalysts can be conveniently obtained in situ combining YCl\textsubscript{3}(\textit{THF})\textsubscript{3},\textit{3} and four equivalents of LiN\textit{P}_{\textit{r}}\textsubscript{2} (LDA), briefly before addition of aminoalkene. Although the largest rare-earth metal centre exhibits the highest IHC activity, it is prone to side reactions as shown for a competitive isomerization reaction in case of 1-amino-2,2-diphenyl-5-hexene (formation of 1-amino-2,2-diphenyl-4-hexene versus the 6-membered heterocycle 2-methyl-4,4-diphenylpiperidine). The occurrence of such isomerization reactions in tandem with hydroamination was previously reported for alkali and alkaline-earth metal-promoted catalysis but not in the case of rare-earth metal catalysis. Moreover, the present diisopropylamide case study clearly revealed the effect of donor solvent (THF), halo co-ligands and alkali metals on the catalytic performance of the rare-earth metal complex. It is shown that the presence of THF slows down drastically substrate conversion \((\text{LiLn(\textit{N}(\textit{Pr})_{2})_{3}(\textit{THF}) versus \text{LiLn(N(Pri)})_{2}\text{THF})})\), most likely by competing with substrate coordination/cyclization at the catalytically active centre. Similarly, the presence of highly mobile AM(THF)\textsuperscript{+} fragments decelerates the conversion rates \((\text{AM = alkali metal; LiLn(\textit{N}(\textit{Pr})_{2})_{3}(\textit{THF}) \Rightarrow \text{NaLn(N(Pr)})_{2}(\textit{THF}))}). The presence of chelating ligands seems to counteract an efficient catalytic process as well shown for heteroleptic complex \([\text{Sc(N(Pr)}_{2})_{3}(\mu-\text{Cl})(\text{THF})])\). Compared to the ubiquitous rare-earth metal bis\text{(trimethylsilyl)amides} \text{Ln}(\textit{N}(\textit{SiMe}_{3})_{2})_{3} (\textit{Ln} = \textit{Sc, Y}, \textit{La}), which require sublimation prior to use, the investigated rare-earth metal diisopropylamide complexes show significantly lower catalytic activity. Exceptionally, 4-coordinate complex LiY(\textit{N}(\textit{Pr})_{2})_{3}(\textit{THF}) outperformed three-coordinate \text{Ln}(\textit{N}(\textit{SiMe}_{3})_{2})_{3} for the IHC of 1-amino-2,2-diphenyl-5-pentene. We assume that the enhanced steric saturation of the rare earth-metal centre in ate complexes AMLn(\textit{N}(\textit{Pr})_{2})_{3}(\textit{THF}), and enhanced thermal instability compared to \text{Ln}(\textit{N}(\textit{SiMe}_{3})_{2})_{3} overcompensate the comparatively higher reactivity of the Ln–N\textit{P}_{\textit{r}} bond \((\text{versus} \text{Ln–N(\textit{SiMe}_{3})}_{2})\). Nevertheless, ate complexes AMLn(\textit{N}(\textit{Pr})_{2})_{3}(\textit{THF}) display an overall higher IHC efficiency than the previously reported rare-earth metal diamidobinaphthyl ate complexes.\textsuperscript{27–29,47,48} Finally, our preliminary observations that tetravalent cerium complex Ce(\textit{N}(\textit{Pr})_{2})_{3} revealed higher conversion rates than Sc(\textit{N}(\textit{Pr})_{2})_{3}(\textit{THF}) might significantly broaden the scope of cerium(iv) catalysis.

### Experimental section

#### General considerations

All operations were performed with rigorous exclusion of air and moisture, using standard Schlenk, high-vacuum, and glovebox...
techniques (MB Braun MB150B-G; <1 ppm O₂, <1 ppm H₂O). n-Hexane, n-pentane, and THF were purified by using Grubbs columns (MBraun SPS, Solvent Purification System) and stored in a glovebox. n-Butyllithium (2.5 M in n-hexane) and disopropylamine (99.95%), isobutyronitrile (99.6%), allyl bromide (99%), lithium aluminium hydride (95%), 4-bromo-1-butene (97%), and tetraakis(p-tolyl)silane (99%) were obtained from Sigma-Aldrich, diphenylacetonitrile (99%) was obtained from ABCR. Benzene-d₆ (99.6%) was received from Sigma Aldrich, dried over NaK alloy for a minimum of 48 h, and filtered twice through a filter pipette (Whatman) before use. Chloroform-d was obtained from Eurisotop and used as received. Complexes Ce(N(SiMe₃)₂)₃ (Ce = La (4), Ln = Sc (5), Gd (6)), NaLn(N(SiMe₃)₂)₃ (Ln = Sc (6a), Y (6b), La (6b)), and Sc(N(SiMe₃)₂)₃(NH₃) (7) were sublimed twice prior to use. NMR spectra were recorded by using J. Young valve NMR tubes and 0.4 mL benzene-

Representative IHC procedure

In a glovebox, the desired amount of precatalyst or precursor mixture of the in situ generated catalyst was introduced in a J. Young NMR tube and 0.4 mL benzene-d₆ was added. The mixture was frozen at −35 °C and a solution of the aminoalkene (0.28 mmol) in 0.3 mL benzene-d₆ was injected onto the solid mixture (\( = e_0 \)). The tube was sealed and frozen again. Then, the tube was removed from the glovebox, loaded immediately into the spectrometer and the progress of the reaction monitored by \(^1\)H NMR spectroscopy at the desired temperature (26 °C or 60 °C). The kinetics for rare-earth metal diisopropylamido complexes 1–5 and Ln[N(SiMe₃)₂]₃ (6) as catalysts were measured by integrating the intrinsic signals of the educt (H₂C=CH₂) and product (H₂), respectively. The signals of hexamethyldisilazane or diisopropylamine which were formed by protonolysis of the appropriate precatalysts at the beginning of the reactions and stayed unchanged during the catalytic runs were chosen as internal standards. The cyclized amines P₁, P₂ and P₃ as well as the isomerized aminoalkene P₄ were identified by \(^1\)H NMR spectroscopy (NMR resonances included in the ESI), the chemical shifts compares to those described in literature.³⁶,⁵⁷

Acknowledgements

We thank the German Science Foundation (Grant AN 238/16-1) for funding and D. Schneider for a sample of Ce(N(SiMe₃)₂)₃.

Notes and references


This journal is © The Royal Society of Chemistry 2016


