Redox activity of a dissymmetric ligand bridging divalent ytterbium and reactive nickel fragments†

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The reaction of a reactive nickel dimethyl 1 bearing a redox-active, dissymmetric ligand, which is obtained by deprotonation of 2-pyrimidin-2-yl-1H-benzimidazole (Hbimpm) with a divalent lanthanide complex, Cp*₂Yb(OEt₂), affords an unprecedented, trimeric 2 with C(sp³)–C(sp³) bond formation between two ligands in an exo position. Meanwhile, the transient, dimeric species 3 can be isolated with the same ligand coupling fashion, however, with a drastic distorsion angle of the bimpm ligand and reactive NiMe₂ fragment, revealing the possible mechanism of this rearrangement. A much more stable dimeric complex, 5, with an exo ligand coupling, is synthesized in the presence of 18-crown-6, which captures the potassium counter ion. The C–C coupling formation between two bimpm ligands results from the effective electron transfer from divalent lanthanide fragments. Without the divalent lanthanide, the reductive coupling occurs on a different carbon of the ligand, nicely showing the modulation of the spin density induced by the presence of the lanthanide ion. The electronic structures of these complexes are investigated by magnetic study (SQUID), indicating a 2F₁/₂ ground state for each ytterbium in all the heterometallics. This work firstly reports ligand coupling reactivity in a redox-active, yet dissymmetric system with divalent organolanthanides, and the reactive nickel moiety can impact the intriguing transition towards a stable homoleptic, trinulear lanthanide species.

Introduction

Electron transfer behaviour in organometallic complexes has been well documented over decades. In these complexes, when the electron is accessibly transferred to an empty ligand orbital while the metal centre remains stable, the ligand is regarded as redox-active. Generally, N-heterocyclic ligands are excellent candidates as redox-active ligands because of their large delocalization extent added to a low-lying π*-system. In redox-active ligand–metal systems, the electron(s) (or hole(s)) can be stored on the ligand, therefore affecting the ground spin state of the complex and ultimately leading to unusual chemical transformation(s) at the metal site, but also at the ligand site. For the latter situation, a cooperative effect of the ligand is invoked and can develop with or without a redox event.

In the extensive studies of complexes with redox active ligands, divalent organolanthanides are of specific interest because of the formation of strongly correlated systems. In the latter, an important question is the role of the symmetry orbitals and the geometry of the ligand in the electronic structure and the subsequent reactivity of the overall complex. For instance, the electronic configurations of decamethyl-ytterbocenes with 2,2'-bipyridine (bpy) and phenanthroline (phen) are drastically different: Cp*₂Yb(bpy) has multiconfigurational singlet ground states, in which Yb is intermediate valent, composed of an open-shell (f¹³, bpy⁻⁻) and a closed-shell (f¹⁴, bpy⁰) state and is stable in solution; while Cp*₂Yb (phen) is a ground state triplet (f¹³, phen⁻⁻), which dimerizes reversibly to form a C–C σ bond at the 4,4'-positions on the phen ligands. This reversible coupling has been also been observed with Sm and Tm analogues and other low-valent metal ions. The chemical correlation between the ligand design and the reactivity of the complex provides a strategic framework for the usage of this type of complex in further reactivity. Our group has recently taken advantage of this work to develop the synthesis of a series of complexes combining a divalent lanthanide (Ln) fragment with a transition metal (TM) fragment bridged by N-heterocyclic aromatics. However, these examples remained based on neutral symmetrical N-aromatics. Thus, furthering the study on these het-
Ligands used with divalent lanthanides in previous and this study, containing 4,5,9,10-tetraazaazaphenanthrene (taphen), 2,2'-bipyrimidine (bipy), and 2-pyrimidin-2-yl-1H-benzimidazole (Hbimpm).

Chart 1

Results and discussion

Synthesis and structural characterization

The first attempt at combining the nickel precursor, \((\text{tmeda})\NiMe_2\), and Hbimpm in chelating solvents such as pyridine or acetonitrile at room temperature led to insoluble solids that were difficult to characterize. Heating up the mixture to higher temperature only yielded decomposition products, which were hardly identifiable, probably due to the temperature sensitivity of the precursor, \((\text{tmeda})\NiMe_2\). However, when the Hbimpm pro-ligand was deprotonated beforehand with a strong base (potassium hexamethyldisilane) prior to an addition of \((\text{tmeda})\NiMe_2\) in THF, dark red microcrystalline solid \(\text{K}(\text{bimpm})\NiMe_2\) (1) was isolated in good yield (60%). The solid can be further re-crystallized from THF-pentane vapor diffusion in moderate yield (40%) as purple crystals. The crystallomeric frameworks by using diisymmetric redox active ligands, such as LX-type ones (Chart 1), is worthy of interest. Particularly, LX-type ligands are widely used in Nickel-catalysed cross-coupling reactions to enhance catalytic efficiency. They are considered to allow significantly facile activation of unreactive carbon-halogen bonds. Inspired by recent work by Diao and co-workers which highlighted the complexity of high-valent nickel-mediated \(\text{sp}^3-\text{sp}^3\) and \(\text{sp}^2-\text{sp}^2\) C-C bond formation using spectroscopic and computational methods, we thought that imidazole-based linkers, such as 2-pyrimidin-2-yl-1H-benzimidazole, namely Hbimpm, would be good candidates to construct original bimetallic Ln–TM complexes and study the electronic modulation within these systems. In addition, the bite angle and the dissymmetry of the ligand are proved to be key parameters for varying the electronic structures and reactivity of metal complexes.

In this article, we present the synthesis and characterization of organic organometallic frameworks with the diisymmetric bimpm ligand, which combines a divalent organolanthanide and a dimethyl nickel fragment. Dimerization between two bimpm ligands occurs in an \(\text{exo}\) position. The lack of stability of the nickel fragment in the dimeric species is demonstrated by the evolution of dimer to a trimer with the identical \(\text{exo}\) coupling formation, in which the nickel fragment has been replaced by a \(\text{Cp}^*\Yb\) fragment.

Fig. 1 ORTEP of 1(THF) (top) and 2 (bottom). Thermal ellipsoids are at 50% level. Carbon atoms are in grey, hydrogen atoms are in white and have been removed for clarity except the ones on the coupled carbons of the ligands, potassium in purple, nitrogen in blue, nickel in bright green and ytterbium atoms in deep green. Co-recrystallized solvent molecules of \(\text{Et}_2\O\) in 2 are omitted. \(\text{Cp}^*\) ligands on ytterbium are presented in wireframe style for clarity.

Chart 1

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orbital calculations.\textsuperscript{36} Such coupling was already reported with pyridine and pyrimidine moieties.\textsuperscript{23,39,40} The effective reduction of the ligand also features a longer C–C distance linking the pyrimidine and benzimidazole heterocycles in 2 (1.476 Å) than in 1 (1.451 Å). This is indicative of a loss of good conjugation in the ligand and charge localization on the nitrogen of the pyrimidine.

This surprising compound, 2, obtained in rather good yield could be the result of the easy formation of KCp*, which is soluble in THF and not in Et2O, the solvent of extraction. The formation of the salt could be explained by the ionic bonding nature of the lanthanide to the Cp ring.\textsuperscript{42} It also demonstrates the relative lability of the nickel dimethyl fragment. As such, 2 is likely to be the thermodynamic product of the reaction by the relative lability of the nickel dimethyl fragment. As such, rearrangement of the expected heterobimetallic dimer. In order to get some insights in this singular rearrangement, another reaction was performed in a similar fashion but that was reacted only for several seconds at room temperature before it became deep green. Co-recrystallized solvate molecules of Et2O are removed and pentamethylcyclopentadienyl ligands on ytterbium are presented in wireframe style for clarity.

The average Yb–Cp* and Yb–N distances in 3 are 2.33(2) and 2.330(8) Å, respectively, which are slightly shorter than the ones in 2 as 2.342(2) and 2.364(2) Å. The data agree well with a trivalent Yb fragment. A longer bimpm bridging distance of 1.459(5) Å is observed in 3 in comparison to that in 1 (1.451 Å). This follows a similar trend of the ligand reduction. The distance of the coupled σ bond (1.56 Å) between two pyrimidine cycles is much longer than the one in 2 (1.520 Å). It could be due to the less compressed coordination environment in dimeric 3 than in 2. Moreover, in comparison with 1, the average distances in 3 of the Ni–N (1.987(2) Å in 3, 1.97(5) in 1 Å) and Ni–CH3 bonds (1.928(5) Å in 3, 1.922(5) Å in 1) are rather similar. It indicates that 1 and 3 possess a similar divalent coordination system around the nickel centre. The presence of one co-crystallized KCp* molecule is an undoubtedly important part of the dimeric to trimeric transition from 3 to 2, given that the KCp* formation in solution can be regarded as a clear driving force leading to the rearrangement. Another interesting observation in 3 is the noticeable distortion of the nickel fragment (Fig. 3). The nearly planar angle (2°) between the bimpm ligand plane and NiMe2 fragment in 1 became

**Table 1** Main distances (Å) and angles (°) for 1–6

|       | 1   | 2   | 3     | 4   | 5     | 6     |
|-------|-----|-----|-------|-----|-------|-------|
| Ni–CH3| 1.922(5) | 1.92(4) | —    | 1.928(5) | 1.92(2) | 1.930(5) |
| Ni–N  | 1.97(5) | 1.970(5) | —    | 1.987(2) | 2.01(4) | 1.973(5) |
| Yb–N  | —    | —    | 2.364(2) | 2.330(8) | 2.32(2) | —     |
| Yb–Cp*centr | —    | —    | 2.342(2) | 2.33(2) | 2.38(3) | —     |
| Bridging C–C\textsubscript{bimpm} | 1.451 | 1.45(6) | 1.476 | 1.459(5) | 1.46(3) | 1.46(8) |
| Coupled C–C\textsubscript{bimpm} | —    | —    | 1.520 | 1.56 | 1.56(5) | 1.537 |
| bimpm–NiMe2 | 2    | 12   | —    | 31  | 19    | 17    |
counter ions are captured by 18-crown-6 (Scheme 2). ORTEP of to cape the active potassium ion.43 The analogous nickel precur-
dition of crown ether (18-crown-6) in solution was considered
igand plane (red) and atoms are labelled; C–Ni–C is NiMe2 plane (green) and also labelled. Thermal ellipsoids are at 50% level. Carbon atoms are in grey, potassium in purple, nitrogen in blue, nickel in bright green and ytterbium atoms in deep green. Half structure of the coupled 5 is presented. Hydrogen atoms have been removed for clarity.

Fig. 3 Comparison of distortion of the NiMe2 fragment in 1 (top) and 3 (bottom) presented by ORTEP. N–C–C–N is regarded as the overall ligand plane (red) and atoms are labelled; C–Ni–C is NiMe2 plane (green) and also labelled. Thermal ellipsoids are at 50% level. Carbon atoms are in grey, potassium in purple, nitrogen in blue, nickel in bright green and ytterbium atoms in deep green. Half structure of the coupled 5 is presented. Hydrogen atoms have been removed for clarity.

Fig. 4 ORTEP of 5. Thermal ellipsoids are at 50% level. Carbon atoms are in grey, hydrogen atoms are in white and have been removed for clarity, except the ones on the coupled carbons of the ligands, potassium in purple, nitrogen in blue, nickel in bright green and ytterbium atoms in deep green. Co-recrystallized solvate molecule of Et2O is removed and pentamethylcyclopentadienyl ligands on ytterbium are presented in wireframe style for clarity.

In the reaction forming 2, the fate of the nickel dimethyl fragment remains uncertain while it is clear that the formation of KCP* helps the rearrangement from 2 to 3. Accordingly, the addition of crown ether (18-crown-6) in solution was considered to cape the active potassium ion.43 The analogous nickel precursor K[18-c-6](bimpm)NiMe2 (4) was synthesized as deep blue crystalline product in good yield (91%). The combination with Cp∗Yb(OEt)3 was performed in both THF and Et2O with different reaction times at room temperature, yielding indifferently an anionic heterobimetallic species containing the Yb-bimpm–Ni fragment, in which two pyrimidine cycles on bimpm ligands are also coupled in exo-position (5). The potassium counter ions are captured by 18-crown-6 (Scheme 2). ORTEP of 4 and 5 are shown in ESI† and Fig. 4, respectively and main distances and angles in Table 1.

The average distance Yb–Cp∗ in 5 is 2.340(2) Å indicating an YbIII fragment. A reduction has taken place in the ligand, which can be noticed by typical longer ligand linker distance (1.464(5) Å) comparing to the one in 4 as 1.45(6) Å. Similar parameters based on the comparison in Ni–CH3 and Ni–N distances of 4 and 5 indicate that the nickel ion remains at its divalent oxidation state. The distortion angle of bimpm and NiMe3 difference in 4 and 5 is only 7°, indicating a more stable coordination environment, compared to the one found in 3.

As discussed before, it is interesting to compare the angles between the bimpm ligand plane and the dimethyl nickel fragment plane in 3 and 5 (Fig. 5). In 5, the average angle is 19°, which is similar to that of 12° in 4. Thus, the small increase in 5 compare to 1 is likely due to steric hindrance because of the 18-crown-6. Additionally, 5 was found to be stable at room temperature in the solid-state, unlike 3. Thus, the fast decomposition of the nickel fragment in 3 is likely to be the reason for the easy formation of 2 as a thermodynamically stable trimer.

In order to estimate the impact of the single-electron transfer system without the lanthanides ion, a reduction was performed on 1 using potassium graphite (in excess) in THF instead of the divalent lanthanide ion reductant. XRD-suitable brown-orange crystals of the reaction product, 6, were isolated via slow diffusion of pentane into THF solution at −35 °C after several days. ORTEP of 6 and main distances and angle are presented in Fig. 6 and Table 1.

In 6, the average distances of the Ni–N and Ni–CH3 bonds are 1.973(5) and 1.930(5) Å, respectively, indicating that the nickel centre remains in a divalent oxidation state. A longer
distance of C–C linkage between pyrimidine and benzimidazole of 1.46(8) Å compared to that of 1.451 Å in 1, is indicative of an efficient reduction on the ligand moiety. The torsion angle between the ligand plane and the NiMe₂ fragment is 17°, which is similar to the one in 5 (19°). Correspondingly, 6 was found to be thermally stable for several days in solution at room temperature under inert atmosphere. Interestingly, a coupled C–C bond between two pyrimidine rings was also observed but in a different position than that in 2, 3 and 5. In 6, the coupling occurs at the para position of the Ni-coordinated nitrogen atom, while in other structures with the divalent lanthanide, the coupling occurs at the ortho site. The length of the coupled C(sp²)–C(sp³) bond is 1.537 Å, which is similar to the ones in 2, 3 and 5.

This difference in the coupling fashion on bimpm ligand in 3 and 6 is intriguing and it is then plausible that the coordination of the divalent lanthanide ions could subtly modulate the electron density on the redox-active ligand fragment because of strong electron correlation. Additionally, the steric hindrance effect of the Cp* ligands on the lanthanide moiety might also participate in regulating the position at which the coupling occurs. Thus computational investigations were performed at the DFT level.

Theoretical studies

Computational investigations were performed on the anionic bimpm ligand, 1 and the monomeric anion of 3 at the DFT level. The corresponding geometries were optimised using the PBE density functional and Kohn–Sham orbitals are depicted in the ESI†.

The optimised geometry of the anionic ligand yields a symmetrical species, in which the LUMO is delocalised equally across the C₂ axis of ligand while the density is more localised in the pyrimidine part. The addition of the Ni fragment significantly modifies the electronic density of the LUMO with strong density located on the pyrimidine nitrogen atom that coordinates the nickel ion and on the carbon in para position to the latter. On the other hand, the ortho position to that coordinated nitrogen atom possesses very little density. Thus, an electron transfer that would occur on this species would definitely strongly localise spin density in the para position, which is consistent with the coupling observed in 6.

Now, the addition of the ytterbocene fragment is accompanied by an electron transfer to the ligand and the SOMO is now delocalised on the ligand while the LUMO is principally centred on the pyrimidine moiety. In the SOMO, the spin density has virtually no contribution on the carbon atoms where the coupling is observed in 6 (para to the nickel-coordinated pyrimidine nitrogen atom) while it has little contribution on the carbon atoms where the coupling is observed in 2, 3 and 5. Additionally, the presence of the lanthanide ion may enforce a multiconfigurational energy state allowing the LUMO to contribute significantly¹¹,¹³ to the spin delocalization and thus explaining the distinct position of the coupling between 6 and 2, 3 and 5. This could be verified by a proper CASPT2 computation that was not possible to handle in our hands.

Solution studies

The dissymmetry of the ligand imposes a C₂ symmetry in the precursor 1 and 4. ¹H NMR of 1 in THF-d⁸ shows seven resonances in total, two for the methyl (6 protons) at 0.02 and −0.40 ppm, and five for the bimpm ligands (7 protons), found in 8.6–6.8 range. The spectrum of 4 recorded in CD₃CN shows six resonances for the bimpm ligands (7 protons), found in 8.8–6.9 ppm range, one signal for 18-crown-6 (24 protons) at 3.55 ppm, as well as two for the methyl (6 protons) at −0.10
and ~0.54 ppm. The addition of the ytterbium fragment drastically shifts these protons, in agreement with the presence of a paramagnetic Yb\(^{3+}\) centre. 2 recorded in THF-d\(^8\) at 293 K nicely shows 14 signals, integrating for 1 proton each and 5 signals, integrating for 15 protons each. This spectrum is in good agreement with a coupled ligand and no symmetry, other than the identity, i.e. a \(C_1\) symmetric molecule in solution. The strong paramagnetism of the complex indicates the presence of at least one trivalent ytterbium.

The \(^1\)H NMR spectra of 3 and 5 (in bracket) present similar spectra in THF-d\(_8\) at 293 K, with seven protons at 187.66 (186.25), 181.49 (176.11), 50.43 (53.04), 27.46 (30.55), 19.17 (23.32), 4.91 (~0.03) and ~8.27 (~4.50) ppm. Additionally, two non-equivalent Cp* signals are found at 12.28 (7.91) and 2.93 (2.29) ppm and two non-equivalent methyl signals at ~4.81 (~0.86) and ~18.17 (~14.03) ppm. The presence of only seven signals for the ligand but two different signals for the methyl and Cp* moieties is in agreement with a dimeric species with a \(C_2\) inversion centre at the centre position of the \(exo\) C–C bond that was formed or a plane of symmetry cutting the C–C bond that was formed. Thus, the NMR spectra are not informative as to the stereochemical nature of the coupling, but allow identifying its formation. Because both 3 and 5 have very similar coordination environment, their NMR chemical shifts are very close to each other. Again, the paramagnetism of 3 and 5 is indicative of an effective electron transfer from the davalent lanthanide to the redox-active ligand-transition metal fragment with bimpn.

The paramagnetic shift of the signals in 2, 3 and 5 were followed by variable temperature \(^1\)H NMR. The chemical shifts of each resonance in these complexes respectively are plotted versus \(1/T\) (see ESI†). A linear \(\delta\) vs. \(1/T\) plot over the set-up temperature range for each, revealing typical Curie behaviour under this temperature range. This is in good agreement with the recorded solid-state temperature-dependent magnetic data.

The possibility of a reversible C–C transfer was studied. This occurred in multiple occasions after electron transfer from davalent lanthanides\(^{13,14,44}\) compared to the relatively stable nature of the Cp*\(^+\)Yb(phen), 2, 3 and 5 are rather thermosensitive. The eventual dimer-monomer equilibrium was not efficiently observed when dissolving the crystals of 2, 3 and 5 in THF-d\(_8\) at room temperature. It might take place at higher temperatures, such as at 60 °C, however, the concomitant decomposition of the dimers occurred when heating up the solutions for extended periods of time, resulting in a number of newly formed, hardly identifiable signals (Fig. S19–24f). Thus, the reversibility of C–C coupling in 2, 3 and 5 remains equivocal.

Magnetism solid-state studies

The organometallic products were analysed by solid-state magnetism using a SQUID (Fig. 7). When the davalent ytterbium is coordinated to the bimpn ligand, one electron is transferred, which allow the coupling to occur. Thus, in 2, 3 and 5, it is expected that Yb centres are at the trivalent state. This was notably indicated by the paramagnetic NMR as well as the Cp*–Yb distance (see previous paragraphs). The solid-state data indicate 300 K \(\chi_T\) values of 6.17, 4.45 and 4.45 emu K mol\(^{-1}\) for 2, 3 and 5, respectively. These values agree with the theoretical values of 2.54 emu K mol\(^{-1}\) for uncorrelated \(2^{3}\) particles ground-states for each ytterbium centre, that is three ytterbium centres in 2 and two ytterbium centres in 3 and 5. The \(\chi_T\) value decreases monotonously up to 6 K with respective values of 3.32, 2.42 and 2.44 emu K mol\(^{-1}\) for 2, 3 and 5. The decrease is due to the depopulation of the higher energy crystal-field states. Note that the very similar decrease of 3 and 5 indicate a very similar crystal field, in agreement with their very similar structural nature. The decrease below 6 K is associated with a mixture of dipolar coupling contributions, while only the ground crystal-field state is populated.

Conclusions

In this article, we have successfully synthesized original redox-active, disymmetric hetero- or homometallic complexes containing davalent organolanthanides, Cp*\(^2\)Yb, which allows effective single electron transfer process and leads to the intermolecular C(sp\(^3\))-C(sp\(^3\)) coupling formation between two bridging ligands. The stereochemistry of this ligand coupling is identified as an \(exo\) formation, and the dimer-trimer transition is affected by a reactive NiMe\(_2\) fragment, which impacts the torsion angle between the bridging ligand and dimethyl functional group. The solid-state explanation of such a rearrangement is provided by the XRD study of the isolated transient \(exo\) species. Magnetic measurements show that 2, 3 and 5 possess triplet ground states. This work implements a new redox-active system of davalent lanthanides, in the presence of a disymmetric ligand, yielding an intermolecular ligand coupling reactivity, yet the reversibility of this bond formation remains ambiguous. This study provides us with a new avenue for the design of our heterometallic architectures with other transition metals using this disymmetric ligand system, which may lead to different reactivity behaviours compared to the one observed for nickel. The related work is currently under investigation.
Experimental section

General considerations

All reactions were performed using standard Schlenk-line techniques or in argon- or nitrogen-filled gloveboxes (MBraun, Garching, Germany). All glassware was dried at 120 °C for at least 12 h prior to use. Tetrahydrofuran (THF), THF-d8, toluene, and toluene-d8 were dried over sodium, degassed; CD3CN was dried over CaH2, degassed. All the solvents were transferred under reduced pressure in a cold flask.

1H NMR spectra were recorded in 5 mm tubes adapted with a J. Young valve on Bruker AVANCE II or III-300 MHz (Bruker, Billerica, MA, USA). 1H chemical shifts were expressed relative to TMS (tetramethylsilane) in ppm. Magnetic susceptibility measurements were made for all samples on a SQUID. Diamagnetic corrections were made using Pascal’s constants. Temperature dependent magnetic measurements were obtained in sealed quartz tube on a SQUID at 0.5 and 2 T. Elemental analyses were obtained from Mikroanalytisches Labor Pascher (Remagen, Germany).

All calculations were performed using the ORCA 4.2.1 software. The geometry optimizations were done at the PBE level of theory,57 using scalar relativistic ZORA Hamiltonian with ZORA-def2-TZVP basis set,48 and SARC/J auxiliary basis set for Coulomb fitting.49–51 Each time, dispersion corrections were added to the functional used in the D3 framework proposed by Grimme with the addition of the Becke-Johnson damping (D3BJ). Frequencies were calculated numerically to ensure by Grimme with the addition of the Becke-Johnson damping (D3BJ). Frequencies were calculated numerically to ensure that all vibrations were real. The optimization was performed in gas phase at the PBE, PBE0,52,53 TPSSH,54,55 and oB97X-D.56

Single crystals of the compounds 1–6 were coated in Paratone-N oil and mounted on a Kapton loop. A BRUKER APEX-II CCD detector and a graphite Mo-Kα monochromator (Nonius, Delft, Netherlands) were used for the data collection. All data were measured at 150 K under a nitrogen stream and a refinement method was used for solving the structure. The structure resolution was accomplished using the SHELXS-97 and SHELXT57 program, and the refinement was done with the SHELXL program.58,59 The structure solution and the refinement were achieved with the PLATON60 and Olex2 softwares.61 During the refinement steps, all atoms except hydrogen atoms were refined anisotropically. The position of the hydrogen atoms was determined using residual electron densities. Finally, in order to obtain a complete refinement, a weighting step followed by multiples loops of refinement was done. ORTEPs of the compound structures were obtained using the MERCURY software. The structures have been deposited in the CCDC with 2021801–2021805 and 2034256 for 1–5 and 6, respectively.†

K[bimpm]Ni(CH3)2 (1). A 50 mL Schlenk was charged with Hbimp (283.6 mg, 1.44 mmol), KHMDS (317.2 mg, 1.59 mmol) in the glovebox. 20 mL of THF were added and the mixture was stirred at ambient temperature for 16 hours, remaining a milky suspension during the reaction time. The solvent was removed under reduced pressure and the residue was washed with diethyl ether for 3 times, allowing the removal of the slight excess of KHMDS, was dried under reduced pressure and used without further characterizations (298.3 mg, 1.27 mmol, 88%). (tmeda)Ni(CH3)2 (174.1 mg, 0.85 mmol) was dissolved in cold THF (−40 °C) and transferred dropwise into a cold THF suspension of Kbimp (199.4 mg, 0.85 mmol) at ambient temperature. The suspension was stirred for 2 hours, resulting in a colour change from olive-green to night blue and was filtered. The solvent of the solution was removing solvent under reduced pressure and K(bimpm)Ni(CH3)2 was isolated as a brown powder in 60% yield (163.6 mg, 0.51 mmol). When CH3CN is used instead of THF, the yield is increased because the better solubility of 1 soluble in CH3CN. However, the necessary drying step is longer and traces of CH3CN may influence the further use with reactive divalent lanthanide. Purple crystals were recrystallized via vapor diffusion by n-pentanse on THF solution at ambient temperature after 24 hours and isolated in 40% yield (110.0 mg, 0.34 mmol). 1H NMR (300 MHz, 293.15 K, THF-d8): δ (ppm) = 8.63 (d, 5.0 Hz, 1H, Kbimpm), 8.47 (d, 4.1 Hz, 1H, Kbimpm), 7.92 (m, 1H, Kbimpm), 7.39 (m, 1H, Kbimpm), 6.86 (m, 3H), 0.02 (s, 3H, Ni–Me1), −0.40 (s, 3H, Ni–Me2).13C NMR (75 MHz, 293.15 K, THF-d8, q is for quaternary carbon): δ (ppm) = 163.08 (Cd1, bimpm), 159.19 (Cd2, bimpm), 153.97 (Csp2, bimpm), 153.10 (Csp2, bimpm), 149.88 (Cq, bimpm), 146.99 (Cq, bimpm), 120.54 (Csp2, bimpm), 120.35 (Csp2, bimpm), 119.63 (Csp2, bimpm), 119.05 (Csp2, bimpm), 7.05 (Csp3, Ni-Me2), −12.23 (Csp3, Ni-Me1). Anal. calcd for C13H13KN4Ni: C, 48.33; H, 4.06; N, 17.34; found: C, 47.42; H, 4.20; N, 15.70.

Cp*Yb(thf)[Cp2Yb(bimpm)]2 (2). Cp*2Yb(OEt3) (94.4 mg, 0.18 mmol) and K[bimpm]NiMe2 (58.9 mg, 0.18 mmol) were dissolved in THF, respectively and cooled down to −35 °C. Transferring the red Cp*Yb THF solution dropwise into the blue Nickel solution at room temperature led to a dark red mixture immediately after the addition. The mixture was stirred at room temperature for one more hour, forming a red suspension. The solvent was removed under reduced pressure, yielding a brown-red solid that was extracted by Et2O (10 mL). Red crystals were obtained and isolated from slow evaporation of the Et2O solution in 51% yield (50.8 mg, 0.031 mmol). 1H NMR (300 MHz, 293.15 K, THF-d8): δ (ppm) = 213.6 (s, 1H, ν1/2 = 280 Hz, bimpm), 205.9 (s, 1H, ν1/2 = 280 Hz, bimpm), 196.8 (s, 1H, ν1/2 = 185 Hz, bimpm), 186.5 (s, 1H, ν1/2 = 185 Hz, bimpm), 175.7 (s, 1H, ν1/2 = 185 Hz, bimpm), 110.3 (s, 1H, ν1/2 = 62 Hz, bimpm), 70.6 (s, 1H, ν1/2 = 56 Hz, bimpm), 63.9 (s, 1H, ν1/2 = 30 Hz, bimpm), 55.8 (s, 1H, ν1/2 = 28 Hz, bimpm), 54.6 (s, 1H, ν1/2 = 26 Hz, bimpm), 46.5 (s, 1H, ν1/2 = 25 Hz,
Ni-Me1), 6.99 (s, 1H, Csp3, bimpm), 6.6 (s, 15H, Csp3, Cp*), −6.6 (s, 15H, Csp3, Cp*), −10.6 (s, 15H, Csp3, Cp*), −12.8 (s, 15H, Csp3, Cp*), −25.2 (s, 1H, Csp3, bimpm). Anal. calc'd for C74H64NiOYb: C, 55.06; H, 5.90; N, 6.76; found: C, 54.41; H, 6.02; N, 6.61.

[KCP*2Yb(bimpm)NiMe2]2 (3). Cp*2Yb(OEt2) (42.6 mg, 0.08 mmol) and K[bimpm]NiMe2 (26.6 mg, 0.08 mmol) were dissolved separately in THF and cooled down to −35 °C. Transferring the red Cp*2Yb THF solution into the deep blue Nickel solution at room temperature led to a dark purple mixture immediately once the addition. The solution was stirred at room temperature for 10 minutes and the solvent was removed under reduced pressure, yielding a red microcrystalline product (82.3 mg, 0.078 mmol, 97% yield).

Deep blue crystals were recrystallized from THF solution by vapor diffusion with Et2O, in 64% yield (54.4 mg, 0.051 mmol). 1H NMR (300 MHz, 293.15 K, CD2CN): δ (ppm) = 186.2 (s, 1H, Csp3, Cp*), 176.1 (s, 1H, Csp3, Cp*), 53.0 (s, 1H, Csp3, Cp*), 30.6 (s, 1H, Csp3, Cp*), 23.3 (s, 1H, Csp3, Cp*), −9.9 (s, 1H, Csp3, Cp*), −4.5 (s, 1H, Csp3, Cp*), −14.0 (s, 1H, Csp3, Cp*). [K2(bimpm)NiMe2]2 (6). K[bimpm]NiMe2 (28.8 mg, 0.09 mmol) was dissolved in THF and cooled down to −35 °C. Then, cold potassium graphite (53.3 mg, 0.39 mmol) was added to the deep blue THF solution of 1 at room temperature, leading to a dark brown red mixture after stirring for a few seconds. The mixture was then filtered, and the solvent was removed under reduced pressure, yielding a brown-red crystalline product that was washed by Et2O (5 mL) in 69% yield (22.4 mg, 0.031 mmol). Brown orange, XRD suitable crystals of 6 were able to be obtained from slow diffusion of pentane into the THF solution at −35 °C. 1H NMR (300 MHz, 293.15 K, THF-d8; δ (ppm) = 7.62 (d, J = 9.2 Hz, 1H), 7.26 (m, 1H), 6.91 (d, J = 7.8 Hz, 1H), 6.64 (m, 1H), 6.22 (d, J = 7.9 Hz, 1H), 4.09 (d, J = 9.0 Hz, 1H), −0.61 (s, 3H), −1.08 (s, 3H). 13C NMR (75 MHz, 293.15 K, THF-d8, q is for quaternary carbon): δ (ppm) = 163.67 (Cq, bimpm), 161.42 (Cq, bimpm), 149.13 (Cq, bimpm), 146.71 (Cq, bimpm), 137.42 (Csp2, bimpm), 118.55 (Csp2, bimpm), 118.35 (Csp2, bimpm), 117.85 (Csp2, bimpm), 117.57 (Csp2, bimpm), 101.14 (Csp3, bimpm-coupled), −9.93 (Csp3, Ni-Me2), −14.35 (Csp3, Ni-Me1). One 13C was missing due to low solubility.

Conflicts of interest
There are no conflicts to declare.

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