C–H Deprotonation and C=C Hydrogenation of N-Heterocyclic Olefin with Calcium Hydride Complexes: Cooperative Ca–H–Ca Bridge versus Terminal Ca–H bond

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Monomeric calcium hydride intermediates with reactive terminal Ca–H bond were recently proposed to deprotonate N-heterocyclic olefin ligands upon moderate heating with dimeric amidinate calcium hydride complexes. In contrast, extensive dispersion-corrected DFT calculations disclose the frustrated Lewis pair (FLP) like reactivity of cooperative Ca–H–Ca bridges for stoichiometric C–H deprotonation and kinetically more favorable catalytic C=C hydrogenation with pressured H₂, thus providing useful insights for metal hydride based hydrogenation catalysts.

Introduction

Catalytic C–H functionalization and C=C hydrogenation reactions are very important in both academia and industry. Traditionally, expensive and toxic heavy transition metal catalysts are usually required for the activation of stable C–H, C=C and H–H bonds.[1] It is highly desirable to develop cheap and environmentally friendly catalysts in this area. Recently, earth-abundant 3d transition metals were successfully applied in catalytic C–H functionalization,[2] while main-group catalysts are also attractive for catalytic C–H activation and C=C hydrogenation reactions.[3] Alkaline-earth metals (especially the abundant and low-toxic calcium)[4] have been successfully applied to a variety of hydroelementation and hydrogenation reactions[5] that mimics transition metal catalysis.[6] Hill et al. disclosed that calcium alkyls even enabled a counterintuitive nucleophilic substitution of benzene.[7] In an early study,[8] intramolecular C–H activation of a methyl group at a ligand backbone within a calcium benzyl complex was demonstrated by Harder et al.; recently, the stoichiometric backbone C–H deprotonation of a N-heterocyclic olefin (NHO) ligand using a calcium hydride complex was also reported (Scheme 1).[9] More recently, calcium hydride catalysts were also applied to the arene C–H alumination with low valent Al,[10] and the regioselective benzylic C–H bond addition of alkyl pyridines to a variety of alkenes.[11] NHOs represent a compound class that formally contains an alkylidene unit terminally appended to an N-heterocyclic carbene framework, with the exocyclic C=C bond being strongly...
polarized with considerable ylidic character like in Wittig ylides. The typical NHO ligand of 1,3-dimethyl-2-methyleimidazolide has been widely used as a highly useful reagent in stoichiometric conversions of polar unsaturated substrates such as ketones and imines, as catalysts in olefin and heterocycle polymerization and as ligands for low oxidation state main group element chemistry. Such olefinic donors can also be structurally derived from imidazole and triazole based heterocyclic carbenes and, as a result, have highly tunable electronic and steric properties.

In the original experimental study on the reaction of NHO with the donor-free calcium hydride complex (LCaH) with ligand L = BuAm, the objective was the NHO-coordinated mononuclear complex LCaH·NHO with a highly reactive terminal Ca–H bond that may be further added to the polarized exocyclic C–C bond of NHO to form an unstabilized calcium alkyl species. However, the actual reaction followed a surprising deprotonation of a NHO backbone Ca–H bond to form a bifunctional anionic NHm⁻ ligand (Scheme 1). Using a truncated mononuclear complex hydride LmCaH (Lm = MeAm), DFT calculations in gas-phase suggested high activation energy barriers of 24.1 and 16.8 kcal/mol for the C–H deprotonation and the C–C addition reaction channels, respectively. However, since a stable dimeric calcium hydride complex (LCaH) with two Ca–H–Ca bridges was actually used experimentally, it is highly desirable to identify the role of such Ca–H–Ca bridges and potential terminal Ca–H bonds in the C–H deprotonation and the potentially catalytic C–C hydrogenation reactions.

Results and Discussion

As disclosed by extensive dispersion-corrected DFT calculations in this work, cooperative activation of C–H and C–C bonds of the NHO ligand by stable Ca–H–Ca bridges is kinetically more favorable than with reactive terminal Ca–H bonds of energetically disfavored mononuclear LCaH complexes.

To gain deep mechanistic insight into the C–H and C–C bond activation of the NHO ligand with the LCaH complex as well as the potential catalytic C–C hydrogenation with H₂, state-of-the-art dispersion-corrected DFT calculations are performed at the PW6B95-D3/def2-QZVP + COSMO-RS/TPSS-D3/def2-TZVP + COSMO level in benzene solution (see below for computational details) that has been well tested in our recent mechanistic studies. The final free energies (at 298.15 K and 1 M concentration) are used in our discussion unless specified otherwise. Test DFT calculations show that the inclusion of dispersion corrections is crucial for the correct energetics for such large calcium hydride complexes: the formation of dimer (LCaH)₂ is −24.8 kcal/mol exergonic from two LCaH monomers, as stabilized by a sizable dispersion contribution of −12.6 kcal/mol. The formation of (LCaH)₂–NHO as the adduct of NHO and (LCaH)₂ is 0.1 kcal/mol endergonic and thus is reversible, again favored by a sizable dispersion contribution of −8.9 kcal/mol. Indeed, the addition of a NHO ligand to a suspension of (LCaH)₂ in benzene at room temperature did not dissolve the dimer in experiment.

As shown in Figure 1, the addition of two NHO molecules to dimer (LCaH)₂ is 13.6 kcal/mol endergonic to form two monomeric ylidic carbon-bound LCaH–NHO complexes, with each LCaH–NHO being 6.8 kcal/mol less stable than the initial reactants of NHO and (LCaH)₂. Starting from the loose Ca–C adduct (LCaH)₂–NHO, the cleavage of one Ca–H–Ca bridge may lead to the higher-lying complex (LCaH)₂–NHO that is stabilized by the remaining Ca–H–Ca bridge but contains a dangling Ca–H bond; backbone C–H bonds of the NHO ligand can be deprotonated with the dangling Ca–H bond. Such cooperative FLP-like backbone C–H deprotonation of NHO is 8.5 kcal/mol endergonic over a sizable barrier of 28.1 kcal/mol (via transition state TS1) to form the dinuclear complex A bound by both a Ca–H–Ca and an anionic NHm⁻ ligand, along with released H₂ gas. In contrast, the previously proposed C–H deprotonation via the mononuclear complex LCaH·NHO is 15.4 kcal/mol endergonic over a high barrier of 35.6 kcal/mol to form the complex A with respect to the dimeric reactant (LCaH)₂ and thus is both kinetically and thermodynamically much less favorable than the dinuclear pathway with cooperative Ca–H–Ca bridges. The loose Ca–C adduct A–NHO is 3.8 kcal/mol higher in free energy than separated A and NHO ligand, and thus is unstable. The remaining Ca–H–Ca bridge of the dinuclear complex A may induce similar C–H deprotonation of another NHO ligand via the adduct A–NHO, which is now −3.0 kcal/mol exergonic over a moderate barrier of 19.5 kcal/mol (via TS2) to form the experimentally observed product B with two anionic NHm⁻ ligands. Since the overall C–H deprotonation of two NHO ligands with the dimeric (LCaH)₂ complex is still 5.5 kcal/mol endergonic over a sizeable free energy barrier of 28.1 kcal/mol (via TS1) to form the product B, it is kinetically possible upon moderate heating at 60°C but thermodynamically prevented in closed reaction system with pressured H₂ gas. Such C–H deprotonation with cooperative Ca–H–Ca bridges is however made possible for open reaction systems allowing H₂ gas escape. In contrast, C–H deprotonation with reactive terminal Ca–H bonds is energetically disfavored.

As shown in Figure 2, though the intramolecular Ca-to-C 1,3-hydride shift within the mononuclear adduct LCaH·NHO is −2.0 kcal/mol exergonic over a moderate barrier of 20.3 kcal/mol (via TS3) to form the calcium alkyl complex mC, the use of dimer (LCaH)₂ as initial reactant leads to a sizable free energy barrier of 27.1 kcal/mol via such mononuclear pathway. On the other hand, the direct C–C addition over a Ca–H–Ca bridge via the dinuclear adduct (LCaH)₂·NHO is 4.9 kcal/mol endergonic over a sizable barrier of 26.1 kcal/mol (via TS3) to form the calcium alkyl complex C, which is kinetically 1.0 kcal/mol more favorable at room temperature but becomes comparable with the mononuclear pathway (via TS3) that is somewhat favored by entropy effects upon moderate heating (see ESI Table S1).

Starting from the dinuclear complex C, direct Ca–C bond hydrogenolysis with dihydrogen H₂ is prevented by a high barrier of 29.6 kcal/mol (via TS4) relative to the dimeric reactant (LCaH)₂, which is kinetically slow even upon moderate heating at 60°C. In contrast, the elimination of a LCaH unit from C is 12.3 kcal/mol endergonic to form the mononuclear complex mC, followed by either dimerization or trapping with another
NHO ligand of the eliminated LCaH to form stable (LCaH)$_2$ dimer or less stable LCaH · NHO adduct. Assuming LCaH elimination into stable (LCaH)$_2$ dimer, facile FLP-like H$_2$ addition over the Ca–C bond of the resultant mononuclear complex mC is kinetically much facilitated over a moderate barrier of 21.0 kcal/mol (via mTS4). Further LCaH elimination into stable dimeric form eventually makes the overall reaction −5.8 kcal/mol exergonic to form the catalytic C–C hydrogenation product NhoHH. For comparison, the stoichiometric C–H deprotonation with (LCaH)$_2$ via TS1 with an overall barrier of 28.1 kcal/mol (Figure 1) is kinetically 2.0 kcal/mol less favorable than the catalytic C–C hydrogenation with pressured H$_2$ gas as reactant via TS3 over a barrier of 26.1 kcal/mol (see also ESI Figure S2).

**Conclusion**

In conclusion, accurate dispersion-corrected DFT calculations reveal that cooperative Ca–H–Ca bridges of the stable calcium hydride complex (LCaH)$_2$ may enable the stoichiometric deprotonation of backbone C–H bonds for open reaction system allowing H$_2$ gas escape; in contrast, with pressured H$_2$ gas as reactant, both cooperative Ca–H–Ca bridge and terminal Ca–H bond may compete with each other in kinetically more favorable catalytic C–C hydrogenation, thus providing deeper mechanistic insights into metal hydride based hydrogenation catalysis.$^{[3c,e,f,h,i,5c,17a,18]}$ Terminal Ca–H bonds are intrinsically more reactive but energetically disfavored than cooperative Ca–H–Ca bridges. Similar cooperative Li–H–Li, K–H–K, Li–N–Li, and Li–P–Li bridges involving Lewis acidic metal cations and Lewis basic hydride or other anionic ligands are also known for such FLP-like reactivity for the activation of small molecules.

**Computational Methods**

All DFT calculations are performed with the TURBOMOLE 7.4 suite of programs.$^{[19]}$ The structures are fully optimized at the TPSS-D3/def2-TZVP + COSMO level in benzene solution, which combines the TPSS meta-GGA density functional$^{[20]}$ with the BJ-damped DFT-D3 dispersion correction$^{[21]}$ and the def2-TZVP basis set$^{[22]}$ using the Conductor-like Screening Model (COSMO)$^{[23]}$ for benzene solvent (dielectric constant $\varepsilon = 2.30$ and diameter $R_{solv} = 3.28 \text{ Å}$). The density-fitting RI-J approach$^{[24]}$
is used to accelerate the calculations. The optimized structures are characterized by frequency analysis (no imaginary frequency for true minima and only one imaginary frequency for transition states) to provide thermal free-energy corrections (at 298.15 K and 1 atm) according to the modified ideal gas-rigid rotor-harmonic oscillator model.

More accurate solvation free energies in benzene solution are computed with the COSMO-RS model[20] (parameter file: BP_TZVP_C30_1601.ctd) using the COSMOtherm package[27] based on the TPSS-D3 optimized structures, corrected by +1.89 kcal/mol to account for the 1 mol/L reference concentration in solution. To check the effects of the chosen DFT functional on the reaction energies and barriers, single-point calculations at both TPSS-D3[20] and hybrid-meta-GGA PW6B95-D3[28] levels are performed using the larger def2-QZVP[22] basis set. Final reaction free energies (ΔG) are determined from the electronic single-point energies plus TPSS-D3 thermal corrections and COSMO-RS solvation free energies. As noted previously for some hydrogenation reactions,[17] the reaction energies from both DFT functionals are in good mutual agreement of 0.3 ± 1.4 kcal/mol (mean ± standard deviation) though as expected 2.6 ± 1.7 kcal/mol higher barriers are found at the PW6B95-D3 level. In our discussion, the more reliable PW6B95-D3 + COSMO-RS free energies (in kcal/mol, at 298.15 K and 1 mol/L concentration) are used unless specified otherwise. The applied DFT methods in combination with the large AO basis set provide usually accurate electronic energies leading to errors for chemical energies (including barriers) on the order of typically 1–2 kcal/mol. This has been tested thoroughly for the huge data base GMTKN55[29] which is the common standard in the field of DFT benchmarking.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.
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