Efficient Rhodium-Catalysed Multicomponent Reaction for the Synthesis of Novel Propargylamines

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Abstract: [Rh(μ-Cl)(H)2(IPr)]2 was found to be an efficient catalyst for the synthesis of novel propargylamines by a one-pot three component reaction between primary arylamines, aliphatic aldehydes and triisopropylsilylacetylene. This methodology offers an efficient synthetic pathway for the preparation of secondary propargylamines derived from aliphatic aldehydes. The reactivity of [Rh(μ-Cl)(H)2(IPr)]2 with amines and aldehydes was studied, leading to the identification of complexes [RhCl(CO)IPr(MesNH2)] and [RhCl(CO)2IPr]. The latter shows very low catalytic activity while the former brings about reaction rates similar to those obtained with [Rh(μ-Cl)(H)2(IPr)]2. Besides, complex [RhCl(CO)IPr(MesNH2)] reacts with an excess of amine and aldehyde to give [RhCl(CO)IPr(MesN=CHCH2CH(CH3)2)], which has been postulated as the active species. A mechanism that clarifies the scarcely studied catalytic cycle of A3-coupling reactions is proposed based on reactivity studies and DFT calculations.

Introduction

In recent times many efforts have been devoted to the development of multicomponent reactions (MCRs). MCRs are one-pot reactions where the final product incorporates most of the atoms of at least three different reactants.[1] This strategy offers several advantages compared to multi-step synthesis: (i) atom economy, as all the starting materials need to be incorporated into the product with minimum atom waste; (ii) time- and solvent-efficiency due to the reduction of synthetic steps; (iii) formation of various bonds in a single synthetic step (high bond-forming efficiency).

In particular, several examples of MCRs have been described for the preparation of propargylamines starting from aldehydes, amines and alkynes, commonly called A3-coupling reaction.[2] These reports have mainly focused on secondary amines (Scheme 1a),[3] while primary amines are more challenging substrates (Scheme 1b-d).[4] For example, the catalyst based on silver oxide nanoparticles reported by Sun and co-workers is efficient for a variety of secondary amines, but no reaction was observed for any of the primary amines tested therein.[3h] Moreover, examples of this type of reaction are in most cases limited to cyclic secondary amines.

In particular, studies that deal with the reaction of primary aromatic amines and aliphatic aldehydes by means of a three-component coupling are scarce, especially on the lookout for methodologies that offer a wide substrate scope (Scheme 1d). Wei and co-workers reported one example,[4b] namely the coupling of pivalaldehyde with aniline and phenylacetylene, which leads to the corresponding propargylamine in a 64% yield with a RuCl3/CuBr system as catalyst. A ZnMe2 mediated alkynylation of imines (three-component reaction from o-anisidine, various aliphatic aldehydes and phenylacetylene) was published by Bolm and co-

workers. This methodology, however, requires over-stoichiometric amounts of ZnMe2 and reaction times that span from 48 to 96 h.
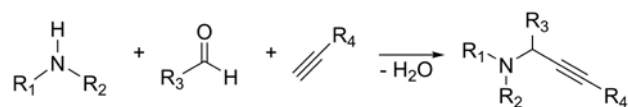
a) R_1 = Alk; R_2 = Alk; R_3 = Alk or Ar; R_4 = Any[2]
b) R_1 = Alk; R_2 = H; R_3 = Ar; R_4 = Any[3c]
c) R_1 = Alk; R_2 = H; R_3 = Alk (^{n}Pr); R_4 = Any[3a]
d) R_1 = Ar; R_2 = H; R_3 = Alk; R_4 = Any[3b,d]
e) R_1 = Ar; R_2 = H; R_3 = Ar; R_4 = Any[3b,d]

Scheme 1. Summary of reported examples of multicomponent reactions for the hydroalkynylation of imines from amines, aldehydes and terminal alkynes.

The importance of new efficient routes to secondary propargylamines is well exemplified by the great amount of drugs based on this organic scaffold, e.g., MAO type B inhibitors and muscarinic agonists/antagonists are commonly used in therapies for the early treatment of Parkinson's disease.[5] Moreover, propargylamines are versatile building blocks for the preparation of biologically active molecules and materials by "click chemistry" reactions.[6] Hence, mechanistic investigations that permit a better understanding of the A3-coupling reaction and the hydroalkynylation of imines may facilitate the development of more active and selective catalysts for the preparation of propargylamines. The few catalytic cycles described in the literature often propose the formation of alkynyl complexes followed by migratory insertion of the imine or iminium cation into the Rh–C bond to finally afford the corresponding propargylamine. The information that can be obtained from these reports, however, is limited from a mechanistic viewpoint.[3e-f,4b-c] In this regard, we have recently postulated a mechanism for the hydroalkynylation of imines catalysed by a bimetallic Ir(II) complex.[7]

N-heterocyclic carbene (NHC) ligands have extensively proved excellent ancillary ligands for homogeneous transition metal catalysts.[8] The high stability of NHC complexes and their ability to promote oxidative addition reactions under mild conditions makes them exceptional candidates for C–H bond functionalization reactions.[9] In particular, NHC-complex [Rh(μ-Cl)(H)2(IPr)]2[10] (IPr = 1,3-bis-(2,6-diisopropylphenyl)imidazol-2-ylidene) has proven an efficient catalyst for processes that require a C–H bond activation step, even improving the performance of its parent complex [Rh(μ-Cl)(COE)(IPr)]2 (1),[11] which has shown good activities for the functionalization of alkynes and olefins.[12]

In this work we report the preparation of a variety of new propargylamines by a Rh(III) catalysed one-pot multicomponent reaction. This methodology converts a wide range of aromatic amines and aliphatic aldehydes into propargylamines in excellent yields under relatively mild reaction conditions employing [Rh(μ-Cl)(H)2(IPr)]2 as precatalyst. Moreover, a study that aims at shedding light on the nature of the active species, as well as the catalytic cycle that operates in this reaction, is presented here.

Results and Discussion

The dearth of examples of hydroalkynylation of imines derived from aromatic primary amines and aliphatic aldehydes prompted us to engage their synthesis using [Rh(□-Cl)(H)2(IPr)]2 (2) as catalyst. Efforts to isolate the imines required for this reaction met with limited success due to the tendency of these compounds to hydrolyse, which accounts for the lack of synthetic methods for the preparation of their related propargylamines. Therefore, in order to circumvent this problem, the corresponding three-component reactions (A3-coupling) were investigated.

At the outset of this study, the reaction of isovaleraldehyde (0.265 mmol) with a range of aniline derivatives (0.265 mmol) and triisopropylsilylacetylene (0.265 mmol) was tested in order to assess the tolerance of this methodology to various functional groups (Scheme 2).

The reactions were carried out in NMR tubes using benzene-d6 as solvent, 5 mol% of catalyst (2) and kept at 80 ºC for periods that spanned from 7 to 24 h to afford the corresponding propargylamines (6a-6g) in good to excellent yields (74-97%). As a general trend, reactions worked well with mono-, di- and trisubstituted anilines containing either electron-donating or withdrawing groups. The presence of halogen substituents such as –F at the ortho position of the aniline has a moderate deactivating effect as the yield for 6g drops to 74%. In the case of 6a with an ortho–OMe group, a comparable yield was obtained (91%). Gratifyingly, the increase of steric hindrance at the aniline, e.g., 2,6-dimethylaniline, 2,4,6-trimethylaniline, 2,6-diisopropylaniline and 2,4,6-tert-butylaniline did not affect the outcome of the reaction, providing the corresponding propargylamines in yields up to 97%.

Noteworthy, the use of less encumbered silylacetylenes such as triethylsilylacetylene or trimethylsilylacetylene led to worse conversions due to the formation of several by-products, which include those originated from alkyne dimerisation, trimerisation and polymerisation.
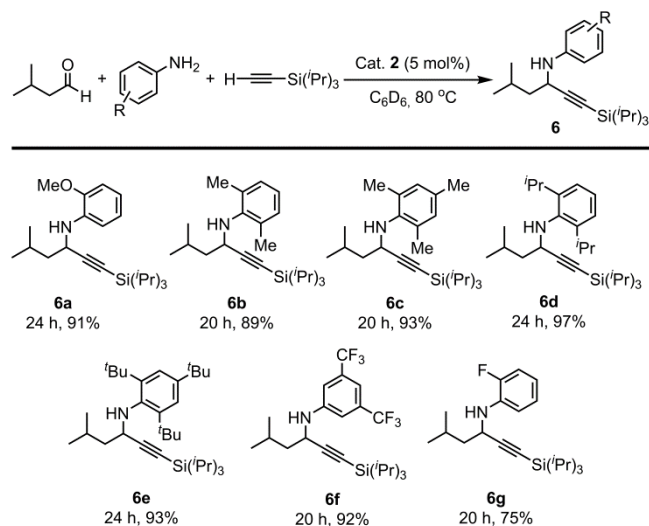

Scheme 2. A3-coupling reaction of isovaleraldehyde, a variety of aniline derivatives and triisopropylsilylacetylene. Reaction conditions: isovaraldehyde (0.265 mmol), aniline derivative (0.265 mmol), triisopropylsilylacetylene (0.265 mmol), catalyst 2 (5 mol%) in C6D6 (0.4 mL) at 80 oC.

With the intention of probing the versatility of complex 2 as a catalyst for the hydroalkynylation of imines, the influence of more sterically hindered aldehydes was explored (Scheme 3). Cyclohexylaldehyde was tested under the conditions previously described for isovaleraldehyde with triisopropylsilylacetylene and aniline derivatives as the coupling partners. The desired propargylamines 7a-h were formed in excellent yields (91-97%). Surprisingly, shorter reaction times were required compared to reactions that use isovaraldehyde as starting material, which could be considered less sterically hindered (6a-f vs 7a-f). In contrast, reactions with aniline and 3,4,5-trimethoxyaniline exhibit poor reactivity and require long reaction times (36% and 52% yield respectively), which might be due to ortho-metalation.
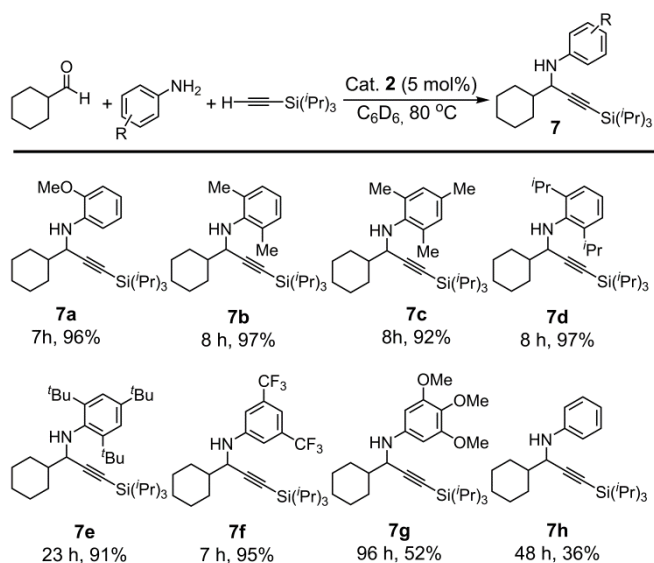
Scheme 3. A3-coupling reaction from cyclohexanecarboxaldehyde, a variety of aniline derivatives and a bulky alkyne. Reaction conditions: cyclohexanecarboxaldehyde (0.265 mmol), aniline derivative (0.265 mmol), triisopropylsilylacetylene (0.265 mmol), catalyst 2 (5 mol%) in C6D6 (0.4 mL) at 80 oC.

The effect exerted by the aliphatic substituent (R) at the RCHO boosted our interest on how the nature of the aldehyde influences the efficiency of the reaction. Therefore, a range of un- and branched aliphatic aldehydes was tested with o-anisidine or 2-fluoroaniline and triisopropylsilylacetylene (Scheme 4).
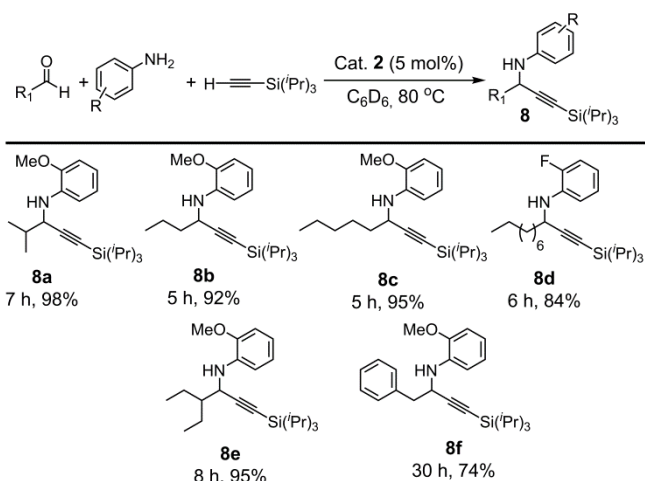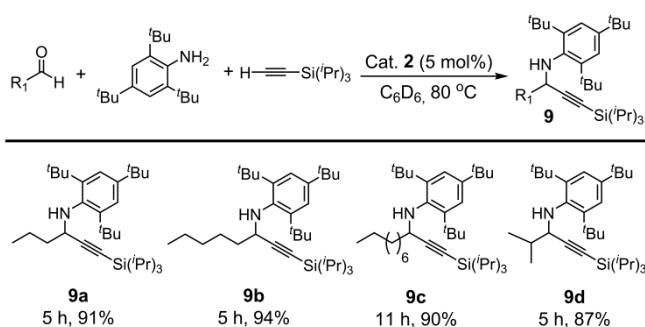
Scheme 4. Influence of the aldehyde. Reaction conditions: aldehyde derivative (0.265 mmol), aniline derivative (0.265 mmol), triisopropylsilylacetylene (0.265 mmol), catalyst 2 (5 mol%) in C6D6 (0.4 mL) at 80 oC.

The reactions are usually completed within 5-30 h. It seems that branched-aldehydes such as isobutyraldehyde and 2-ethylbutanal are the most reactive aldehydes, giving the products 8a and 8e with yields up to 98%. Un-branched aldehydes led to propargylamines 8b-d in good to excellent yields. Propargylamine 8f derived from benzylacetaldehyde required prolonged heating and was obtained in moderate yields (74%).

In addition to the screening of aliphatic aldehydes, the reactivity with the most sterically hindered aniline at our disposal, namely 2,4,6-tert-butylaniline, has also been investigated under analogous conditions to the ones described above (Scheme 5).

In all cases, the corresponding products 9a-d were formed in high yields (87-94%) and short reaction times, which demonstrates the tolerance of this methodology to highly hindered substrates.


Scheme 5. Substrate scope based on a bulky aniline substitution. Reaction conditions: aldehyde derivative (0.265 mmol), 2,4,6-tri-tert-butylaniline (0.265 mmol), triisopropylsilylacetylene (0.265 mmol), catalyst 2 (5 mol%) in C6D6 (0.4 mL) at 80 ºC.

The dearth of detailed mechanistic information available for A3-coupling reactions in the literature prompted us to perform several stoichiometric experiments that would help to disclose the nature of the active species and the intermediates involved in the reaction mechanism (Scheme 6). Treatment of complex 2 with isovaleraldehyde at room temperature

led to the formation of the bis-carbonyl complex [RhCl(CO)2IPr] (3), probably via decarbonylation of the aldehyde.[13] This complex has been previously prepared by placing [RhCl(COD)IPr] under an atmosphere of carbon monoxide.[14] Remarkably, when 2 equivalents of isovaleraldehyde and 2 equivalents of 2,4,6-trimethylaniline were added to 2 in toluene, a new complex that presents a coordinated amine is formed instead of 3. The formulation of the new complex, [RhCl(CO)IPr(MesNH2)] (4) (MesNH2 = 2,4,6-trimethylaniline), has been proposed based on elemental analysis, NMR and IR spectroscopy. The 1H NMR spectra show the expected set of resonances for the MesNH2 moiety. A broad signal assigned to the coordinated –NH2 moiety appears at δ 3.93 ppm, whereas the resonance corresponding to the free –NH2 from 2,4,6-trimethylaniline was highfield-shifted to δ 2.95 ppm. The 13C{1H}-APT NMR spectrum displays two doublets at δ 185.7 (JC-Rh = 82.3 Hz) and 181.6 ppm (JC-Rh = 55.6 Hz) corresponding to the CO ligand trans to the chloride and the carbene carbon atom, respectively. Interestingly, the absence of Rh-C coupling for the carbon atoms of the aromatic ring of the aniline derivative (see spectra in Supporting Information) confirms the coordination by the nitrogen atom and discards an interaction by the π-system of the aromatic ring. In the IR spectrum of the resulting pale yellow solid, a single υCO band is observed at 1949 cm−1.

When 4 is reacted with an excess of isovaleraldehyde (3 eq.) and 2,4,6-trimethylaniline (3 eq.) at 40 °C for 30 min, imine complex [RhCl(CO)IPr(MesN=CHCH2CH(CH3)2)] (5) is formed in ca. 60% conversion. An increase of the temperature to 80 ºC does not result in a noticeably improved conversion, which may suggest that complexes 4 and 5 are in equilibrium under these reaction conditions. Complex 5 was characterised in situ by NMR spectroscopy. The 1H NMR spectrum showed a triple of doublets at δ 8.58 ppm (JH-H = 5.7, JRh-H = 1.3 Hz) attributed to the coordinated imine hydrogen –N=CH. The signal corresponding to the free –N=CH appears at δ 7.60 ppm as a triplet (JH-H = 6.1 Hz). The 13C{1H}-APT NMR shows the presence of two sets of doublets at δ 185.3 (JRh-C = 82.6 Hz) and 182.7 ppm (JRh-C = 51.9 Hz), which are assigned to the coordinated carbonyl ligand and the carbene carbon atom, respectively. A singlet at δ 177.7 ppm corresponds to the –NCH moiety, while the free imine formed in situ is observed at δ 166.6 ppm. Noteworthy, addition of alkyne to this mixture resulted in the formation of the corresponding propargylamine, even when the temperature was progressively increased from 183 K.

Additionally, we found that complex 3 did not react with isovaleraldehyde (3 eq.) and 2,4,6-trimethylaniline (3 eq.) in toluene-d8 at 40 °C to afford 5, even under forcing conditions (80 oC for 1 h), probably due to the strong coordination of the CO ligands to the rhodium centre.
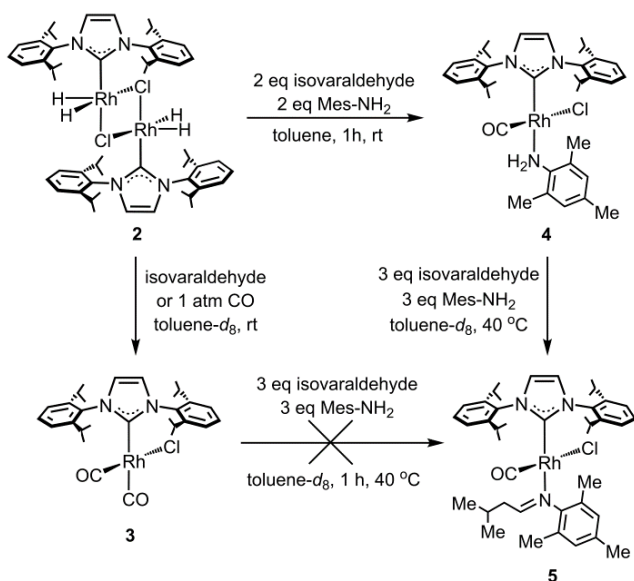
Scheme 6. Detected intermediates for the A3-coupling reaction.

The use of complexes 1-4 as catalysts for the A3-coupling reaction of isovaraldehyde, 2,4,6-trimethylaniline and triisopropylsilyl acetylene provided interesting insights into the nature of the active species and the reaction mechanism (Figure 1). The reactions were carried out in NMR tubes using toluene-d8 as solvent with a 5 mol% of catalyst (1) and kept at 80 ºC. With the exception of complex 3, all catalysts led to excellent conversions. When the reaction was conducted with complex 4, the conversion was almost identical to that found for 2, giving turnover frequencies at 50% conversion (TOF1/2) of 21 h–1. The dimer [Rh($\square$-Cl)(COE)(IPr)]2 (1) was less efficient, with a TOF1/2 of 8 h-1 and a maximum conversion of 73%. This behaviour can be explained by the ability of the COE ligand to re-enter the coordination sphere, thus hindering the access of substrates to the active site.[11a] The rhodium dicarbonyl complex 3, on the other hand, was virtually inactive under the same reaction conditions, which suggests that 3 is not the active species for the A3-coupling reaction.

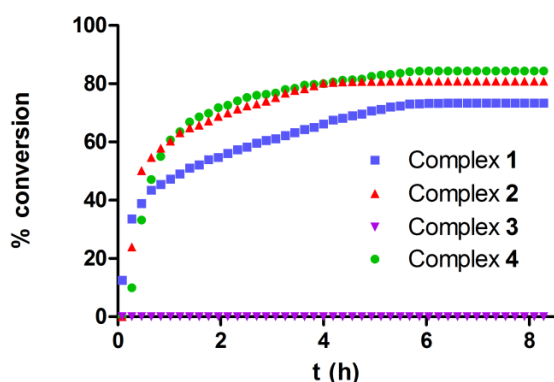Fig 1. Catalysts used for the A3-coupling of isovaraldehyde, o-anisidine and triisopropylsilylacetylene in in C6D6 (0.4 mL) at 80 ºC.

According to the experimental data complex 5 may be postulated as the most plausible active species since imine coordination seems to be predominant compared to that of amines, in fact, 5 is formed in a 60% yield in the presence of 3 equivalents of amine and aldehyde. The

higher imine to complex ratio under catalytic conditions would probably favour the formation of 5 against 4, nevertheless, the presence of the latter should not be discarded. Consequently, an active species containing a coordinated amine trans to the NHC is also conceivable, but less likely than its analogous imine derivative. At first glance, a catalytic cycle that entails (i) interaction of the alkyne with the metal centre followed by (ii) oxidative addition of the C–H bond, (iii) insertion of the imine into the Rh–C bond and, finally, (iv) elimination of the propargylamine (Scheme 7; pathway A), would seem a plausible postulation.

In order to shed light into the reaction mechanism, a computational study at the DFT level using the B3LYP-D3/def2-SVP methodology has been carried out on a model system of complex 5, where the diisopropylphenyl wingtip groups and the imine substituents were replaced by phenyl moieties. The Gibbs energy profile for the hydroalkynylation of imines (R = Ph) by trimethylsilylacetylene is shown in Figure 2.
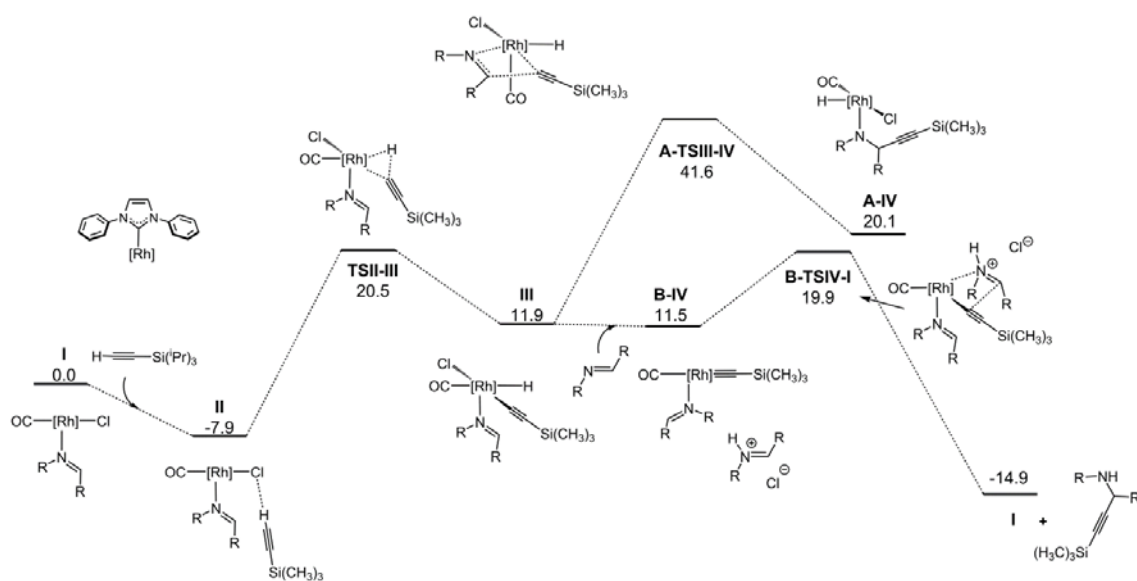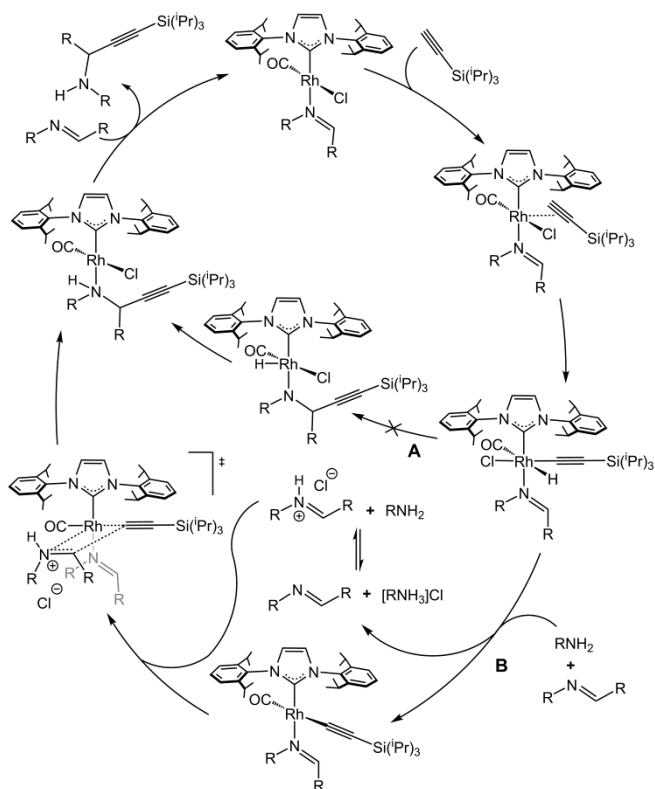

Fig. 2. Gibbs energy profile (in kcal/mol, relative to I and isolated molecules) for the hydroalkynylation of imines (R = Ph) by trimethylsilylacetylene catalysed by I (complex 5).

Scheme 7. Intramolecular (A) and Intermolecular (B) catalytic cycle postulated for the A3-coupling reaction.

The proposed reaction mechanism would entail as first step the interaction of the alkyne molecule with I (complex 5) to form adduct II via a hydrogen bond interaction with the chloride ligand.

Subsequently, oxidative addition of the C–H bond to the metal centre would take place via TSII-III to afford octahedral Rh(III) intermediate (III). This step would be the rate determinig step, with an activation barrier of 28.4 kcal mol–1. At this stage, the theoretical calculations show that the migratory insertion of the imine into the Rh–C bond is not possible due to the high activation barrier obtained for A-TSIII-IV, which presents a relative energy of 41.6 kcal mol–1, unaffordable at the experimental conditions. The instability of A-TSIII-IV can be explained by the perpendicular orientation of the N–C π bond and the Rh–C axis. Thus, this inefficient orbital overlapping in the transition state requires decoordination of the imine to afford a viable transition state (see Supporting Information).

A plausible alternative (pathway B) would entail the approximation of a second molecule that deprotonates intermediate III, with concomitant formation of the iminium (or amonium) salt, release of the chloride anion, and formation of the Rh(I) intermediate B-IV. In this regard, it must be noted that abundant free imine has been observed in the reaction mixture during catalysis at 80 ºC. A 1/4 ratio imine/amine is present at the initial stages, increasing as the reaction proceeds, which indicates that the imine in solution is in equilibrium with the aldehyde and amine. The similar pKa of imines and primary aromatic amines implies that an acid-base equilibrium should lead to the co-existence of RNH2, [RNH3]Cl, R'N=CHR'' and [R'NH=CHR'']Cl throughout the catalytic cycle. Nevertheless, the only substrate interaction that

permits the reaction to proceed successfully is that of the protonated imine. Then, B-IV intermediate in presence of protonated imine would undergo migratory insertion via B-TSIV-I (Figure 2), with a relative energy of 19.9 kcal mol–1. Finally, the release of the propargylamine and the regeneration of the active species is favoured thermodynamically, resulting in an exergonic reaction (14.8 kcal/mol).

To conclude, it is worth noting that the proposed mechanism is consistent with that previously reported by us for the hydroalkynylation of imines catalysed by a bimetallic Ir(II) complex.[7]

Conclusions

In summary, we have developed a three-component coupling reaction of aliphatic aldehydes, aniline derivatives and triisopropylsilylacetylene catalysed by a Rh-NHC complex that operates under relatively mild conditions. This catalytic system has allowed us to generate a library of new propargylamines in good to excellent yields, which may be utilised as building blocks for the preparation of a wide variety of value-added products by the deprotection of the silyl moieties. Moreover, we have proposed a catalytic cycle that sheds light on the hitherto scarcely studied mechanism for the hydroalkynylation of imines. Remarkably, theoretical calculations reveal that the catalytic cycle cannot proceed by direct migratory insertion of the imine into the Rh–alkynyl bond as it would be expected for a "classical" mechanism. Instead, reductive elimination of HCl assisted by the free imine (or amine) in the reaction mixture and formation of a Rh(I) intermediate must occur previous to the migratory insertion of the into the Rh–C bond. In summary, this novel reaction mechanism entails (i) oxidative addition of the alkyne's C–H bond, (ii) protonation of "free" imine, (iii) insertion of the iminium cation into the alkynyl ligand and, finally, liberation of the corresponding propargylamine with concomitant regeneration of the active species.

Experimental Section

General

All reactions and manipulations were performed under an Ar atmosphere by using Schlenk-type techniques. Hexane was dried by standard procedures and distilled under argon before to use or obtained oxygen and water-free from a Solvent Purification System (Innovative Technologies). The starting complexes [Rh(μ-Cl)(IPr)(coe)]2 and [Rh(μ-Cl)(H)2(IPr)]2 were prepared following the procedures described in the literature.[10,14] All other chemicals were used as purchased from Sigma-Aldrich, Merck and Acros. 1H and 13C spectra were recorded either on a Bruker ARX 300 (300 and 75 MHz respectively) or Bruker Avance 400 MHz (400 and 121 MHz respectively) spectrometers using TMS as the internal reference. All chemical shifts (δ) are reported in ppm and coupling constants (J) are reported in Hz to apparent peak multiplicities. 1H-1H COSY, 13C attached proton test (APT), 1H/13C HSQC and 1H/13C HMB sequences were used to help the assignments of the 1H and 13C spectra. C, H, and N analyses were carried out in a Perkin-Elmer 2400 CHNS/O analyzer. GC/MS analyses were recorded on an Agilent 5973 mass selective detector interfaced to an Agilent 6890 series gas chromatograph system using a HP-5MS 5% phenyl methylsiloxane column (30 m × 250 mm with a 0.25 mm film thickness).

[RhCl(CO)IPr(MesNH2)] (4). A solution of [RhH2(µ-Cl)(IPr)]2 (2) (200 mg, 0.379 mmol), 2,4,6-trimethylaniline (80 µL, 1.5 eq, 0.568 mmol), isovaleraldehyde (81 µL, 2.0 eq, 0.757 mmol) in toluene was stirred for 1 h at room temperature. After filtration through Celite®, the solvent was evaporated to dryness. Addition of hexane induced the precipitation of a pale yellow solid that was washed with hexane (3 x 5 mL) and dried in vacuum. Yield: (45%, 117 mg). IR (υ cm-1): 2964, 2279, 1949(CO), 1486, 1466, 1329, 1034, 1023, 800, 754. 1H NMR (400 MHz, C6D6, 298 K): δ 7.30 (dd, JH-H = 8.9, 6.4, 2H, Hp-IPr), 7.22 (dd, JH-H = 8.9, 6.4, 4H, Hm-IPr), 6.67 (s, 2H, =CHN), 6.41 (s, 2H, Hm-Ph), 3.93 (s, 2H, NH2), 3.23 (sept, JH-H = 6.5, 4H, CHMeIPr), 1.91 (s, 3H, p-Me), 1.80 (s, 6H, o-Me), 1.52 and 1.06 (both d, JH-H = 6.5, 24H, CHMeIPr). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 185.7 (d, JC-Rh = 82.3, CO-Rh), 181.6 (d, JC-Rh = 55.6, CIPr-Rh), 146.6 (s, Cq-IPr), 139.2 (s, Cq-Ph), 136.6 (s, CqN), 131.7 (s, Cq-pMe), 129.8 (s, Cp-IPr), 128.7 (s, Cm-Ph), 125.8 (s, Cq-oMe), 123.8 (s, Cm-IPr), 28.7 (s, CHMeIPr), 26.2 and 22.6 (both s, CHMeIPr), 20.2 (s, p-Me), 17.8 (s, o-Me). Anal. Calc. for C37H50ClN3ORh: C, 64.30; H, 7.29; N, 6.08. Found: C, 64.38; H, 7.29; N 6.24.

[RhCl(CO)IPr(MesN=CHCH2CH(CH3)2)] (5). A solution of 4 (30 mg, 0.043 mmol) in toluene-d8 (0.5 mL, NMR tube) was treated with 2,4,6-trimethylaniline (18 µL, 3 eq, 0.130 mmol) and isovaleraldehyde (14 µL, 3 eq, 0.130 mmol) and heated at 40 °C for 30 min. After this time, the resulting solution was analyzed at room temperature by NMR spectroscopy. 1H NMR (400 MHz, C6D6, 298 K): δ 8.58 (td, JH-H = 5.6, 1.3, 1H, N=CH), 7.31 (t, JH-H = 7.2, 2H, Hp-IPr), 7.23 (d, JH-H = 7.2, 4H, Hm-IPr), 6.74 (s, 2H, =CHN), 6.63 (s, 2H, Hm-Ph), 3.27 (sept, JH-H = 6.7, 4H, CHMeIPr), 2.06 (s, 3H, p-Me), 1.95 (s, 6H, o-Me), 1.52 and 1.10 (both d, JH-H = 6.7, 24H, CHMeIPr), 1.45 (dsept, JH-H = 6.4, 6.3, 1H, CHMe), 1.34 (dd, JH-H = 6.3, 5.6, 2H, CH2), 0.57 (d, JH-H = 6.4, 6H, CHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 185.3 (d, JC-Rh = 82.6, CO-Rh), 182.7 (d, JC-Rh = 51.9, CIPr-Rh), 177.7 (s, N=CH), 147.2 (s, Cq-Ph), 147.0 (s, Cq-IPr), 137.0 (s, CqN), 134.2 (s, Cq-pMe), 129.9 (s, Cp-IPr), 129.0 (s, Cm-Ph), 127.8 (s, Cq-oMe), 124.0 (s, Cm-IPr), 123.9 (s, =CHN), 40.8 (s, CH2), 29.0 (s, CHMeIPr), 26.5 and 23.1 (both s, CHMeIPr), 26.4 (s, CHMe), 22.4 (s, CHMe), 20.4 (s, p-Me), 18.5 (s, 2o-Me).

Synthesis of N-Propargylamines.

An NMR tube was charged with 0.01 mmol of catalyst, 0.2651 mmol of aniline derivative, 0.2651 mmol of aldehyde and 0.2651 mmol of triisopropylsilylacetylene in 0.4 mL of C6D6. After sealing it under an argon atmosphere the resulting solution was heated at 80 ºC and monitored by NMR. Reaction product formation was monitored at periodic times and the conversion was quantified by the integration of the 1H NMR signals of imine formed in situ and the products.

N-(1-(triisopropylsilyl)-5-methylhex-1-yn-3-yl)-2-methoxybenzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 6.78 (td, JH-H = 8.3, 1.2, 1H, Hm1-Ph), 6.66 (td, JH-H = 7.6, 1.4, 1H, Hp-Ph), 6.51 (d, JH-H =8.3, 1.2, 1H, Ho-Ph), 6.48 (dd, JH-H = 7.6, 1.4, 1H, Hm2-Ph), 4.29 (t, JH-H = 7.2, 1H, CHNH), 3.32 (s, 3H, OMe), 3.11 (br, 1H, CHNH), 1.89 (m, 1H, CHMe), 1.53 (m, 2H, CH2), 1.13 (d, JH-H = 6.2, 18H, SiCHMe), 1.03 (sept, JH-H = 6.2, 3H, SiCHMe), 0.82 and 0.81 (both d, JH-H = 6.8, 6H, CHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 146.7 (s, Cq-OMe), 136.7 (s, Cq-Ph), 121.1 (s, Cm1-Ph), 117.8 (s, Cp-Ph); 114.7 (s, Cm2-Ph), 110.5 (s, C1), 110.4 (s, Co-Ph), 84.0 (s, C2), 61.1 (s, CHNH), 54.7 (s, OMe), 46.9 (s, CH2),

24.9 (s, CHMe), 22.4 and 22.1 (both s, CHMe), 18.4 (s, SiCHMe), 11.2 (s, SiCHMe). GC-MS m/z: 373 (M+), 358 (M+ - Me), 342, 316, 286, 258, 245, 229, 216, 202, 178.

N-(1-(triisopropylsilyl)-5-methylhex-1-yn-3-yl)-2,6-dimethylbenzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 6.99 (d, JH-H = 7.5, 2H, Hm-Ph), 6.78 (t, JH-H = 7.5, 1H, Hp-Ph), 4.41 (t, JH-H = 7.4, 1H, CHNH), 2.87 (br, 1H, CHNH), 2.18 (s, 6H, MeIMes), 2.01 (m, 1H, CHMe), 1.68 (m, 2H, CH2), 1.22 (d, JH-H = 6.5, 18H, SiCHMe), 1.14 (sept, JH-H = 6.5, 3H, SiCHMe), 0.93 and 0.92 (both d, JH-H = 7.5, 6H, CHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 151.4 and 126.1 (both s, Cq-Ph), 128.0 (s, Cm-Ph), 117.9 (s, Cp-Ph), 110.7 (s, C1), 83.8 (s, C2), 60.9 (s, CHNH), 47.0 (s, CH2), 24.7 (s, CHMe), 22.4 and 22.3 (both s, CHMe), 18.4 (s, SiCHMe), 18.3 (s, MeIMes), 11.3 (s, SiCHMe). GC-MS m/z: 371 (M+), 356 (M+ - Me), 329, 314, 308, 295, 260, 234, 218, 190, 174.

N-(1-(triisopropylsilyl)-5-methylhex-1-yn-3-yl)-2,4,6-trimethylbenzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 6.77 (s, 2H, Hm-Ph), 4.30 (t, JH-H = 7.1, 1H, CHNH), 2.71 (br, 1H, CHNH), 2.18 (s, 3H, p-Me), 2.07 (s, 6H, o-Me), 1.85 (m, 1H, CHMe), 1.56 (m, 2H, CH2), 1.13 (d, JH-H = 6.1, 18H, SiCHMe), 1.01 (sept, JH-H = 6.1, 3H, SiCHMe), 0.83 and 0.81 (both d, JH-H = 6.6, 6H, CHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 149.1 (s, Cq-Ph), 128.7 (s, Cm-Ph), 126.3 and 121.1 (both s, Cq-Me), 110.5 (s, C1), 83.5 (s, C2), 60.8 (s, CHNH), 47.0 (s, CH2), 25.8 (s, CHMe), 22.1 and 22.0 (both s, CHMe), 20.2 (s, p-Me), 18.3 (s, o-Me), 18.2 (s, SiCHMe), 11.0 (s, SiCHMe). GC-MS m/z: 385 (M+), 342, 317, 300, 274, 248, 232, 204, 188, 162.

2,6-diisopropyl-N-(5-methyl-1-(triisopropylsilyl)hex-1-yn-3-yl)aniline.

1H NMR (400 MHz, C6D6, 298 K): δ 7.12 (d, JH-H = 8.0, 2H, Hm-IPr), 6.95 (t, JH-H = 8.0, 1H, Hp-IPr), 4.40 (t, JH-H = 7.3, 1H, CHNH), 3.20 (br, 1H, CHNH), 2.77 (sept, JH-H = 7.4, 2H, CHMeIPr), 2.00 (m, 1H, CHMe), 1.64 (m, 2H CH2), 1.25 (d, JH-H = 7.4, 12H, CHMeIPr), 1.21 (d, JH-H = 6.4, 18H, SiCHMe), 0.95 and 0.93 (both d, JH-H = 6.5, 6H, CHMe), 1.16 (sept, JH-H = 6.4, 3H, SiCHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 140.7 and 131.9 (both s, Cq-Ph), 122.7 (s, Cm-IPr), 118.7 (s, Cp-IPr), 110.8 (s, C1), 83.6 (s, C2), 61.0 (s, CHNH), 47.2 (s, CH2), 28.7 (s, CHMe), 27.9 (s, CHMeIPr), 22.4 and 22.3 (both s, CHMe), 22.3 (s, CHMeIPr), 18.4 (s, SiCHMe), 11.2 (s, SiCHMe). GC-MS m/z: 427 (M+), 407, 384, 370, 359, 344, 330, 316, 290, 274, 260, 230, 202, 188.

2,4-6-tri-tert-butyl-N-(5-methyl-1-(triisopropylsilyl)hex-1-yn-3-yl)aniline.

1H NMR (400 MHz, C6D6, 298 K): δ 7.47 (s, 2H, HPh), 4.40 (t, JH-H = 7.1, 1H, CHNH), 3.77 (br, 1H, CHNH), 1.66 (m, 2H, CH2), 2.02 (sept, JH-H = 7.0, 1H, CHMe), 1.51 (s, 18H, o-tBu), 1.48 (s, 9H, p-tBu), 1.26 (d, JH-H = 6.1, 18H, SiCHMe), 1.15 (sept, JH-H = 6.1, 3H, SiCHMe), 0.95 and 0.93 (both d, JH-H = 7.0, 6H, CHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 141.0 (s, Cq-Ph), 139.7 and 133.5 (both s, Cq-Ph-tBu), 121.4 (s, CPh), 110.5 (s, C1), 84.1 (s, C2), 61.2 (s, CHNH), 47.1 (s, CH2), 34.6 and 34.4 (both s, Cq-tBu), 31.8 (s, p-tBu), 30.3 (s, o-tBu), 24.8 (s, CHMe), 22.3 and 22.2 (both s, CHMe), 18.5 (s, SiCHMe), 11.3 (s, SiCHMe). GC-MS m/z: 511 (M+ not observed), 454 (M+ - tBu), 439, 407, 381, 353, 337, 321, 295, 279, 261, 246, 230, 215, 189.

N-(1-(triisopropylsilyl)-5-methylhex-1-yn-3-yl)-2,6-dimethylbenzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 7.18 (s, 1H, Cp-Ph), 6.41 (s, 2H, Co-Ph), 4.29 (t, JH-H = 7.24, 1H, CHNH), 2.94 (br, CHNH), 1.89 (m, 1H, CHMe), 1.66 (m, 2H, CH2), 1.25 (d, JH-H = 6.7, 18H, SiCHMe), 1.16 (sept, JH-H = 6.7, 3H, SiCHMe), 0.86 and 0.84 (both d, JH-H = 7.5, 6H, CHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 147.7 (s, Cq-Ph), 132.2 (q, JC-F = 31.8, Cq-Ph), 123.7 (q, JC-F = 271.2, C-F), 113.7 (q, JC-F = 4.2, Co-Ph), 110.6 (q, JC-F = 4.1, Cp-Ph), 110.2 (s, C1), 84.3 (s, C2), 61.2 (s, CHNH), 47.2 (s, CH2), 24.7 (s, CHMe), 22.3 and 22.2 (both s, CHMe), 18.5 (s, SiCHMe), 11.2 (s, SiCHMe). GC-MS m/z: 479 (M+), 437, 422, 394, 378, 360, 338, 321, 304, 288, 272, 246, 229, 207, 181.

2-fluoro-N-(1-(triisopropylsilyl)-5-methylhex-1-yn-3-yl)benzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 6.90 (dd, JH-F = 11.5, JH-H = 8.1, 1H, Hm1-Ph), 6.83 (dd, JH-H = 9.3, 7.9, 1H, Hm2-Ph), 6.55 (ddd, JH-H = 8.1, 7.9, JH-F = 5.0, 1H, Hp-Ph), 6.45 (dd, JH-H = 9.3, JH-F = 7.6, 1H, Ho-Ph), 4.40 (t, JH-H = 7.5, 1H, CHNH), 3.01 (br, CHNH), 2.01 (m, 1H, CHMe), 1.65 (m, 2H, CH2), 1.21 (d, JH-H = 6.6, 18H, SiCHMe), 1.11 (sept, JH-H = 6.6, 3H, SiCHMe), 0.95 and 0.93 (both d, JH-H = 6.6, 6H, CHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 151.7 (d, JC-F = 239.4, Cq-Ph), 134.8 (d, JC-F = 12.8, Cq-Ph), 124.3 (d, JC-F = 3.5, Cm2-Ph), 118.1 (d, JC-F = 7.3, Cp-Ph), 116.7 (d, JC-F = 4.1, Co-Ph), 115.0 (d, JC-F = 19.0, Cm1-Ph), 110.2 (s, C1), 84.2 (s, C2), 61.1 (s, CHNH), 47.2 (s, CH2), 24.9 (s, CHMe), 22.4 and 22.2 (both s, CHMe), 18.4 (s, SiCHMe), 11.3 (s, SiCHMe). GC-MS m/z: 361 (M+), 349 (M+ - Me), 321, 304, 279, 265, 241, 232, 207, 192, 178.

N-(1-cyclohexyl-3-(triisopropylsilyl)prop-2-ynyl)-2-methoxybenzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 6.90 (td, JH-H = 8.2, 1.1, 1H, Hm1-Ph), 6.79 (td, JH-H =7.7, 1.3, 1H, Hp-Ph), 6.64 (dd, JH-H = 8.2, 1.1, 1H, Ho-Ph), 6.60 (dd, JH-H = 7.7, 1.3, 1H, Hm2-Ph), 4.16 (d, JH-H = 6.4, 1H, CHNH), 3.44 (s, 3H, OMe), 3.2 (br, 1H, CHNH), 2.04, 1.93, 1.79, 1.67, and 1.60 (all br, 10H, CH2), 1.58 (m, 1H, CHcy), 1.25 (d, JH-H = 6.7, 18H, SiCHMe), 1.17 (sept, JH-H = 6.7, 3H, SiCHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 147.5 (s, Cq-OMe), 146.8 (s, Cq-Ph), 121.5 (s, Cm1-Ph), 118.2 (s, Cp-Ph), 114.9 (s, Cm2-Ph), 110.6 (s, Co-Ph), 109.5 (s, C1), 85.2 (s, C2), 67.5 (s, CHNH), 54.9 (s, OMe), 44.5 (s, CHcy), 29.0, 28.3, 26.9, 26.3, and 26.2 (all s, CH2), 18.8 (s, SiCHMe), 11.5 (s, SiCHMe). GC-MS m/z: 399 (M+), 384, 371, 356, 316, 272, 245, 221, 178.

N-(1-cyclohexyl-3-(triisopropylsilyl)prop-2-ynyl)-2,6-dimethylbenzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 7.0 (d, JH-H = 7.4, 2H, Hm-Ph), 6.79 (t, JH-H = 7.4, 1H, Hp-Ph), 4.16 (d, JH-H = 7.4, 1H, CHNH), 2.87 (br, 1H, CHNH), 1.58 (m, 1H, CHcy), 2.03, 1.91, 1.86, 1.79, and 1.67 (all m, CH2cy), 2.01 (s, 6H, Me), 1.25 (d, JH-H = 6.5, 18H, SiCHMe), 1.14 (sept, JH-H = 6.5, 3H, SiCHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 142.8 (s, Cq-Ph), 128.3 (s, Cm-Ph), 121.2 (s, Cq-Me), 117.9 (s, Cp-Ph), 109.3 (s, C1), 85.1 (s, C2), 67.3 (s, CHNH), 44.2 (s, CHcy), 29.3, 28.7, 28.1, 26.6, and 26.1 (all, CH2cy), 18.6 (s, SiCHMe), 17.2 (s, Me), 11.4 (s, SiCHMe). GC-MS m/z: 397 (M+), 383, 368, 323, 303, 279, 260, 234, 218, 190.

N-(1-cyclohexyl-3-(triisopropylsilyl)prop-2-ynyl)-2,4,6-trimethylbenzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 6.80 (s, 2H, Hm-Ph), 4.16 (d, JH-H = 5.9, 1H, CHNH), 2.70 (br, 1H, CHNH), 2.30 (m, 1H, CHcy), 2.28 (s, 3H, Mep-Ph), 2.03 (s, 6H, Meo-Ph), 2.02, 1.90, 1.78, 1.72, and 1.66 (all br, 10H, CH2cy), 1.25 (d, JH-H = 6.6, 18H, SiCHMe), 1.16 (sept, JH-H = 6.6, 3H, SiCHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 140.5 (s, Cq-Ph), 129.0 (s, Cm-Ph), 126.5 and 121.2 (both s, Cq-Me), 109.3 (s, C1), 85.0 (s, C2), 67.0 (s, CHNH), 44.3 (s, CHcy), 29.4, 28.7, 28.0, 26.6, and 26.0 (all s, CH2cy), 20.2 (s, Mep-Ph), 18.6 (s, SiCHMe), 11.3 (s, SiCHMe), 17.2 (s, Meo-Ph). GC-MS m/z: 411 (M+), 389, 368, 328, 300, 279, 264, 233, 209, 181.

N-(1-cyclohexyl-3-(triisopropylsilyl)prop-2-ynyl)-2,6-diisopropylbenzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 7.13 (d, JH-H = 7.8, 2H, Hm-Ph), 6.96 (t, JH-H = 7.8, 1H, Hp-Ph), 4.16 (d, JH-H = 5.8, 1H, CHNH), 3.04 (br, 1H, CHNH), 2.78 (sept, JH-H = 6.8, 2H, CHMeIPr), 1.93, 1.82, 1.78, 1.65, and 1.29 (all m, CH2cy), 1.58 (m, 1H, CHcy), 1.25 (d, JH-H = 6.8, 12H, CHMeIPr), 1.21 (d, JH-H = 6.6, 18H, SiCHMe), 1.16 (sept, JH-H = 6.6, 3H, SiCHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 140.5 (s, Cq-Ph), 131.9 (s, Cq-Ph-o-IPr), 122.8 (s, Cm-Ph), 118.7 (s, Cp-Ph), 109.1 (s, C1), 85.2 (s, C2), 67.4 (s, CHNH), 44.4 (s, CHcy), 29.3, 28.8, 26.1, 26.0, and 25.5 (all m, CH2cy), 27.9 (s, CHMeIPr), 18.6 (s, CHMeIPr), 18.4 (s, SiCHMe), 11.3 (s, SiCHMe). GC-MS m/z: 453 (M+), 411, 385, 367, 359, 344, 316, 274, 260, 230, 204, 188, 172.

2,4,6-tri-tert-butyl-N-(1-cyclohexyl-3-(triisopropylsilyl)prop-2-ynyl)benzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 7.47 (s, 2H, HPh), 4.18 (d, JH-H = 5.9, 1H, CHNH), 3.59 (br, 1H, CHNH), 2.05, 1.96, 1.83, 1.80, and 1.69 (all m, CH2cy), 1.62 (m, 1H, CHcy), 1.52 (s, 18H, o-tBu), 1.48 (s, 9H, p- tBu), 1.27 (d, JH-H = 6.5, 18H, SiCHMe), 1.22 (sept, JH-H = 6.5, 3H, SiCHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 141.4 (s, Cq-Ph), 139.2 (s, Cq-Ph-p-tBu), 133.7 (s, Cq-Ph-o-tBu), 121.7 (s, CPh), 109.2 (s, C1), 85.5 (s, C2), 67.3 (s, CHNH), 44.4 (s, CHcy), 34.8 and 34.6 (both s, Cq-tBu), 31.9 (s, Cp-tBu), 30.3 (s, Co-tBu), 28.9, 28.3, 26.9, 26.3, and 26.2 (all s, CH2cy), 18.9 (s, SiCHMe), 11.6 (s, SiCHMe). GC-MS m/z: 537 (M+ not observed), 507 (M+ - 2Me), 490, 476, 461, 419, 379, 357, 321, 261, 246, 215, 191.

N-(1-cyclohexyl-3-(triisopropylsilyl)prop-2-ynyl)-3,5-bis(trifluoromethyl)benzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 7.15 (s, 1H, Cp-Ph), 6.40 (s, 2H, Co-Ph), 4.02 (d, JH-H = 5.9, 1H, CHNH), 3.01 (s, 1H, CHNH), 1.89, 1.79, 1.67, 1.19, and 1.13 (all br, 10H, CH2cy), 1.42 (m, CHcy), 1.12 (d, JH-H = 6.0, 18H, SiCHMe), 1.04 (sept, JH-H = 6.0, 3H, SiCHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 147.7 (s, Cq-Ph), 132.1 (q, JC-F = 33.0, Cq-Ph), 123.8 (q, JC-F = 272.0, C-F), 113.6 (q, JC-F = 3.3, Co-Ph), 110.4 (q, JC-F = 4.0, Cp-Ph), 108.7 (s, C1), 85.4 (s, C2), 67.2 (s, CHNH), 44.1 (s, CHcy), 28.6, 27.9, 26.4, 25.9, and 25.8 (all s, CH2cy), 18.4 (s, SiCHMe), 11.2 (s, SiCHMe). GC-MS m/z: 505 (M+), 489, 462, 436, 422, 407, 389, 365, 321, 279, 255, 225, 09, 195, 181, 157.

N-(1-cyclohexyl-3-(triisopropylsilyl)prop-2-ynyl)-2,4,6-trimethoxybenzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 5.81 (s, 2H, HPh), 4.24 (d, JH-H = 5.7, 1H, CHNH), 3.89 (s, 3H, Hp-OMe), 3.54 (s, 6H, Ho-OMe), 3.41 (br, 1H, CHNH), 1.99, 1.96, 1.78, 1.26, and 1.22 (all m, CH2cy), 1.65 (m, 1H, CHcy), 1.20 (d, JH-H = 6.2, 18H, SiCHMe), 1.14 (sept, JH-H = 6.2, 3H,

SiCHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 154.5 and 143.3 (both s, Cq-OMe), 131.6 (s, Cq-Ph), 109.4 (s, C1), 93.3 (s, CPh), 84.9 (s, C2), 67.2 (s, CHNH), 60.3 (s, Cp-OMe), 55.6 (s, Co-OMe), 44.2 (s, CHcy), 29.5, 28.8, 26.7, 26.0, and 25.5 (all s, CH2cy), 18.4 (s, SiCHMe), 11.5 (s, SiCHMe). GC-MS m/z: 459 (M+ not observed), 416 (M+ - iPr), 401, 387, 357, 346, 322, 303, 288, 276, 162, 246, 233, 209, 177.

N-(1-cyclohexyl-3-(triisopropylsilyl)prop-2-ynyl)benzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 7.14 (dd, JH-H = 7.8, 7.4, 2H, Hm-Ph), 6.80 (t, JH-H = 7.4, 1H, Hp-Ph), 6.48 (d, JH-H = 7.8, 2H, Ho-Ph), 4.18 (d, JH-H = 5.7, 1H, CHNH), 3.36 (br, 1H, CHNH), 1.90, 1.73, 1.63, 1.32, and 1.20 (all m, CH2cy), 1.61 (m, 1H, CHcy), 1.22 (d, JH-H = 6.0, 18H, SiCHMe), 1.16 (sept, JH-H = 6.0, 3H, SiCHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 146.8 (s, Cq-Ph), 128.9 (s, Cm-Ph), 118.4 (s, Cp-Ph), 114.8 (s, Co-Ph), 109.3 (s, C1), 84.9 (s, C2), 67.3 (s, CHNH), 44.0 (s, CHcy), 29.4, 26.6, 26.1, 25.9, and 25.5 (all s, CH2cy), 18.5 (s, SiCHMe), 11.5 (s, SiCHMe). GC-MS m/z: 369 (M+), 354 (M+ - Me), 326 (M+ - iPr), 310, 298, 286, 270, 258, 242, 218, 202, 187, 178.

N-(1-(triisopropylsilyl)-4-methylpent-1-yn-3-yl)-2-methoxybenzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 6.90 (td, JH-H =8.0, 0.9, 1H, Hm1-Ph), 6.79 (td, JH-H =7.9, 1.2, 1H, Hp-Ph), 6.64 (dd, JH-H = 8.0, 0.9, Ho-Ph), 6.60 (dd, JH-H = 7.9, 1.2, 1H, Hm2-Ph), 4.15 (d, JH-H = 5.5, 1H, CHNH), 3.44 (s, 3H, OMe), 3.3 (br, 1H, CHNH), 1.88 (septd, JH-H = 6.7, 5.5, 1H, CHMe), 1.24 (d, JH-H = 6.6, 18H, SiCHMe), 1.16 (sept, JH-H = 6.6, 3H, SiCHMe), 1.13 and 1.06 (both d, JH-H = 6.7, 6H, CHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 147.3 and 146.7 (both s, Cq-Ph), 121.3 (s, Cm1-Ph), 117.9 (s, Cp-Ph), 114.8 (s, Cm2-Ph), 110.5 (s, Co-Ph), 108.8 (s, C1), 85.1 (s, C2), 67.8 (s, CHNH), 54.6 (s, OMe), 34.7 (s, CHMe), 18.6 (s, SiCHMe), 18.1 and 17.2 (both s, CHMe), 11.3 (s, SiCHMe). GC-MS m/z: 359 (M+), 345, 329, 316, 202, 177.

N-(1-(triisopropylsilyl)hex-1-yn-3-yl)-2-methoxybenzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 6.90 (td, JH-H =8.1, 1.3, 1H, Hm1-Ph), 6.79 (td, JH-H =7.7, 1.7, 1H, Hp-Ph), 6.64 (dd, JH-H = 8.1, 1.3, 1H, Ho-Ph), 6.59 (dd, JH-H =7.7, 1.7, 1H, Hm2-Ph), 4.32 (t, JH-H = 6.6, 1H, CHNH), 3.44 (s, 3H, OMe), 3.40 (s, CHNH), 1.70 (m, 2H, CH2), 1.56 (m, 2H, CH2), 1.23 (d, JH-H = 6.8, 18H, SiCHMe), 1.15 (sept, JH-H = 6.8, 3H, SiCHMe), 0.92 (t, JH-H = 7.3, 3H, Me). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 147.3 and 146.6 (both s, Cq-Ph), 121.3 (s, Cm1-Ph), 117.9 (s, Cp-Ph), 114.7 (s, Cm2-Ph), 110.5 (s, Co-Ph), 110.4 (s, C1), 84.0 (s, C2), 62.3 (s, CHNH), 54.8 (s, OMe), 40.2 (s, CH2), 18.7 (s, CH2), 18.6 (s, SiCHMe), 13.7 (s, Me), 11.2 (s, SiCHMe). GC-MS m/z: 359 (M+), 345, 331, 316, 301, 278, 262, 245, 221, 202, 178, 164.

N-(1-(triisopropylsilyl)oct-1-yn-3-yl)-2-methoxybenzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 6.89 (td, JH-H =8.0, 1.5, 1H, Hm1-Ph), 6.78 (td, JH-H = 7.7, 1.7, 1H, Hp-Ph), 6.64 (dd, JH-H = 8.0, 1.5, 1H, Ho-Ph), 6.60 (dd, JH-H = 7.7, 1.7, 1H, Hm2-Ph), 4.34 (t, JH-H = 7.0, 1H, CHNH), 3.44 (s, 3H, OMe), 3.40 (br, 1H, CHNH), 1.75, 1.55, 1.33, and 1.29 (all m, 8H, CH2), 1.25 (d, JH-H = 6.5, 18H, SiCHMe), 1.14 (sept, JH-H = 6.5, 3H, SiCHMe), 0.95 (t, JH-H = 6.9, 3H, Me). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K):

δ 147.3 and 146.6 (both s, Cq-Ph), 121.1 (s, Cm1-Ph), 118.0 (s, Cp-Ph), 114.8 (s, Cm2-Ph), 110.5 (s, Co-Ph), 110.4 (s, C1), 83.8 (s, C2), 62.4 (s, CHNH), 54.5 (s, OMe), 38.0, 31.4, 25.0, and 22.6 (all s, CH2), 18.6 (s, SiCHMe), 13.9 (s, Me), 11.4 (s, SiCHMe). GC-MS m/z: 387 (M+), 372 (M+ - Me), 344, 316, 287, 272, 244, 229, 202, 187, 165.

2-fluoro-N-(1-(triisopropylsilyl)undec-1-yn-3-yl)benzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 6.92 (dd, JH-F = 11.5, JH-H = 8.2, 1H, Hm1-Ph), 6.83 (dd, JH-H = 9.1, 8.1, 1H, Hm2-Ph), 6.56 (ddd, JH-H = 8.2, 8.1, JH-F = 5.0, 1H, Hp-Ph), 6.45 (dd, JH-H = 9.1, JH-F = 7.1, 1H, Ho-Ph), 4.35 (t, JH-H = 6.6, 1H, CHNH), 3.20 (br, 1H, CHNH), 2.75, 2.26, 2.25, 1.76, 1.74, 1.56, 1.33 (all m, CH2), 1.25 (d, JH-H = 6.0, 18H, SiCHMe), 1.14 (sept, JH-H = 6.0, 3H, SiCHMe), 1.01 (t, JH-H = 6.8, 3H, Me). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 151.9 (d, JC-F = 232.0, Cq-Ph), 134.9 (d, JC-F = 14.8, Cq-Ph), 124.3 (d, JC-F = 4.7, Cm2-Ph), 118.0 (d, JC-F = 7.7, Cp-Ph), 116.6 (d, JC-F = 4.5, Co-Ph), 115.1 (d, JC-F = 18.7, Cm1-Ph), 110.0 (s, C1), 84.6 (s, C2), 62.5 (s, CHNH), 38.0, 32.0, 29.6, 28.7, 25.6, 25.3, and 22.9 (all m, CH2), 18.6 (s, SiCHMe), 14.0 (s, Me), 11.3 (s, SiCHMe). GC-MS m/z: 417 (M+), 397, 374, 357, 339, 318, 304, 286, 274, 254, 240, 228, 216, 203, 188.

N-(4-ethyl-1-(triisopropylsilyl)hex-1-yn-3-yl)-2-methoxybenzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 6.89 (td, JH-H = 7.9, 1.4, 1H, Hm1-Ph), 6.78 (td, JH-H =7.7, 1.8, 1H, Hp-Ph), 6.64 (dd, JH-H = 7.9, 1.4, 1H, Ho-Ph), 6.60 (dd, JH-H = 7.7, 1.8, 1H, Hm2-Ph), 4.43 (d, JH-H = 5.2, 1H, CHNH), 3.44 (s, 3H, OMe), 3.40 (br, 1H, CHNH), 1.54 (m, 4H, CH2), 1.52 (m, 1H, CHEt2), 1.22 (d, JH-H = 6.6, 18H, SiCHMe), 1.13 (sept, JH-H = 6.6, 3H, SiCHMe), 1.01 and 0.97 (both t, JH-H = 7.3, 6H, Me). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 147.3 and 146.6 (both s, Cq-Ph), 121.2 (s, Cm1-Ph), 117.9 (s, Cp-Ph), 114.9 (s, Cm2-Ph), 110.5 (s, Co-Ph), 109.3 (s, C1), 85.1 (s, C2), 64.8 (s, CHNH), 54.7 (s, OMe), 47.6 (s, CHEt2), 22.6 and 22.2 (both s, CH2), 18.6 (s, SiCHMe), 11.5 and 11.1 (both s, Me), 11.3 (s, SiCHMe). GC-MS m/z: 387 (M+), 358, 344, 316, 276, 261, 237, 221, 205, 181.

N-(4-(triisopropylsilyl)-1-phenylbut-3-yn-2-yl)-2-methoxybenzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 7.53 (d, JH-H = 8.3, 2H, Ho-bz), 7.34 (m, 2H, Hm-bz), 6.89 (td, JH-H = 7.4, 1.3, 1H, Hm1-Ph), 6.80 (m, 1H, Hp-bz), 6.78 (td, JH-H =7.8, 1.7, 1H, Hp-Ph), 6.64 (dd, JH-H = 7.4, 1.3, 1H, Ho-Ph), 6.58 (dd, JH-H = 7.8, 1.7, 1H, Hm2-Ph), 4.53 (t, JH-H = 6.7, CHNH), 3.34 (s, 3H, OMe), 3.11 (br, 1H, CHNH), 2.97 (d, JH-H = 6.7, CH2), 1.21 (d, JH-H = 6.3, 18H, SiCHMe), 1.17 (sept, JH-H = 6.3, 3H, SiCHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 147.0 (s, Cq-OMe), 141.0 and 136.7 (both s, Cq-Ph), 129.3 (s, Co-bz), 128.5 (s, Cm-bz), 121.6 (s, Cp-bz), 121.2 (s, Cm1-Ph), 118.0 (s, Cp-Ph), 114.8 (s, Cm2-Ph), 110.6 (s, Co-Ph), 109.4 (s, C1), 85.7 (s, C2), 63.5 (s, CHNH), 54.7 (s, OMe), 44.3 (s, CH2), 18.4 (s, SiCHMe), 11.0 (s, SiCHMe). GC-MS m/z: 407 (M+, not observed), 392, 365, 317, 285, 228, 185, 165.

2,4,6-tri-tert-butyl-N-(1-(triisopropylsilyl)hex-1-yn-3-yl)benzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 7.46 (s, 2H, HPh), 4.32 (t, JH-H = 6.2, 1H, CHNH), 3.78 (br, 1H, CHNH), 1.51 (s, 18H, o-tBu), 1.47 (s, 9H, p- tBu), 1.72 (m, 2H, CH2), 1.56 (m, 2H, CH2CH3), 1.22 (d, JH-H = 6.3, 18H, SiCHMe), 1.16 (sept, JH-H = 6.3, 3H, SiCHMe), 0.94 (t, JH-H = 7.4, 3H,

Me). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 141.2 (s, Cq-Ph), 139.0 and 133.5 (both s, Cq-Ph-tBu), 121.5 (s, CPh), 110.1 (s, C1), 84.2 (s, C2), 62.3 (s, CHNH), 40.3 (s, CH2), 34.6 and 34.5 (both s, Cq-tBu), 31.8 (s, Cp-tBu), 30.3 (s, Co-tBu), 18.6 (s, CH2CH3), 18.4 (s, SiCHMe), 13.6 (s, Me), 11.1 (s, SiCHMe). GC-MS m/z: 497 (M+, not observed), 440 (M+ - tBu), 426, 396, 382, 368, 354, 321, 285, 270, 246, 228, 207, 181.

2,4,6-tri-tert-butyl-N-(1-(triisopropylsilyl)oct-1-yn-3-yl)benzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 7.46 (s, 2H, HPh), 4.33 (t, JH-H = 6.6, 1H, CHNH), 3.78 (br, 1H, CHNH), 1.76 (td, JH-H = 7.1, 6.6, 2H, CH2), 1.54, 1.34, and 1.31 (all m, 6H, CH2), 1.51 (s, 18H, o-tBu), 1.47 (s, 9H, p- tBu), 1.26 (d, JH-H = 6.2, 18H, SiCHMe), 1.17 (sept, JH-H = 6.2, 3H, SiCHMe), 0.96 (t, JH-H = 7.3, 3H, Me). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 141.1 (s, Cq-Ph), 138.9 (s, Cq-Ph-p-tBu), 133.5 (s, Cq-Ph-o-tBu), 121.4 (s, CPh), 110.3 (s, C1), 84.2 (s, C2), 62.6 (s, CHNH), 38.0, 31.6, 25.0, and 22.8 (all s, CH2), 34.6 and 34.4 (both s, Cq-tBu), 31.7 (s, Cp-tBu), 30.3 (s, Co-tBu), 18.5 (s, SiCHMe), 13.9 (s, Me), 11.2 (s, SiCHMe). GC-MS m/z: 525 (M+, not observed), 468 (M+ - tBu), 451, 442, 421, 398, 377, 337, 321, 284, 265, 246, 223, 197, 181.

2,4,6-tri-tert-butyl-N-(1-(triisopropylsilyl)undec-1-yn-3-yl)benzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 7.46 (s, 2H, HPh), 4.35 (t, JH-H = 7.3, 1H, CHNH), 3.75 (br, 1H, CHNH), 1.77 (m, 2H, CH2), 1.56 (m, 2H, CH2), 1.50 (s, 18H, o-tBu), 1.47 (s, 9H, p-tBu), 1.4-1.3 (m, 10H, CH2), 1.22 (d, JH-H = 6.2, 18H, SiCHMe), 1.16 (sept, JH-H = 6.2, 3H, SiCHMe), 1.01 (t, JH-H =6.4, 3H, Me). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 141.0 (s, Cq-Ph), 139.0 and 133.4 (both s, Cq-Ph-tBu), 121.5 (s, CPh), 110.4 (s, C1), 84.3 (s, C2), 62.7 (s, CHNH), 38.1, 32.0, 31.8, 29.5, 25.3, 22.9, and 22.8 (s, CH2), 34.6 and 34.4 (both s, Cq-tBu), 31.8 (s, Cp-tBu), 30.2 (s, Co-tBu), 18.4 (s, SiCHMe), 14.1 (s, Me), 11.3 (s, SiCHMe). GC-MS m/z: 567 (M+, not observed), 509 (M+ - tBu), 494, 479, 463, 447, 424, 396, 370, 340, 311, 283, 265, 246, 230, 201, 185.

2,4,6-tri-tert-butyl-N-(1-(triisopropylsilyl)-4-methylpent-1-yn-3-yl)benzenamine.

1H NMR (400 MHz, C6D6, 298 K): δ 7.47 (s, 2H, HPh), 4.13 (d, JH-H = 5.3, 1H, CHNH), 3.78 (br, 1H, CHNH), 1.89 (septd, JH-H = 6.9, 5.3, 1H, CHMe), 1.51 (s, 18H, o-tBu), 1.47 (s, 9H, p-tBu), 1.25 (d, JH-H = 6.3, 18H, SiCHMe), 1.18 (sept, JH-H = 6.3, 3H, SiCHMe), 1.13 and 1.06 (both d, JH-H = 6.9, 6H, CHMe). 13C{1H}-APT NMR plus HSQC and HMBC (100 MHz, C6D6, 298 K): δ 141.2 (s, Cq-Ph), 139.0 (s, Cq-Ph-p-tBu), 133.6 (s, Cq-Ph-o-tBu), 121.5 (s, CPh), 108.6 (s, C1), 85.2 (s, C2), 68.0 (s, CHNH), 34.6 (s, CHMe), 34.5 and 34.4 (both s, Cq-tBu), 31.8 (s, Cp-tBu), 30.2 (s, Co-tBu), 18.6 (s, SiCHMe), 18.0 and 17.2 (both s, CHMe), 11.3 (s, SiCHMe). GC-MS m/z: 497 (M+, not observed), 441 (M+ - tBu), 426, 398, 382, 365, 337, 304, 284, 261, 246, 230, 201, 181.

Computational details

All DFT theoretical calculations have been carried out using the Gaussian program package.[15] The B3LYP method[16] including the D3 dispersion correction scheme developed by Grimme[17] or both energies and gradient calculations has been employed in combination to the def2-SVP basis set[18] for all atoms. Solvent corrections were estimated by single point

energy calculations on optimised geometries using the PCM[19] approach with benzene as solvent. The nature of the stationary points has been confirmed by analytical frequency analysis, and transition states were characterised by a single imaginary frequency corresponding to the expected motion of the atoms. Due to the well-known overestimation of the entropy in the solution calculated using the gas-phase approach, the vibrational and rotational entropy terms only are included in the free energy in solution at 353.15 K.[20] Molecular structures were represented using CYLView software.[21]

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