N-Heterotricyclic cationic carbene ligands. Synthesis, reactivity and coordination chemistry

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The direct dialkylation of triazolo[4,3-b]isoquinolin-3-ylidene structures readily afford dicaticonic N-heterotricyclic azolium salts. These are suitable starting materials for the synthesis of transition metal complexes containing N-heterotricyclic, cationic ligands characterized by extended charge delocalization. Silver and gold complexes as well as mono- and dicaticonic rhodium(0) complexes have been prepared and characterized, and the electronic properties of the ligand have been evaluated by using the TEP parameter and by comparison with a non-cationic analogue. X-Ray diffraction analysis of several carbene-metal complexes show a negligible effect of the charge in the structures of the complexes. The catalytic activity of a tricaticonic gold complex has been evaluated in the intramolecular hydroarylation of a terminal alkyne.

Introduction

Chiral N-heterocyclic carbenes (NHCs) constitute not only a privileged class of ligands in transition-metal catalysis, but also a useful class of Lewis bases with a plethora of applications in asymmetric organocatalysis. Although research on metal NHC complexes has focused primarily on their excellent σ-donor properties, recent examples of ligands with increased π-acceptor character have been reported. Transition metal complexes based on these π-acidic NHCs exhibit enhanced Lewis acidity, consequently performing a superior catalytic activity in π-acid-catalyzed reactions. For instance, Fürstner and co-workers reported different reactions pathways in cycloisomerization reactions using various NHC-gold complexes and rationalized a correlation of the reaction fate with the π-accepting properties of the ligands. Commonly, the π-accepting ability of NHCs has been modulated by modifying the backbone structures and N-substituents, usually with the introduction of electron-withdrawing groups. While the introduction of remote anionic moieties into the NHC backbone has emerged as an efficient strategy to increase the electron-donating properties and reveal new reactivities, the introduction of cationic charges into the carbenic moiety should efficiently provide more π-acidic NHC ligands. However, cationic ligands with a positive charge on (or adjacent to) the coordinating atom are rare, as its coordination ability is logically compromised. Nevertheless, metal species with cationic ligands have been synthesized and have shown their superior activity in a number of challenging processes such as the electrophilic C-H bond activation of hydrocarbons and electrophilic cyclizations of unsaturated systems. There are examples in literature that include nitrenium cations, α-cationic phosphines and pyridinophosphines but examples with NHCs have been scarce. In the last years, however, a handful of reports dealing with cationic NHCs have appeared (Figure 1). For example, Ganter has described cationic NHCs with an attached Cp*Ru fragment or a fused pyridinium moiety. These carbenes showed attenuated donor properties with enhanced π-accepting character. Recently, César and Weigand have reported cationic imidazol-ylidene NHCs with an ammonium and a phosphonium substituent, respectively, in an imidazolidine scaffold. Finally, the electronic properties of a known triazoliumylidene have also been very recently reported by Ganter and co-workers.

Figure 1 Selected examples of cationic N-heterocyclic carbenes.
During the last years our group has been involved in the design, synthesis and applications of new families of N-heterocyclic carbenes, focusing in particular in NHCs fused in heterobicyclic systems like imidazopyridines or triazolopyridines, as well as larger tricyclic systems such as imidazoloisoquinolinilylidene structures. More recently, we have been also interested in the development of applications for these type of ligands in Au(I)-catalysed asymmetric transformations. During these investigations it became evident that the activation of the substrate is the rate determining step in many cases and, therefore, more η-acidic ligands should provide superior catalytic activities. In this context, we envisaged a new strategy based on the synthesis of dicationic salts as direct precursors of cationic N(1),N(2)-dialkylated triazolo[4,3-b]isoquinolin-3-ylidene structures. In this article we report our results on the synthesis, structure, and electronic properties of these new type of ligands.

The synthesis of 1 was readily accomplished according to the reaction sequence indicated in the Scheme 1. The process involves a selective Suzuki coupling between 1,3-dichloroisquinoline 2 and mesityl boronic acid 3, followed by Buchwald-Hartwig amination of the resulting product 4 with BocNHNHBoc to yield hydrazine 5. Finally, a 'one pot' deprotection/formylation/cyclization protocol using HCl, formic acid and POCl3 as reagents yielded the desired triazoisquinoline 1.

Our first approach consisted on a dialkylation reaction using 1,3-bis(trifluoromethanesulfonyloxy)propane 6 to obtain azolium salt 7 (Scheme 2). We initially assumed that the second intramolecular alkylation would be favoured in relative terms by entropic factors. However, this proved to be a very challenging reaction; most tested conditions led to a mixture.

Results and discussion
On the light of the above-mentioned antecedents, we anticipated that triazoisquinoline derivative 1 could be a particularly well suited model system for double alkylations leading to the required dicaticonic azolium salts. The choice of this particular system was made on the basis of the following considerations:
1. The corresponding carbene has the advantage of a considerable steric protection.
2. It is a good model for future work in asymmetric catalysis: a desymmetrization of the aromatic substituent in CS would easily incorporate axial chirality in the resulting cationic NHC ligands.
3. A particularly low-lying LUMO energy is expected as a consequence of very efficient charge delocalization in the heterotricyclic scaffold.

Scheme 1 Synthesis of 1. Reagents and conditions: (a) Pd(PPh3)4, CsF, DME, reflux, 24 h, 78%; (b) BocNHNHBoc, Pd2(dba)3, dppf, Cs2CO3, toluene, reflux, 24 h, 92%; (c) HCl 2M dioxane, rt, 12 h; (d) HCOOH, reflux, 24 h; (e) POCl3 toluene, reflux, 24 h, 62% overall.

Scheme 2 Synthesis of dicationic salt 7 and tricationic silver complex 8.
of compounds resulting from intermolecular dialkylation of 6. Finally, slow addition of a 1,2-dichloroethane solution of compound 1 to bis-triflate 6 led to the desired salt 7 after 4 days at reflux. This salt proved to be very sensitive to ring-opening nucleophilic attacks at the N=CH₂ methylene carbons, thereby relaxing the charge concentration in the heterocycle. Nevertheless, a careful manipulation under inert atmosphere in the absence of nucleophilic solvents allowed its isolation in a reasonable 56% yield. Treatment of this salt with Ag₂O in CH₃CN led to the corresponding tricationic, silver tris-triflate complex 8 in excellent yield (80%). The structure of this complex was unequivocally determined by single-crystal X-ray diffraction (Figure 2). As the most remarkable feature, the C–Ag–C angle shows a record deviation from linearity [158.28(11)°] for dicoordinated complexes of this type. Experiments performed in the presence of NaI, aimed to obtain the monocarbene NHC-Ag̷ complex, were unsuccessful. In order to obtain a similar tricationic gold complex, salt 7 was treated with Ag₂O and the crude product was transmetalated with AuI, leading to a very unstable compound that decomposed rapidly in solution.

Aiming to overcome these stability problems, we considered the synthesis of dicationic salts lacking the strained aliphatic cyclic moiety. Interestingly, azolium salt 9 (a direct precursor of the alternative carbene 10) could be easily prepared in quantitative yield from cyclic compound 1 and methyl triflate (Scheme 3). The corresponding silver complex was prepared again with Ag₂O in CH₃CN. In this case, however, the analysis of NMR spectra (¹H, ¹³C, HSQC and DOSY experiments) indicated a 1:2.2 mixture of two different NHC-Ag̷ species: the expected tricationic silver complex 11 and a second silver complex 12. Crystallization of the latter could be accomplished by slow diffusion of pentane into a saturated acetone solution of the above mixture, and the single-crystal X-ray diffraction analysis showed a dicationic silver monocarbene complex with solvent acetonitrile as ligand (Figure 3). Attempts to obtain exclusively the NHC-silver

![Figure 2 X-Ray structure of silver complex 8. Triflate anions and H atoms are omitted for clarity.](image1)

![Figure 3 ORTEP drawing of NHC-Ag̷ complex 12. Triflate anions and H atoms are omitted for clarity.](image2)

**Scheme 3 Synthesis of dicationic salt 9 and derivative complexes 11-13.**
complex 11 using non-coordinating solvents failed for the poor solubility of the triazolium dextrinate 9 in such media. However, in situ treatment of this mixture with Aul in acetonitrile led exclusively to the corresponding tricationic gold complex 13 in excellent yield. As anticipated, this complex exhibited a much higher stability and could be fully characterized. Moreover, crystals of 13 suitable for X-ray diffraction analysis were grown by slow diffusion of pentane into a saturated acetone solution of this complex (Figure 4).

The intramolecular hydroarylation of propargyl aryl ether 14 was used as a model system for a preliminary evaluation of the potential of this type of complexes in catalysis. Thus, the reaction carried out using a 3 mol% of 13 in dioxane at room temperature led to the corresponding chromene 15 in an excellent 91% yield in 5 h (Scheme 4). This result compares well with previously reported Pt or Au catalysts. Remarkably, bulky, neutral Au(NHC) complexes such as [IMes(NCMe)]SbF 6 or [IPrAu(NCMe)]SbF 6 show a relatively poor performance in the hydroarylation reaction.

We were next interested in the quantification of the electronic properties of the new cationic NHC ligand 10, and perform a comparative analysis with a similar non-cationic system. We considered N-heterocyclic carbene 16 as a suitable reference for comparison purposes (Figure 5). Azolium salt 17, direct precursor of 16, was prepared in excellent yield from cyclic compound 1 by regioselective alkylation with adamantyl bromide (Scheme 5). This monocationic salt showed high solubility in chlorinated solvents in clear contrast with the triazolium dextrinate 9. In addition, the chemical shift of the C5 proton at the triazolium ring appears at 10.15 ppm, whereas the second positive charge in salt 9 induced a stronger deshielding to this proton (11.07 ppm). Silver and gold complexes were easily obtained from 17: after anion exchange, metallation of the chloride salt 18 with Ag 2 O (→19) followed by transmetallation with AuCl·Me 2 S gave the desired gold complex 20 in good yield.

On the other hand, azolium salt 18 was deprotonated with potassium tert-butoxide and treated with [Rh(COD)Cl] 2 in dry THF to give the corresponding Rh(NHC)(COD)Cl complex 21 in 61% yield (Scheme 6). The preparation of a similar complex from dicationic salt 9, however, was a challenging reaction. Direct deprotonation by KOBu, NaH or KHMS led to decomposition of the starting material. On the other hand,
transmetallation from the silver complex in acetonitrile was used to access dicationic rhodium complex 22 as the main product. Again, the poor solubility of 9 prevented the use of non-coordinating solvents in this reaction. Finally, treatment of ditriflate 9 with 0.5 mol equivalents of \textit{in situ} generated \((\text{Rh}[\text{N(SiMe}_3]_2][\text{COD}])_2\) led to the formation of the monocationic rhodium complex 23 in good yield (70%). This complex has been fully characterized by spectroscopic and analytical techniques. The coordinated carbene carbon resonates at 185.3 ppm \((J_{\text{Rh-C}} 54.3 \text{ Hz})\) in the \(^{13}\text{C}\) NMR spectrum, which is significantly shifted to low field in comparison to the corresponding carbene signal in the neutral complex (δ 175.2 ppm, \(J_{\text{Rh-C}} 51.6 \text{ Hz}\)). Crystals suitable for X-ray diffraction analysis of 22 were grown by slow diffusion of diethyl ether into a solution of the complex in acetonitrile. Similarly, crystallization of 23 was accomplished by slow diffusion of pentane into a solution of the complex in acetone. Very similar bond lengths and angles, corresponding to nearly perfect planar geometries, were observed for both complexes. Additionally, dicarbonyl complexes 24 and 25 were...
quantitatively obtained by bubbling a slow CO stream through a THF solution of the corresponding Rh(NHC)(COD)Cl complexes 21 and 23. Crystals of both dicarbonyl complexes were also grown by slow diffusion of pentane into acetone solutions of the complexes. X-Ray diffraction analysis (Figure 6) of both structures showed that the delocalized charge in the latter has no significant influence on the structure of these complexes. On the other hand, IR spectra of both complexes were recorded and the CO stretching vibrations were used to calculate their corresponding TEP values23 according to the linear regression established by Plenio and Nolan24 (Figure 7). As expected, the introduction of a positive charge in the heterocyclic system modifies significantly the β-donation ability of the carbene. A shift of approximately 15 cm\(^{-1}\) towards a higher frequency is observed for the cationic ligand 10 (TEP = 2056 cm\(^{-1}\)) with respect of the neutral analogue 16 (TEP = 2041.5 cm\(^{-1}\)). Nevertheless, the donor ability of the cationic ligand remains relatively good, in particular compared with the monocyclic cationic NHC ligand 27 recently described by Ganter, with a record TEP of 2073 cm\(^{-1}\) [\(\Delta\text{[TEP]} = -17 \text{ cm}^{-1}\)]. The effect of the inclusion of the carbene into a heterotricyclic system is quantitatively very similar in the neutral series; the TEP for the monocyclic ligand 26 of 2058 cm\(^{-1}\) is 16.5 cm\(^{-1}\) higher than the tricyclic derivative 16, suggesting that the donation ability is markedly improved by the inclusion of the NHC in the fused tricyclic system.\(^{6}\) On the other hand, the use of \(^{77}\text{Se}\) NMR chemical shifts in their corresponding NHC(=Se) adducts was envisaged as a convenient method to assess the β-accepting ability of these ligands.\(^{25}\) It was anticipated that the extended π system in ligands 16 and 10 should result in a marked lowering of the LUMO with respect of the monocyclic derivatives. In fact, the δ[\(^{77}\text{Se}\)] value of 197 ppm in 16(=Se) is strongly shifted with respect to the monocyclic species [δ[\(^{77}\text{Se}\)] = 23 ppm in 26(=Se)]. Unfortunately, any attempts to synthesize the cationic adduct 10(=Se) were unsuccessful and the comparative analysis with 16(=Se) and 27(=Se) could not be performed, although an even better acceptor ability of 10 is logically inferred from the available data.

**Conclusions**

In summary, dicaticionic [1,2,4]triazolo[4,3-b]isoquinoline-1,2-dium salt 9, readily available by double methylation of 5-mesityl-[1,2,4]triazolo[4,3-b]isoquinoline 1, can be used as a precursor of cationic N-heterotricyclic carbene ligands in silver, gold and rhodium complexes. Cationic [Rh(NHC)(CO)]\(_2\) complexes have been prepared and used to calculate the TEP parameter of the ligand, and the comparison with neutral and monocyclic analogues indicate a relatively good donation ability at the level of a neutral monocyclic 1,2,4-triazol-2-ylidene. However, \(^{77}\text{Se}\) NMR data recorded for the neutral, tricyclic NHC(=Se) adduct show a remarkable acidity that, arguably, must be even higher in the cationic analogue. Modifications of the model system to obtain axially chiral analogues and their application in asymmetric metal-catalyzed reactions are currently under investigation in our laboratory.

**Experimental**

**General information.** Solvents were purified and dried by standard procedures. Flash chromatography was carried out on silica-gel (Merck Kiesegel 40-60). Melting points were recorded in a metal block and are uncorrected. The NMR spectra were recorded on a Bruker Avance 300, Bruker Avance III 300, Bruker Avance 500, and a Bruker Avance III 700. All \(^1\)H and \(^13\)C NMR spectra were referenced to the chemical shifts of residual solvent signal: \(\delta_{\text{Me}}\text{(CDCl}_3\text{)} = 7.26 \text{ ppm, } \delta_{\text{CD}}\text{(CDCl}_3\text{)} = 77.00 \text{ ppm, } \delta_{\text{Me}}\text{(CD}_3\text{CO)} = 2.05 \text{ ppm, } \delta_{\text{CD}}\text{(CD}_3\text{CO)} = 29.84 \text{ ppm, } \delta_{\text{Me}}\text{(CD}_2\text{CN)} = 1.94 \text{ ppm, } J\text{ values are given in Hz.} \) \(^{77}\text{Se}\) chemical shifts were referenced indirectly\(^{26}\) using the signal of TMS as the reference frequency (\(\Xi = 19.071513 \text{ for} \) \(^{77}\text{Se}\)). NMR samples of all cationic complexes have been prepared under inert atmosphere. Mass spectra were recorded on an Orbitrap ELITE (ESI) and DFS (CI or El) mass spectrometers. X-Ray crystal structure data were collected on a Bruker Kappa APEX DUO diffractometer. \(^1\)H, \(^1\)D-Chloroisoquinoline (2)\(^{27}\) and \(^1\)D-bis(trifluoromethanesulfonyloxy)propane (6)\(^{28}\) were prepared following previously described procedures.

**Synthesis of 3-chloro-1-mesitylsquinoline (4).**

A round-bottom flask was charged with \(1,3\)-dichloroisoquinoline 2 (5.50 g, 27.7 mmol), mesitylboronic acid 3 (5.00 g, 30.5 mmol), Pd(PPh\(_3\))\(_2\) (1.60 g, 5 mmol%), and CsF (9.40 g, 60.9 mmol) and dry 1,2-dimethoxyethane (55 mL) under an argon atmosphere. The mixture was deoxygenated and heated under reflux for 24 h. Et\(_2\)O was added (100 mL) and the mixture was filtered through a celite pad. The organic layer was washed with brine (2 \(\times\) 40 mL), dried (MgSO\(_4\)), filtered and concentrated. The residue was purified by flash chromatography (1:3 EtOAc–cyclohexane).

Yield 6.01 g, 78%. White solid. Mp 108–110 °C.
1H NMR (300 MHz, CDCl3) δ 7.81 (1H, d, J = 7.6 Hz), 7.72 (1H, d, J = 0.9 Hz), 7.68 (1H, d, J = 7.9, 6.9, 1.5 Hz), 7.55–7.52 (1H, m), 7.44 (1H, d, J = 7.9, 6.7, 1.2 Hz), 6.97 (2H, d, J = 0.6 Hz), 2.36 (3H, s, CH3), 1.88 (6H, s, 2CH3).

13C NMR (75 MHz, CDCl3) δ 162.6, 145.0, 138.3, 138.1, 136.1, 134.3, 131.1, 128.3, 127.0, 126.5, 126.2, 118.6, 21.1, 19.8.

m/z (ESI) 284 (32%, M+1, 37Cl), 282 (100, M+1, 35Cl), 214 (7). HRMS m/z calcd for C43H37ClN2 288.1495, found 288.1486.

Synthesis of dicaticionic salt 7.

Neutral heterocycle 1 (210 mg, 0.730 mmol) was dissolved in dry 1,2-dichloroethane (10 mL) and was added slowly (0.6 mL/h) to 1,3-bis(trifluoromethanesulfonyloxy)propane 6 (620 mg, 1.83 mmol). Next, dry 1,2-dichloroethane (6 mL) was added and the reaction was stirred under reflux for 4 days. Then, the mixture was concentrated in vacuo and the residue was washed with dry diethyl ether.

Yield 257 mg, 56%. Yellow solid.

1H NMR (300 MHz, CDCl3) δ 10.91 (1H, d, J = 1.1 Hz), 9.37 (1H, s), 8.52 (1H, d, J = 9.1 Hz), 8.23–8.18 (1H, m), 7.95 (1H, d, J = 9.0, 6.6, 1.0 Hz), 7.80 (1H, dq, J = 9.0, 1.0 Hz), 7.32 (2H, br s), 5.48 (2H, td, J = 7.6, 1.2 Hz, NCH3), 5.39 (2H, t, J = 7.2 Hz, NCH3), 3.52 (2H, m, J = 7.3 Hz, CH2CH2CH2), 2.48 (3H, s, CH3), 1.96 (6H, s, 2CH3).

Synthesis of triazolium salt 9.

Triazolium salt 7 (50 mg, 0.080 mmol), Ag2O (18 mg, 0.080 mmol) and 3Å molecular sieves were suspended in dry CH3CN (1 mL) under an argon atmosphere and in darkness. The mixture was stirred at 10 °C for 3 h, filtered under argon via cannula and the concentrated to dryness.

Yield 38 mg, 80%. Yellow solid.

1H NMR (300 MHz, CDCl3) δ 9.00 (2H, s), 8.33 (2H, d, J = 8.9 Hz), 8.04–7.99 (2H, m), 7.72 (2H, ddd, J = 9.0, 6.6, 0.9 Hz), 7.49–7.46 (6H, m), 5.15 (8H, br t, J = 7.2 Hz, 4NCH3), 3.35 (4H, quintet, J = 7.2 Hz, 2CH2CH2CH2), 2.30 (6H, s, 2CH3), 1.99 (12H, s, 4CH3).

15N NMR (75 MHz, CDCl3) δ 170.5 (2d, J,C,N = 236.1 and 204.3 Hz, C–Ag), 145.5, 143.9, 140.8, 138.9, 137.9, 136.0, 130.9, 130.7, 129.1, 128.6, 127.1, 126.3, 124.5, 122.0 (q, J,C,F = 321.3 Hz, CF3), 117.7, 106.7, 52.7, 49.6, 21.6, 20.3.

Synthesis of 5-mesylyl-1,2-dimethyl-[1,2,4]triazolo[4,3-b]isoquinolin-1,2-dium bis(triflate) (9).

1 (600 mg, 2.09 mmol) was dissolved under an argon atmosphere in methyltrifluoromethanesulfonate (31.0 mmol, 3.50 mL) and heated at 110 °C for 15 h. The mixture was concentrated in vacuo and the residue was washed with dry Et2O.

Yield 1.29 g, quant. Yellow solid.

1H NMR (700 MHz, CDCl3) δ 11.07 (1H, s), 9.44 (1H, s), 8.46 (1H, d, J = 8.8 Hz), 8.17–8.15 (1H, m), 7.93–7.91 (1H, m), 7.76 (1H, d, J = 9.0 Hz), 7.31 (2H, br s), 4.91 (3H, s, NCH3), 4.86 (3H, s, NCH3), 2.47 (3H, s, CH3), 1.95 (6H, s, 2CH3).

13C NMR (175 MHz, CDCl3) δ 144.0, 142.6, 141.9, 140.7, 139.7, 137.6, 135.9, 132.8, 130.6, 129.0, 127.2, 126.2, 123.1, 107.3, 40.2, 36.1, 21.4, 19.7.

HRMS (ESI) m/z calcd for [C51H27ClN5]+ 158.5941, found 158.5940.
Synthesis of silver complexes 11 and 12.

Triazolium salt 9 (300 mg, 0.500 mmol), Ag₂O (113 mg, 0.500 mmol) and 3Å molecular sieves were suspended in dry CH₂CN (1.5 ml) under an argon atmosphere and in darkness. The mixture was stirred at 10 °C for 4 h and then filtered under argon via cannula. The solvent was evaporated and the resulting oil was solidified by treatment with dry Et₂O. Removal of the solvent via cannula yielded complexes 11 and 12 as a yellow solid (ratio 1:2.2) in quantitative combined yield (341 mg). Complex 12 was recrystallized from a pentane–acetone mixture.

¹H NMR data of complex 12 from recrystallized product (500 MHz, (CD₂)₂CO) δ 9.09 (1H, s), 8.34 (1H, d, J = 8.8 Hz), 8.04–8.01 (1H, m), 7.07 (1H, dd, J = 8.3, 6.7 Hz), 7.47–7.45 (3H, m), 4.69 (3H, s, NCH₃), 4.67 (3H, s, NCH₃), 2.28 (3H, s, CH₃), 1.99 (6H, s, CH₃).

¹H NMR data of complex 11 from mixture of 11 and 12 (500 MHz, (CD₂)₂CO) δ 9.06 (2H, s), 8.33–8.30 (2H, m), 8.01–7.96 (2H, m), 7.73–7.68 (2H, m), 7.51 (2H, d, J = 8.8 Hz), 7.33 (4H, s), 4.72 (6H, s, NCH₃), 4.66 (6H, s, NCH₃), 2.49 (6H, s, CH₂), 1.90 (12H, s, 4CH₂).

¹³C NMR (125 MHz, (CD₂)₂CO) data of 11 and 12 δ 176.0 (2d, JCA = 238.1 and 206.2 Hz, C–Ag), 145.3, 144.6, 144.0, 143.3, 141.5, 141.1, 139.0, 138.9, 136.1, 135.9, 131.1, 130.9, 130.7, 130.6, 128.6, 128.5, 127.0, 126.9, 125.9, 124.8, 124.7, 122.0 (q, JCF = 321.4 Hz, CF₂), 118.4, 106.6, 106.0, 42.0, 40.8, 35.8, 35.4, 21.5, 21.2, 20.4, 19.9, 1.4.


A mixture of complexes 11 and 12 (ratio 1:2.2, from 0.50 mmol of salt 9), Aul (81 mg, 1.0 mmol) and 3Å molecular sieves were suspended in dry CH₂CN (1.5 ml) under an argon atmosphere and in darkness. The mixture was stirred at rt for 4 h and then filtered under argon via cannula. The solvent was evaporated and the resulting oil was solidified by treatment with dry Et₂O. Removal of the solvent via cannula led to gold complex 13.

Yield 290 mg, 92% from salt 9. Yellow solid.

¹H NMR (700 MHz, (CD₂)₂CO) δ 9.17 (2H, s), 8.35 (2H, d, J = 9.1 Hz), 8.07 (2H, dd, J = 8.7, 6.6 Hz), 7.77 (2H, ddd, J = 9.0, 6.6, 0.9 Hz), 7.44 (2H, dd, J = 9.0, 0.9 Hz), 7.40 (4H, s), 4.75 (12H, s, 4NCH₃), 2.25 (s, 6H, 2CH₃), 1.97 (12H, s, 4CH₂).

¹³C NMR (175 MHz, (CD₂)₂CO) δ 177.8, 144.6, 143.8, 141.7, 141.3, 139.3, 136.7, 131.7, 130.8, 128.6, 127.1, 126.4, 125.4, 106.9, 42.3, 36.1, 21.5, 20.5.

HRMS (ESI) m/z calcd for [C₄₃H₄₅AuN₄][¹⁹] 274.4246, found 274.4418.

Synthesis of 2-(adamantan-1-yl)-5-mesityl-[1,2,4]triazolo[4,3-b]isoquinolin-2-im chloride (18).

Bromide 17 (154 mg, 0.310 mmol) was eluted through a Dowex 22 anion exchange resin column using methanol as eluant. The solvent was removed in vacuo and the residue was solved in CH₂Cl₂, dried (MgSO₄) and concentrated.

Yield 142 mg, quantitative. Yellow solid. Mp 180–183 °C.

¹H NMR (300 MHz, CDCl₃) δ 10.39 (1H, s), 8.34 (1H, s), 7.87 (1H, d, J = 9.0 Hz), 7.51 (1H, ddd, J = 8.7, 5.8, 1.6 Hz), 7.31–7.26 (2H, m), 7.15 (2H, s), 2.56–2.55 (6H, m, 6Hₕₐd), 2.41 (3H, s, CH₃), 2.31 (3H, br s, 3Hₕₐd), 1.91 (6H, s, 2CH₂), 1.87–1.72 (m, 6H, 6Hₕₐd).

¹³C NMR (75 MHz, CDCl₃) δ 145.3, 142.0, 137.8, 136.9, 136.2, 130.9, 129.7, 128.8, 127.5, 124.9, 124.1, 123.5, 110.1, 66.7, 41.7, 35.4, 29.5, 21.4, 19.9.

Synthesis of silver complex 19.

Triazolium salt 18 (106 mg, 0.230 mmol), Ag₂O (35 mg, 0.05 mmol) and 4Å molecular sieves were suspended in dry CHCl₃ (1.5 ml) under an argon atmosphere and in darkness. The mixture was stirred at rt for 12 h and then filtered through a celite pad and concentrated to dryness.

Yield 130 mg, quantitative. Yellow foam.

¹H NMR (300 MHz, CDCl₃) δ 8.10 (1H, s), 7.67 (1H, d, J = 8.9 Hz), 7.34–7.28 (1H, m), 7.18 (2H, s), 7.09 (2H, br s), 2.55–2.54 (6H, m, 6Hₕₐd), 2.50 (3H, br s, CH₃), 2.29 (3H, br s, 3Hₕₐd), 1.79–1.72 (12H, m, 2CH₂ + 6Hₕₐd).

¹³C NMR (75 MHz, CDCl₃) δ 177.4, 145.6, 145.5, 139.3, 136.5, 135.2, 130.0, 129.4, 127.2, 126.9, 126.5, 125.3, 121.7, 109.3, 63.7, 44.3, 35.8, 29.8, 21.6, 19.7.

Synthesis of gold complex 20.

A solution of silver complex 19 (130 mg, 0.230 mmol) and AuCl·Me₂S (88 mg, 0.30 mmol) in dry toluene (0.7 ml) was stirred at rt in darkness for 2 h. The mixture was filtered through a celite pad and concentrated to dryness. The residue was purified by flash chromatography (45:45:10 EtOAc–cyclohexane–CH₂Cl₂).

Yield 130 mg, 86%. Yellow solid.

¹H NMR (500 MHz, CDCl₃) δ 8.10 (1H, s), 7.67 (1H, d, J = 9.0 Hz), 7.33–7.30 (1H, m), 7.13 (2H, br s), 7.11–7.09 (2H, m), 3.81 (2H, s), 3.46 (2H, s), 3.16 (2H, s), 2.60 (2H, s), 2.31 (3H, br s, 3Hₕₐd).

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Synthesis of rhodium complex 23.
A solution of KHMDS (0.50 M in toluene, 0.28 mL, 0.14 mmol, 1.05 equiv) was added dropwise to a solution of [Rh(COD)]2 (35 mg, 0.07 mmol, 0.5 equiv) in dry 1:1 THF–toluene (1 mL) at −80 °C. After 30 min, solid bis(triflate) 9 (82 mg, 0.13 mmol, 1.0 equiv) was added and the solution stirred at rt overnight. The solvent was evaporated and the resulting oil was solidified by treatment with dry Et2O. Removal of the solvent via cannula led to rhodium complex 23.

Yield 66 mg, 70%. Yellow solid.

Synthesis of rhodium complex 22.
A mixture of complexes 11 and 12 (ratio 1:2:2, from 0.070 mmol of salt 9), [Rh(COD)]2 (35 mg, 0.070 mmol) and 3Å molecular sieves were suspended in dry CH3CN (1.0 mL) under an argon atmosphere and in darkness. The mixture was stirred at rt for 4 h and then filtered under argon via cannula. The solvent was evaporated and the resulting residue was treated with dry Et2O. Removal of the solvent via cannula and recrystallization of the precipitate from acetonitrile/Et2O led to the corresponding rhodium complex.

Yield 36 mg, 60% from salt 9. Yellow solid.

General procedure for the synthesis of dicarbonyl rhodium complexes 24-25.
CO gas was bubbled into a solution of the corresponding rhodium complex (0.07 mmol) in dry CH2Cl2 (1 mL) for 10 min, during which time the colour changed from bright yellow to pale yellow. After 30 min, all volatiles were removed under vacuum to obtain the corresponding dicarbonyl rhodium complexes in quantitative yield.

Rhodium complex 24.

Yield 97%, 35 mg, 0.13 mmol, 1.0 equiv.

IR (CH2Cl2) νco 1950, 1920 cm−1.
m/z (ESI) 580 (100%, M^−−Cl), 552 (98, M^−−Cl-CO), 524 (8, M^−−Cl-2CO). HRMS m/z calcd for C_{41}H_{32}O_{2}N_{2}ClRhNa 638.1052, found 638.1053.

Rhodium complex 25.

^1^H NMR (500 MHz, CDCl_3) δ 8.62 (1H, s), 8.00 (1H, d, J = 8.9 Hz), 7.70–7.67 (1H, m), 7.49–7.44 (2H, m), 7.24 (1H, s), 7.22 (1H, s), 4.75 (3H, s, NCH_3), 4.56 (3H, s, NCH_3), 2.51 (3H, s, CH_3), 1.95 (3H, s, CH_3), 1.88 (3H, s, CH_3).

^1^C NMR (125 MHz, CDCl_3) δ 183.6 (d, J_{C=O} = 58.3 Hz, NCN), 179.6 (d, J_{C=CN} = 73.6 Hz, Rh–CO), 177.7 (d, J_{C=CN} = 46.9 Hz, Rh–CO), 146.4, 142.3, 140.5, 140.3, 139.3, 138.5, 134.9, 130.1, 129.5, 129.1, 128.7, 127.6, 126.9, 125.6, 124.4, 120.3 (q, J_{C=O} = 319.6 Hz, CF_3), 104.7, 41.2, 35.2, 21.4, 21.1, 20.1.

IR (CHCl_3) Y_{CO} 2011, 2083 cm^{-1}.

Synthesis of 2-(adamantan-1-yl)-5-mesityl[1,2,4]triazolo[4,3-b]isoquinoline-3(2H)-selenone [(16=Se)].

A mixture of triazolium chloride 18 (50 mg, 0.11 mmol) and Se (13 mg, 0.16 mmol) were suspended in dry THF (1 mL) under an argon atmosphere. A solution of KHMSD (0.50 M in toluene, 0.26 mL, 0.13 mmol) was added. The mixture was stirred at rt for 5 h. The solvent was evaporated and the residue was purified by flash chromatography (CH_2Cl_2-cyclohexane 1:1).

Yield 44 mg, 81%. Pink solid.

^1^H NMR (500 MHz, CDCl_3) δ 7.84 (1H, s), 7.47 (1H, d, J = 8.8 Hz), 7.13 (1H, t, J = 6.4 Hz), 7.00 (1H, d, J = 9.2 Hz), 6.94–6.91 (3H, m), 2.92 (6H, s, 2CH_3), 2.41 (3H, s, CH_3), 2.29 (3H, br s, 3H_{ad}), 1.85–1.71 (12H, m, 12H_{ad}).

^1^C NMR (125 MHz, CDCl_3) δ 147.1, 145.3, 139.9, 139.4, 138.3, 135.2, 129.1, 128.1, 127.4, 126.7, 125.9, 125.8, 121.9, 110.0, 66.6 (C_{ad}), 39.1 (C_{ad}), 36.1 (C_{ad}), 30.2 (C_{ad}), 21.4 (CH_3), 20.8 (2CH_3).

^7^Se NMR (96 MHz, CDCl_3) δ 197.0.

m/z (ESI) 502 (1%, M^−+1), 422 (100, M^−−Se). HRMS (ESI) m/z calcd for C_{40}H_{31}N_{2}Se 502.1744, found 502.1756.

Gold(i)-catalyzed intramolecular hydroarylation reaction.

Catalyst 13 (3 mmol) was added to a solution of 1,3-dimethyl-5-(prop-2-yl-1-xylo)benzene 14 (30 mg, 0.17 mmol) in dry dioxane (0.15 M) under nitrogen atmosphere. The mixture was stirred at rt for 5 h and then filtered over celite. The solvent was evaporated and the residue was purified by flash chromatography (2:1 cyclohexane–CH_2Cl_2) to yield 5,7-dimethyl-2H-chromene 15. The NMR data was in complete agreement with those reported in literature.21a

Yield 25 mg, 91% (mixed with 9% of unreacted starting material).

Conflicts of interest

There are no conflicts to declare.

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Notes and references

6 Noteworthy, heterobicyclic [1,2,4]triazolo[4,3-d]pyridin-3-ylidenes also follow this trend. For instance, a TEP of 2051 was calculated by linear regression from the IR data for the 5-methyl-2-phenyl derivative shown below. See ref. 17.

References


