

The Potential of Self-Activating Au(I) Complexes in Gold Catalysis

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Gold catalysis has emerged as a groundbreaking field in synthetic chemistry, revolutionizing numerous organic transformations. Despite the significant achieved advancements, the mechanistic understanding behind many gold-catalyzed reactions remains elusive. This Concept article covers the so-called “self-activating” Au(I) complexes, sorting out their pivotal role in gold catalysis. We comment on how Au(I) complexes can undergo self-activation, triggering diverse catalytic transformations without the need for external additives. The most important examples reported so far that underlie the catalytic activity of these species are discussed. This intrinsic reactivity

represents a paradigm shift in gold catalysis, offering new avenues for the design of efficient and sustainable catalytic systems. Furthermore, we explore the factors influencing the stability, reactivity, and selectivity of these Au(I) complexes, providing insights into their synthetic utility and potential applications. This area of research not only advances our fundamental understanding of gold catalysis but also paves the way for the development of novel catalytic strategies with broad implications in organic synthesis and the chemical industry.

1. Introduction

Gold homogeneous catalysis has experienced significant progress since 1990, marked by the discovery of the carbophilic properties of gold species.^[1] Over the later three decades, a plethora of examples have been reported, primarily focusing on the π activation of C–C multiple bonds (alkenes, allenes and alkynes) by exploiting gold(I) complexes as soft Lewis acids.^[2] Moreover, more complex transformations have also been achieved, such as gold capability for carbene transfer from diazo compounds, which demonstrates a broad scope and high levels of selectivity.^[3] Thus, gold(I) catalysis has emerged as an invaluable tool in modern organic synthesis, offering efficient and sustainable methodologies for the construction of intricate molecular architectures.^[4]

In typical gold(I)-catalyzed reactions, the prevalent complexes employed are of the form [LAuCl], where L represents a two-electron donor neutral ligand, such as carbenes or phosphanes.^[5] The use of different ligands to fine-tune the properties of these gold(I) complexes has further expanded their synthetic utility, offering a platform for tailoring their

catalytic activity to suit specific reaction pathways.^[6] Despite being formally coordinatively unsaturated, these [LAuCl] complexes exhibit limited catalytic activity on their own.^[7] Instead, they serve as precatalysts that require *in situ* activation through chloride scavengers. This process generates LAu⁺ species in solution, identified as the most common active species in gold(I) catalysis (Scheme 1a).^[8]

Although LAu⁺ species have been proposed in most gold(I) catalytic cycles, they remain elusive, and their existence is still speculative. These species are thought to play a key role in gold(I) catalysis; however, there is still no structural proof of their existence as stable and isolable entities.^[9]

Chloride abstraction is commonly achieved by introducing a silver or copper salt containing a weakly coordinating anion, such as AgSbF₆ or CuOTf.^[10] However, this method has two principal drawbacks: i) it requires the use of an additional metal, and ii) the inclusion of a Ag(I) salt often has a detrimental impact on the reaction outcome due to light sensitivity and hygroscopic nature of silver salts, added to the non-innocent catalytic behavior of silver additives, commonly known as the “silver effect”.^[11] Consequently, there is a significant interest in current research to explore alternative chloride abstractors and designing novel gold(I) catalytic systems (Scheme 1b).^[12]

Several approaches to alternative chloride abstractors have been studied. One straightforward alternative to metal salts involves the use of polar solvents, such as water,^[13] alcohols,^[14] or deep eutectic solvents (DES).^[15] In these cases, the hydrogen bonding network of the solvent facilitates the abstraction of the chloride atom from the gold(I) precatalyst.^[16] Another strategy is the utilization of alkali metal salts, specifically sodium and potassium salts with non-coordinating anions, which have proven to be effective as halide scavengers. Notably, the sodium salt Na[BAR^F₄] has demonstrated outstanding performance among other salts. The lipophilic anion [BAR^F₄][−] (tetrakis[3,5-bis(trifluoromethyl)phenyl]borate) can abstract the

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chloride anion, leading to the formation of insoluble NaCl and a cationic gold(I) complex.^[17] Additionally, an alternative method for Au–Cl bond activation involves non-covalent interactions, such as iodonium^[18] and telluronium salts,^[19] capable of chloride abstraction through halogen or chalcogen bonding respectively (Scheme 1b).

However, it is crucial to recognize that all these approaches require the addition of an external reagent, typically acting as the pre-catalyst activator itself. This introduction of an extra component not only diminishes the sustainability of the process but also introduces an additional factor that must be considered when studying the mechanism underlying the catalyzed reaction.

For this reason, self-activating gold catalysts emerge as an alternative beyond external additives. The concept of “self-activation” implies a tailor-made ligand capable of intramolecularly abstracting the chloride anion from the gold center. In this unique design, the complex itself presents both a 14-electron linear gold metal and a chloride scavenger moiety within the same molecule. This innovative approach not only simplifies the catalytic process but also eliminates the need for external reagents, contributing to the overall sustainability and efficiency of gold catalysis.^[20]

In this regard, this Concept article will systematically revisit various approaches reported on self-activating gold catalysts. Our focus is particularly directed towards understanding the details of the activation process and the structural features

surrounding the tailored ligands utilized in their synthesis. We will cover a detailed examination of the usual methodologies, including, weak donor ligands, the incorporation of bridging ligands, and the utilization of other non-covalent interactions such as hydrogen, triel, tetrel, pnictogen, chalcogen and halogen bonding. By placing a special emphasis on these aspects, we aim to provide a comprehensive overview of the methodologies employed in self-activation in gold catalysis, shedding light on the crucial role of ligand design in determining the catalytic behavior of these systems.

2. Self-Activating Gold Catalysts

2.1. Single Heteroatom Bridging Ligands

Bridging ligands are a class of ligands that act as connectors between multiple metal ions. Within this context, this section is focused on single heteroatom bridges, specifically those derived from groups 16 and 17, between two gold metal centers (Scheme 2).

In this class of compounds, the self-activation pathway is intentionally designed, enabling the dinuclear complex to act as a reservoir of “naked gold”, releasing LAu^+ species (Scheme 2a). Interestingly, the electron density of the bridging ligand can be modulated to enhance the lability of the Au–bridging atom bond.^[22] This modulation influences the avail-



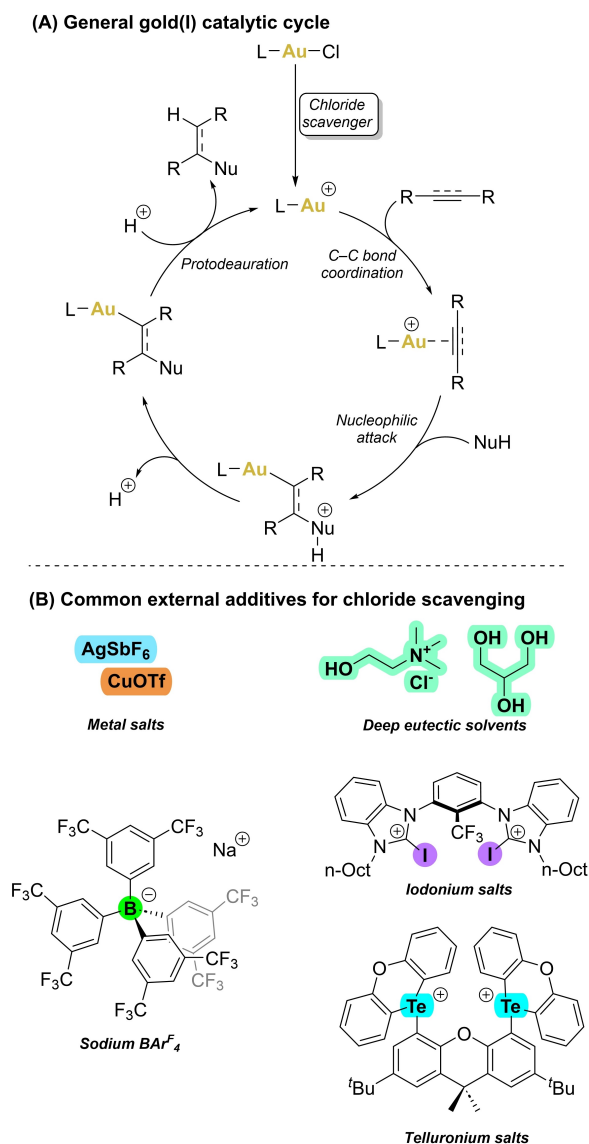
Juan Carlos Pérez-Sánchez born in 1999 in Zaragoza, Spain. He earned his Bachelor's degree in Chemistry with the highest honors, receiving the “Bachelor Extraordinary Award” from the University of Zaragoza in 2021. In 2023, he completed a Master's degree in Molecular Chemistry and Homogeneous Catalysis, also with honors and an “Extraordinary Award”. Currently pursuing a Ph.D. at the University of Zaragoza, supported by an FPU grant, his research, supervised by Dr Raquel P. Herrera and Prof. M. Concepción Gimeno, focuses on Group 11 Metals & Ferrocene Chemistry, aiming to develop molecular complexity for diverse applications in catalysis, synthesis, reactivity, and exploration of biological properties.



Raquel P. Herrera completed her Ph.D. (1999–2003) at the University of Alicante. After a European postdoctoral contract in Bologna (2003–2006), she joined IIQ-CSIC in Seville (2006–2008). Then, she was appointed as group leader (ARAD program) at the ISQCH-University of Zaragoza (2008) and in 2012 she obtained a permanent position as Tenured Scientist (CSIC) at the same Institute. Currently, she is Scientific Researcher since 2021 at the ISQCH. She received the Lilly Prize (2012) and an accessit in the Tercer Milenio 2021 Award in the category “Research and Future”. She is the group leader of the Asymmetric Organocatalysis research group.



M. Concepción Gimeno earned her PhD from the University of Zaragoza. Following postdoctoral research with Prof. Stone at the University of Bristol, she joined ISQCH, CSIC-UZ, becoming Research Professor in 2008. Her research focuses on the study of new group 11 metal compounds for catalytic, luminescent, and/or biological applications. With more than 300 scientific publications, she has received numerous awards, including IUPAC 2017 Distinguished Women in Chemistry or Chemical Engineering, GEO-Excellence in Organometallic Chemistry Research Award (2017), RSEQ-Excellence Research Award (2018), Rafael Usón Medal (2022) and Chemistry Europe Fellow (2023), among others. She leads the Gold and Silver Chemistry research group



Scheme 1. a) General catalytic cycle for gold-catalyzed functionalization of C–C multiple bonds; b) Common external additives used for chloride abstraction.

ability of the crucial LAu^+ species, impacting the catalytic reaction. Moreover, these precatalysts demonstrate stability in both solid and solution states, ensuring the controlled liberation of catalytically active species, and subsequently facilitating the regeneration process. Scheme 2b highlights pivotal examples of such self-activating dinuclear gold(I) catalysts, and this concept aims to provide a succinct description of their significance.

In 2010, Nolan and coworkers reported the synthesis of the first digold hydroxide, $[(\mu\text{-OH})\{\text{Au}(\text{IDipp})\}_2]\text{BF}_4$, **1**, (IDipp = 1,3-bis(2,6-diisopropyl-phenyl)-imidazol-2-ylidene).^[23] In catalytic reactions, the unique feature of this family of complexes lies in its ability to dissociate into a Lewis acid and a Brønsted base, allowing π -activation and nucleophilic activation of substrates, respectively.

Similarly, bridging halide complexes have been known since 1979,^[24] but it was not until 2006, when Hashmi and coworkers employed the chloronium gold complex $[(\mu\text{-Cl})\{\text{Au}(\text{PPh}_3)\}_2]\text{BF}_4$ and the trimesityl phosphane analogue $[(\mu\text{-Cl})\{\text{Au}(\text{PMes}_3)\}_2]\text{BF}_4$ in a catalytic intermolecular reaction of an alkyne with a furan, which opened the door to a synthetically promising field.^[25]

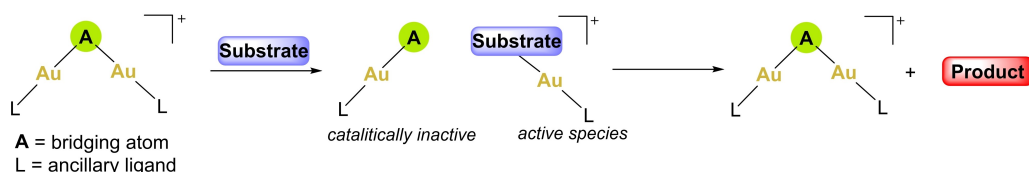
Furthermore, in 2016, van der Vlugt and coworkers reported the first intramolecular chloride bridged complex **2** (Scheme 2b), based on a PNP diphosphane redox-active ligand.^[26] Hence, **2** was used as a pre-catalyst in the reaction involving terminal alkynes, such as in the cycloaddition of urea-functionalized alkynes, providing dual gold activation with high regioselectivity for the *anti*-Markovnikov product which demonstrated the advantage of forcing the gold centers proximity by using this class of ligand.

A year later, Corma and coworkers studied the catalytic A^3 -coupling of ethynyltrimethylsilane, secondary amines, and formaldehyde.^[27] The performance of gold catalysis was influenced by the solvent, which could induce desilylation of silyl acetylene or deactivate the gold catalyst by forming gold halide species, rendering them inactive in the catalytic process. As a result, when the acetylene precursor 1-iodo-2-(trimethylsilyl)acetylene was utilized instead of ethynyltrimethylsilane with $[\text{Au}(\text{JohnPhos})(\text{NCMe})]\text{SbF}_6$, (JohnPhos = (2-Biphenyl)-di-*tert*-butylphosphane) a unique iodide-bridged complex $[(\mu\text{-I})\{\text{Au}(\text{JohnPhos})\}_2]\text{SbF}_6$ **3** was synthesized. X-ray analysis revealed symmetric coordination of the iodine atom to each gold center. However, the catalytic activity of this complex was evaluated in the same reaction, yielding the expected poor performance.

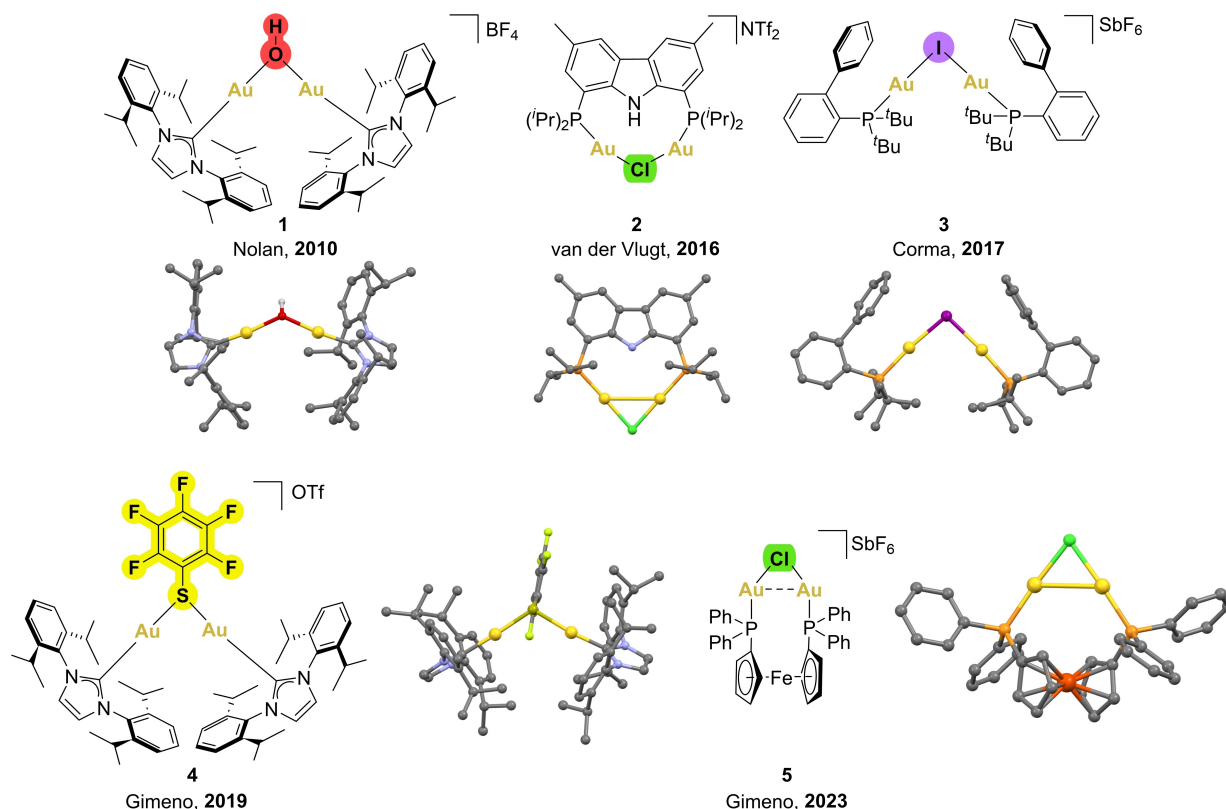
In 2019, Gimeno's group reported the synthesis of a series of pentafluorophenylthiolate digold carbene complexes **4**, $[(\mu\text{-SC}_6\text{F}_5)\{\text{Au}(\text{L})\}_2]\text{OTf}$, (L = IDipp = 1,3-bis(2,6-diisopropyl-phenyl)-imidazol-2-ylidene, SIDipp = 1,3-bis(2,6-diisopropyl-phenyl)-4,5-dihydroimidazol-2-ylidene, IMes = 1,3-bis(2,4,6-trimethylphenyl)imidazol-2-ylidene, SIMes = 1,3-bis(2,4,6-trimethylphenyl)-4,5-dihydroimidazol-2-ylidene).^[28] These complexes could slowly release the active catalytic species $[\text{Au}(\text{NHC})]^+$ and the precursor $[\text{Au}(\text{NHC})(\text{SC}_6\text{F}_5)]$ in the reaction medium, in the absence of any silver additive, and both species remain stable throughout the catalytic cycle. Then, they used these active complexes in the gold-catalyzed intramolecular hydroalkoxylation of alkynes and were able to clarify all the steps of the catalytic cycle, together with the characterization of the thermodynamic and kinetic intermediates, along with the pure final spiroketals, shedding light on the final steps after protodeauration, where the final product is obtained by protonation of the intermediates.

More recently, in 2023, Gimeno and coworkers described another chloride bridging gold complex, in this case employing the dppf ligand (dppf = 1,1'-bis(diphenylphosphane)ferrocene),^[29] whose crystal structure revealed to be among one of the shortest Au...Au distances reported for gold(I) chloronium complexes.^[30] They compared the activity of complex **5**, with its pentafluorophenylthiolate counterpart which resulted to be less catalytically active than its chloride analogue. This demonstrates that, although dinuclear

(A) Proposal of release of the catalytic species and recovery of the pre-catalyst



(B) Selected examples of self-activating dinuclear gold(I) catalysts supported by single heteroatom bridging ligands



Scheme 2. a) Proposal of release of the catalytic species; b) pivotal examples of self-activating dinuclear gold(I) complexes supported by a single heteroatom bridging ligand.^[21]

gold(I) complexes with bridging ligands are often considered as deactivation pathways in catalytic cycles, they can also serve as catalysts themselves.^[31] However, this field holds promise for further improvement; as the main drawback of these complexes is that formally, only half of the gold may be catalytically active.

2.2. Non-Covalent Interactions

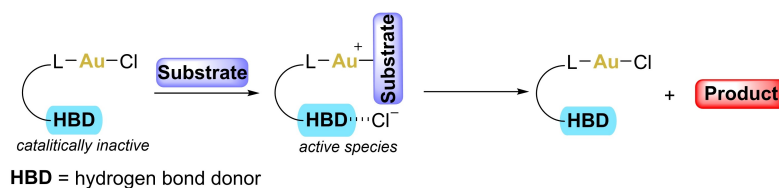
2.2.1. Hydrogen Bonding

Unlike the use of bridging ligands, an additional mode of activation relies on the establishment of non-covalent interactions, which can operate in multiple ways. Firstly, complexes with tethered mono- and bidentate hydrogen bond donors (HBD) aid in the activation of the gold(I) metal center by chloride abstraction, facilitated by the establishment of hydro-

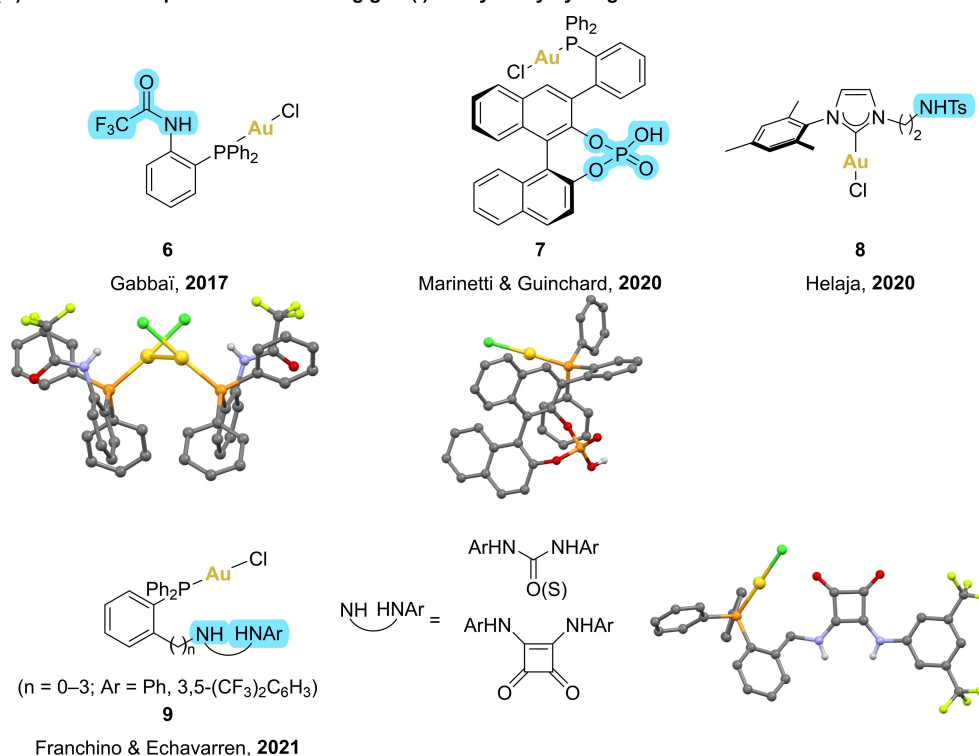
gen bonds based on NH...Cl interactions.^[32] The activity of these type of complexes is attributed to the HBD moiety acting as an anion binder, cleaving the chloride anion from the electrophilic metal and rendering the metal center catalytically active (Scheme 3a).

In this particular context, Gabbaï's group reported a Au(I) chloride complex **6** (Scheme 3b), featuring a trifluoroacetamide group attached to a modified PPh₃ scaffold.^[33] The efficacy of complex **6** was ascribed to the trifluoroacetamide capability to establish a hydrogen bond with the chloride ligand, facilitating its abstraction from Au(I) and activating the metal center for catalysis. While this study provided a compelling proof of concept, it focused solely on a single complex with modest activity, limited to the cyclization of *N*-propargyl benzamide. In a separate instance, Marinetti, Guinchard, and coworkers reported another isolated example, a phosphane Au(I) chloride complex **7** (Scheme 3b).^[34] This complex featured a chiral

(A) Proposal of release of the catalytic species and recovery of the pre-catalyst



(B) Selected examples of self-activating gold(I) catalysts by hydrogen bond donors

**Scheme 3.** a) Proposal of release of the catalytic species; b) pivotal examples of self-activating gold(I) complexes bearing a hydrogen bond donor moiety.^[21]

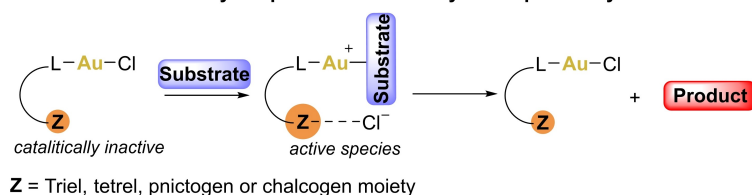
phosphoric acid moiety and exhibited catalytic activity in the silver-free tandem cycloisomerization-indole addition reaction of 2-alkynyl enones, giving rise to very good results in terms of enantioselectivity and reactivity. Additionally, Helaja's group recently introduced NHC-based Au(I) complexes **8** (Scheme 3b), incorporating an amide sidearm.^[35] These complexes displayed remarkable performance in the absence of additives, yet their catalytic competence was once again confined to the cyclization of terminal *N*-propargyl benzamides. Notably, computational analyses suggested that the NH groups from both the benzamide substrate and the ligand cooperated to stabilize the displaced chloride ion. Subsequently, Franchino, Echavarren, and collaborators described a library of gold(I) chloride complexes **9** (Scheme 3b) featuring phosphane ligands with pendant (thio)urea and squaramide hydrogen-bond donors.^[36] Complexes bearing squaramides and trifluoromethylated aromatic ureas exhibited robust catalytic activity, demonstrating efficacy in diverse reactions such as the cyclization of *N*-propargyl benzamides, 1,6-enyne cycloisomerization, tandem cyclization-indole addition, and the hydrohydrazination of

phenylacetylene. A discernible correlation between hydrogen-bonding capability and catalytic activity emerged, indicating that hydrogen-bonding interactions play a pivotal role in facilitating chloride abstraction from the Au(I) center, a proposal supported through computational studies.

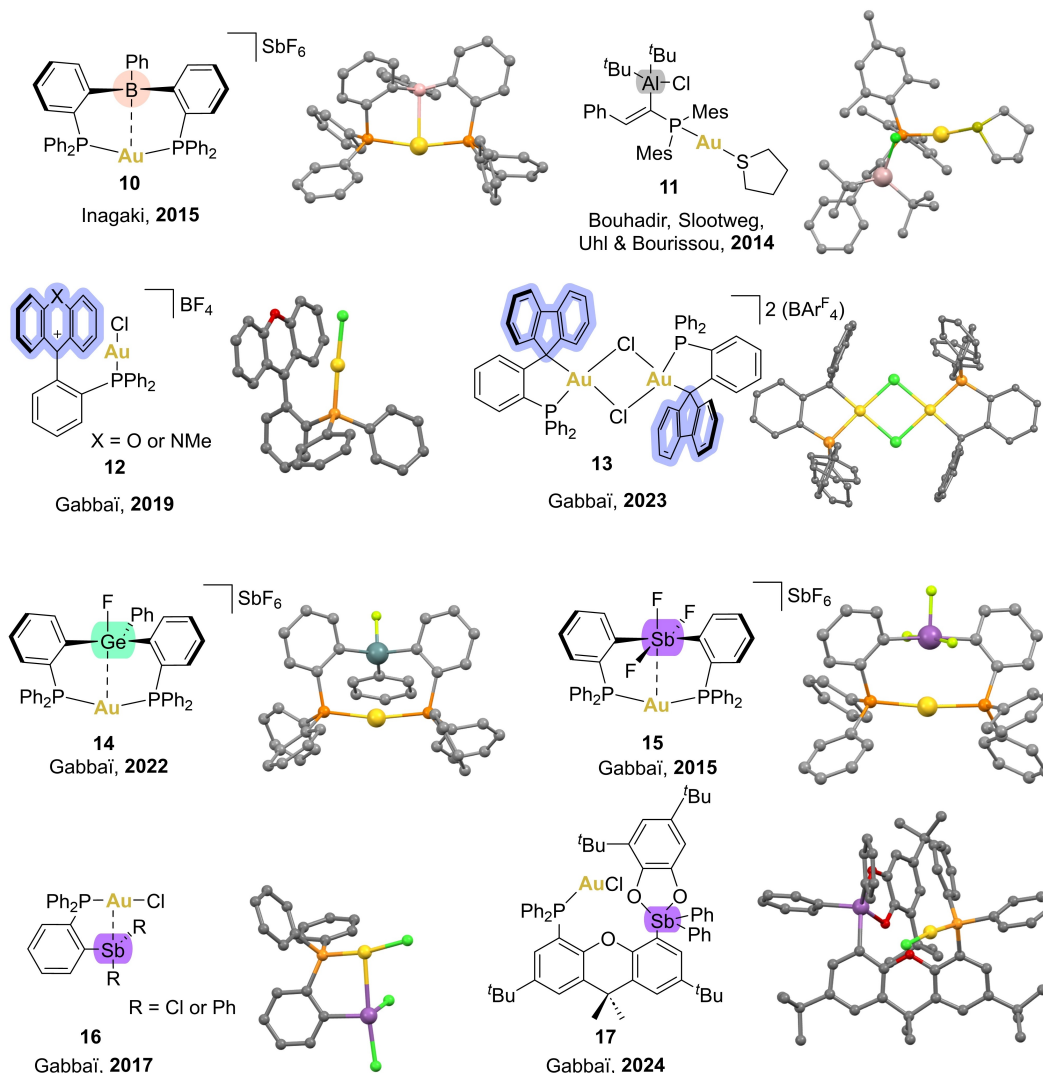
2.2.2. Triel, Tetrel, Pnictogen and Chalcogen Bonding

The terms "triel bond", "tetrel bond", "pnictogen bond" and "chalcogen bond" have been coined in recent years to characterize non-covalent interactions that involve, group 13 (triels), group 14 (tetrels), group 15 (pnictogen) and group 16 (chalcogens) atoms, respectively. In these interactions, these elements act as the electrophilic site, seeking a nucleophilic region in another molecule. Therefore, these regions can be seen as σ -acceptor or π -acceptor ligands behaving as Lewis acids that receive electron density from the metal center, thus increasing its electrophilicity and modulating its catalytic activity (Scheme 4a).^[37]

(A) Proposal of release of the catalytic species and recovery of the pre-catalyst



(B) Selected examples of self-activating gold(I) catalysts by triel, tetrel and pnictogen bonding

**Scheme 4.** a) Proposal of release of the catalytic species; b) pivotal examples of self-activating gold(I) complexes bearing a triel, tetrel or pnictogen ligand.^[21]

Regarding “triel bonding”, Inagaki’s group investigated a cationic complex **10**,^[38] derived from the neutral gold(I) chloride complexes reported previously by Bourissou and coworkers.^[39] They discovered that these complexes serve as markedly more efficient catalysts for enyne cyclizations compared to simpler model cations like $[\text{Au}(\text{PPh}_3)_2]^+$. This finding supports that the improved catalytic activity of **10** arises from the strong σ -accepting properties of the Lewis acidic boron atom located *trans* to the catalytically active site. In this context, Bourissou’s, Uhl’s and Slootweg’s groups jointly reported the use of a gold(I) tht (tetrahydrothiophene) adduct using an ambiphilic

phosphorus-aluminum ligand **11**, which proved to be active in the cycloisomerization of propargyl amides. This ambiphilic ligand reacted with $[\text{AuCl}(\text{tht})]$ via Au–Cl dissociation instead of tht displacement, representing a rare example of Lewis acid-controlled coordination. The aluminum center drives the reaction toward the formation of zwitterionic complexes, thereby activating the gold(I) pre-catalyst.^[40]

Concerning “tetrel bonding”, in 2019, Gabbaï reported complexes **12** presenting a phosphane ligand incorporating a xanthylium or acridinium unit.^[41] The carbenium center, possessing an empty p_x orbital with lower energy than an

analogous borane fragment,^[42] has the potential to serve as a more robust σ -acceptor ligand for gold, thereby overall enhancing the electrophilicity of the metal center. Similarly, the authors hypothesize a substrate push/carbenium pull working mode to elucidate the activity observed in the cyclization of propargylbenzamides. Notably, no reaction occurred using $[\text{AuCl}(\text{PPh}_3)]$ with phenylacridinium or phenylxanthylum salts, underscoring the necessity for the carbenium moiety to be embedded in the ligand scaffold. More recently, the same group successfully isolated a chloride-bridged gold dimer **13** featuring a genuine $\text{Au}-\text{C}^+$ dative interaction.^[43] In this instance, the antiaromatic fluorenyl cation served as the carbenium moiety. This behavior contrasts with previous efforts that had led to the successful isolation of complexes featuring a phosphane gold moiety flanked by a weakly Lewis acidic carbenium ion. Bonding analyses revealed that the $\text{Au}-\text{C}$ bond in these complexes exhibits distinct dative character, proving to be particularly potent catalysts in enyne cyclization reactions. Gabbaï also explored the utilization of a heavier tetrel element, germanium, through a diphosphane germylene (Ge^{IV}) complex **14**, featuring a proposed $\text{Au}-\text{Ge}^{\text{IV}}$ interaction involving the donation of a gold d-orbital lone pair to the $\text{Ge}-\text{Cl}$ σ^* orbital.^[44] This complex exhibited high efficiency in the hydroamination of alkynes, achieving nearly full conversion within 6 hours using *p*-toluidine at room temperature. However, the authors noted significantly higher activity for the putative germylene (Ge^{II}) dication of **14**, aligning with its anticipated enhanced electrophilic characteristics. This observation strengthens the concept that the accumulation of charge on such main group/late transition metal complexes serves as a conduit for enhancing the electrophilic reactivity of the gold metal center.

In the context of “pnictogen bonding”, Gabbaï’s group has made substantial contributions, particularly with a seminal work in 2015, which introduced a new class of self-activating $\text{Au}(\text{I})$ complexes **15**.^[45] Complex **15**, demonstrated remarkable efficacy as a catalyst for the hydroamination of phenylacetylene with *p*-toluidine, achieving more than 95% conversion after 1 hour. Both structural and computational studies suggest that **15** possesses a robust $\text{Au}-\text{Sb}^{\text{V}}$ bond. This stronger interaction translates into a more electrophilic gold center, leading to enhanced catalytic activity. Notably, under the same conditions, a trivalent Sb^{III} analogue exhibited significantly lower activity than **15**. It is noteworthy that the activity of **15** appears substantially higher than that of **14**, which features a weaker $\text{Au}-\text{Ge}^{\text{IV}}$ bond compared to the $\text{Au}-\text{Sb}^{\text{V}}$ bond in **15**. Subsequently, Gabbaï and coworkers reported gold(I) complexes featuring a modified triphenylphosphane ligand with an *ortho* $\text{Sb}(\text{III})$ atom **16**.^[46] The Lewis acid nature of the Sb center in complex **16** is evidenced by intramolecular $\text{Sb}\cdots\text{Cl}-\text{Au}$ contacts observed in the solid state and the facile formation of zwitterionic species. The authors propose that the Lewis acidic Sb atom may abstract the gold-bound chloride ligand in the presence of a coordinating substrate, thereby activating the Au center. Noteworthy, the use of PhSbCl_2 , in combination with $[\text{AuCl}(\text{PPh}_3)]$, proved ineffective as a chloride scavenger, underscoring the crucial role of intramolecular chloride abstraction facilitated by a pendant Lewis acid.

In a more recent development in 2024, Gabbaï’s group have further contributed to the field of gold–stiborane complexes.^[47] In this specific case, the catalyst self-activating properties arise from the incorporation of a catecholostiborane (Sb^{V}) unit positioned adjacent to the gold chloride moiety, as shown in complex **17**. As observed previously, the synergy between these two functionalities establishes an intramolecular $\text{Sb}(\text{V})\cdots\text{Cl}-\text{Au}$ interaction, the formation of which benefits from the distinctive pnictogen bond donor properties of the antimony compound. Catalysis experiments involving propargyl amides and their cycloisomerization also reveal that the oxidation of the antimony center from the +III to the +V oxidation state triggers the carbophilic reactivity of the gold center.

Overall, this enhancement in reactivity validates the concept that the redox state of non-innocent ligands capable of establishing non-covalent interactions may be utilized to control the catalytic activity of the adjacent gold(I) center.

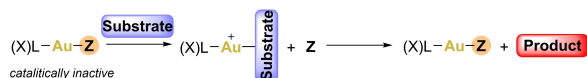
2.3. Weakly Donor Ligands

One of the simplest strategies for creating a self-activating catalyst involves the use of ligands weakly bound to the metal center, facilitating their easy displacement by substrates (Scheme 5a). Various approaches have been explored in this context, including the use of weakly coordinating anions (such as NTf_2 or OTf), solvent solvate complexes, or more sophisticated ligands like phosphaaalkenes and phosphinines (Scheme 5b).

In 2006, Echavarren and coworkers presented the pioneering utilization of an acetonitrile gold(I) solvate complex **18** as an effective catalyst for [4 + 2] cycloadditions involving 1,3-enynes and arylalkynes with alkenes.^[48] The use of bulky dialkyl biarylphosphanes, known as Buchwald-type phosphanes (such as JohnPhos), in the development of gold(I) complexes has rendered them robust and exceptionally active catalysts. As a result, this type of complex, notably $[\text{Au}(\text{JohnPhos})\text{NCMe}]\text{SbF}_6$ **18**, has emerged as ubiquitous complex in homogeneous gold(I) catalysis, finding widespread application across multiple reactions.^[49]

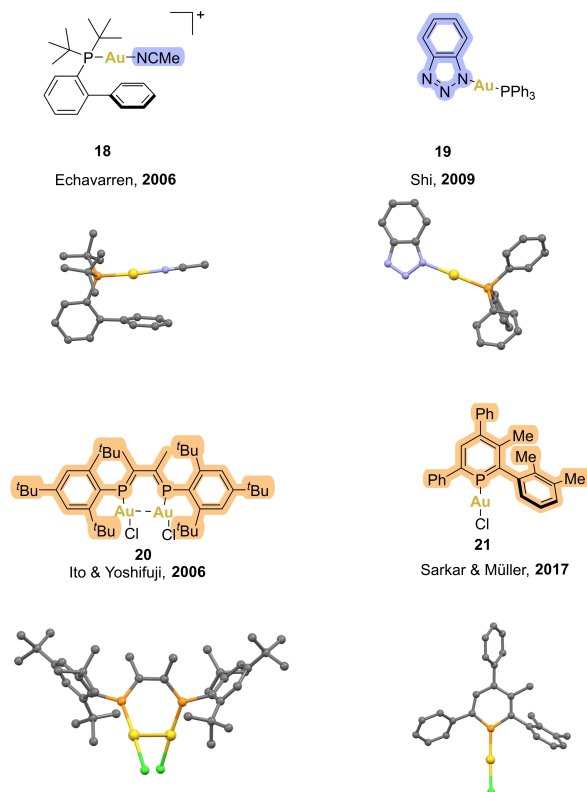
Continuing with the utilization of weakly donor ligands, Shi and collaborators made a significant contribution in 2009 by introducing a triazole analogue **19** of the well-known $[\text{Au}(\text{OTf})(\text{PPh}_3)]$ complex. These triazole- $\text{Au}(\text{I})$ complexes exhibited remarkable thermal stability, serving as catalysts for challenging alkyne activation under harsh conditions.^[50] This discovery was particularly intriguing as it offers an alternative approach to modulating the reactivity of Au catalysts. Rather than modifying the phosphorus ligands, the reactivity of the catalyst can be fine-tuned by manipulating the anionic ligand. This presents a noteworthy advancement, considering the primary challenge associated with $[\text{Au}(\text{OTf})(\text{PPh}_3)]$, its susceptibility to decomposition. Lastly, phosphinines and phosphaaalkenes also fall into the category of weakly donor ligands (Scheme 5b). These phosphorus ligands have been utilized as potent π -accepting ligands due to their lower LUMO levels, comparable to carbon monoxide.

(A) Proposal of release of the catalytic species and recovery of the pre-catalyst



Z = Weakly donor ligand (e.g. MeCN, phosphinine, OTf)
L = Ancillary ligand (e.g. carbene or phosphane)
X = Halide ion (when Z = phosphinine or phosphalkene)

(B) Selected examples of self-activating gold(I) catalysts bearing weakly donor ligands



Scheme 5. a) Proposal of release of the catalytic species; b) pivotal examples of self-activating gold(I) complexes bearing a weakly donor ligand.^[21]

Typically, catalytically active phosphane gold complexes should avoid chloride, as the Cl^- ion strongly binds to gold, hindering substrate coordination and subsequent molecular transformations. However, certain phosphalkene or phosphinine-chlorogold(I) complexes have demonstrated the ability to catalyze molecular transformations without requiring activation through silver additives. This suggests that the strong π -accepting nature of the $P=C$ moiety may promote the Lewis acid functionality of the gold center(s), even in the presence of Cl^- ions. Additionally, the soft character of the phosphorus center in such ligands may aid in the stabilization of cationic Au(I) intermediates.

Yoshifuji, Ito, and coworkers demonstrated that phosphalkene-based Au(I) chloride complexes **20** were able to catalyze the cycloisomerization of a 1,6-enyne to a vinylcyclopentene in the absence of any chloride scavenger.^[51] The authors also noted that auriphilic interactions appear to facilitate catalysis, as evidenced by the *trans* isomer of **20**, where the conformation of the ligand hindered Au...Au contacts in the solid state, leading to very low activity. However, these auriphilic inter-

actions, or the presence of two Au(I) centers, are not mandatory requirements for catalytic activity, as demonstrated by the performance of a mononuclear $[AuCl(\text{phosphaalkene})]$ complex.

Inspired by the electronic and structural similarity between phosphalkenes and phosphinines, Sarkar, Müller, and their collaborators reported the first study on the catalytic activity of Au(I) phosphinine complexes.^[52] In phosphinines, the reactivity of the $P=C$ double bond is attenuated by incorporation into an aromatic system, while the 2,4,6-triaryl substituents confer further stability to the ligands, as shown in complex **21** (Scheme 5b). The authors contextualized their results by providing comparisons with external activators and several commercial Au(I) complexes. In the additive-free cycloisomerization of a malonate-tethered 1,6-enyne, good conversions to the diene were observed over 24 hours using complex **21**. However, it should be noted that the impact of this effect is far from being as efficient as conventional chloride scavenging performed by $AgSbF_6$ or $Cu(OTf)_2$. Indeed, employing these additives to abstract the chloride ligand from phosphinine complexes resulted in significantly decreased reaction times, from 24 hours to 1–30 minutes.

3. Summary and Outlook

The design of ligands in gold complexes has been crucial for developing self-activating gold(I) catalysts, enabling activation without the need for external additives throughout the catalytic cycle.

Among these approaches are dinuclear gold complexes featuring a range of bridging ligands. Notably, the utilization of single heteroatom bridges derived from groups 16 and 17 has demonstrated their capacity to function as reservoirs of catalytically active species, with adjustable electron densities exerting influence over their catalytic efficiency. Bridging ligands like chalcogens and halogens have exhibited stability in both solid and solution states, ensuring controlled release of active species and facilitating regeneration processes.

Furthermore, the incorporation of non-covalent interactions, including hydrogen bonding, triel, tetrel, pnictogen, and chalcogen bonding, has emerged as a complementary strategy for catalyst activation. These interactions increase the electrophilicity of the metal center, thereby modulating its catalytic activity. Particularly noteworthy is the synergistic effect between Lewis acidic functionalities, such as antimony and catecholatosilborane units, and gold chloride moieties, which has played a pivotal role in achieving self-activating properties and enhancing catalytic performance across various transformations.

Moreover, the utilization of weakly donor ligands, with a focus on exotic labile ligands such as phosphinines and phosphalkenes, has provided a straightforward yet effective means of creating self-activating catalysts. These ligands, by facilitating coordination of the substrates, have enabled catalysis without reliance on silver additives. Additionally, the soft character of these ligands has proven instrumental in

stabilizing cationic Au(I) intermediates, thereby further enhancing catalytic efficiency.

In conclusion, the multifaceted approaches discussed herein highlight the tremendous potential of self-activating gold catalysis. Significant contributions have been made in the advancement of these catalysts through innovative ligand design and the discovery of novel modes of autoactivation. This knowledge holds promise for innovating organic transformations, including asymmetric catalysis, while mitigating the risk of reaction poisoning from traditional catalyst-generating additives. Despite the progress made over the last decade with self-activating gold(I) complexes, their catalytic activity remains modest, and the scope of transformations they can perform is still limited and underdeveloped. Continued research aimed at refining and enhancing these self-activating catalysts could offer promising avenues for developing efficient and sustainable synthetic methodologies, along with expanding their application to a broader range of products of interest.

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Conflict of Interests

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords: Additive-free · Catalysis · Gold · Self-activation · Silver-free

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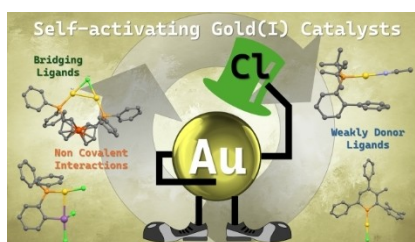
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CONCEPT

The multifaceted approaches discussed herein highlight the tremendous potential of self-activating gold catalysis. Significant contributions have been made in the advancement of these catalysts through innovative ligand design and the discovery of novel modes of autoactivation. This knowledge holds promise for innovating organic transformations, including asymmetric catalysis, while mitigating the risk of reaction poisoning from traditional catalyst-generating additives.



J. C. Pérez-Sánchez, R. P. Herrera, M. C. Gimeno**

1 – 11

The Potential of Self-Activating Au(I) Complexes in Gold Catalysis