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Gold and Rhodium Transmetalation: Mechanistic Insights and Dual-Metal Reactivity

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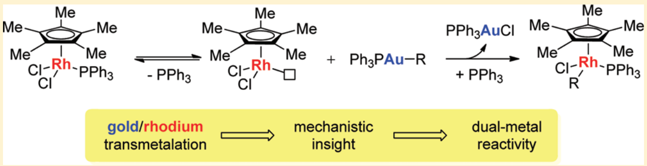
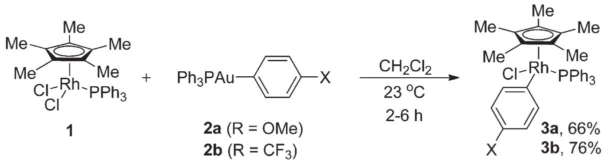
ABSTRACT: A transmetalation reaction between rhodium(III) and sp^2- and sp^3-hybridized organogold(I) compounds proceeds rapidly at ambient temperature (15 min to 6 h). Mechanistic experiments demonstrate that ligand dissociation on rhodium(III) precedes transmetalation; synthetic applications of the gold/rhodium transmetalation are highlighted by linking rhodium-mediated C−H activation, conjugate addition, and reductive elimination to transmetalation from organogold compounds.



Transmetalation reactions are relatively poorly understood, which causes difficulty in accurately predicting reactivity;[1] for example, the oxidation states and coordination environments around the two metals can result in unanticipated transmetalation reactions[2−4] that elude the simplicity of the typical electronegativity-based hard/soft method of predictive analysis.[5] Herein we report the first transmetalation reaction between organogold and rhodium complexes.[6,7] This reaction exhibits marked oxidation state and coordination environment effects. The predictive power derived from these fundamental observations enables access to the chemistry of rhodium from organogold complexes: rhodium-mediated C−H activation/transmetalation and rhodium-catalyzed conjugate addition showcase the unique reactivity available to this dual-metal system. The demonstrated compatibility and reactivity of this dual-metal system increases the functionalization possibilities for the numerous reported organogold intermediates[8] by providing complementary reactivity to the recent functionalization of organogold intermediates by palladium.[6]

Treatment of $Cp^*RhCl_2(PPh_3)$ (**1**) with the electron-rich and electron-poor arylgold complexes **2a**,**b** at ambient temperature resulted in transmetalation products **3a**,**b** (66% and 76%, 2 and 6 h, respectively; eq 1). The arylrhodium product **3a** was air stable and could be isolated by column chromatography.[9] Notably, the transmetalation reaction shown in eq 1 could be carried out under "open flask" conditions,[10] in air and in wet solvent, without decreased yield (69%), demonstrating the operational facility of both organogold(I) and rhodium(III) complexes and their combined reaction chemistry.[11] Transmetalation between **1** and the vinylgold species **2d** was rapid (<15 min) and yielded the previously unknown vinylrhodium complex **3d**, as observed by ^1H NMR spectroscopy (eq 3). Upon precipitation of the gold byproducts from the crude reaction mixture complex **3d** decomposed; however, transmetalation between the (trimethylphosphine)rhodium complex **4** and organogold species **2d** generated **3e**, a stable trimethylphosphine analogue of **3d**, which was robust toward isolation by precipitation, permitting full characterization (78%; eq 4). Rhodium complexes **3a**,**b** displayed restricted bond rotation at ambient temperature, as observed by ^1H NMR spectroscopy, consistent with the reported characterization data for the analogous Cp* rhodium compounds described by Jones.[12]



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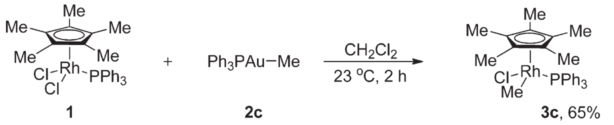

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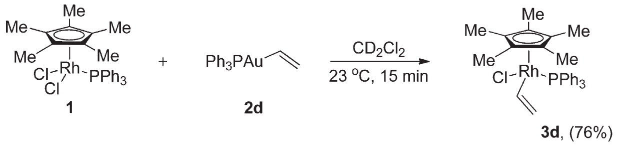

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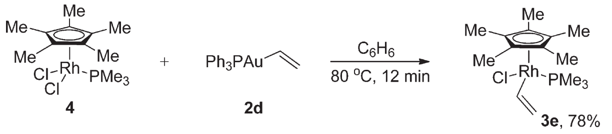

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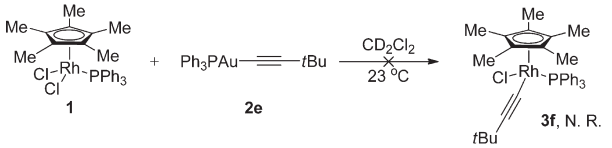

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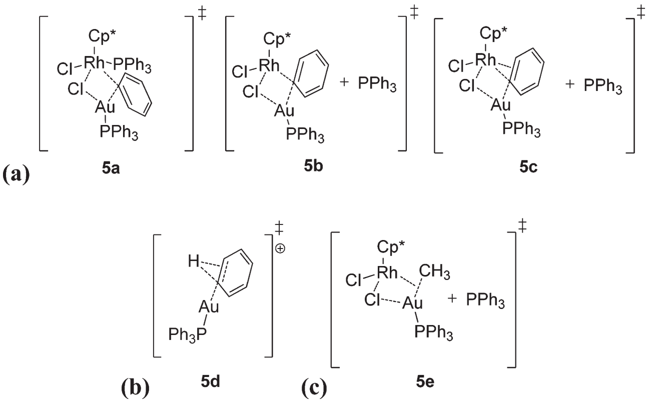


Figure 1. (a) Three possible transition states for the Rh/Au transmetalation reaction that differ by the coordination environment around rhodium. (b) Proposed protodeauration transition state, **5d**, showing π system involvement analogous to **5c**. (c) Possible transition state for the Rh/Au transmetalation reaction that involves a σ complex.

With standard transmetalation conditions for sp^2-hybridized carbon in hand, we next explored the hybridization dependence of this reaction. Transfer of the sp^3-hybridized methyl group from Ph_3PAuMe (**2c**) occurred on a time scale (65%, 2 h; eq 2) similar to that for sp^2-hybridized carbon. This similarity in reaction rate between methyl and aryl groups was unexpected because of the well-established kinetic preference for transfer of sp^2- over sp^3-hybridized groups in traditional cross-coupling reactions.[13,14] In contrast to the clean transfer reactions of sp^2- and sp^3-hybridized carbon from gold, the sp-hybridized alkynylgold compound **2e** was consumed upon treatment with rhodium complex **1**, as observed by ^1H NMR spectroscopy, but the organorhodium compound **3f** was not detected, possibly due to the tendency of alkynylrhodium complexes to form heterobridged dinuclear complexes that could result in product decomposition (eq 5).[15]

We next investigated the mechanism of transmetalation between organogold(I) and rhodium complexes with the goal of understanding the functional relationship between the coordination environment at rhodium and the propensity toward transmetalation. Several distinct mechanisms have been established for transmetalation steps in various transition-metal catalyzed reactions, and mechanistic insight into a transmetalation step can translate into improved reaction efficiency.[16] For the rhodium/gold transmetalation we considered three mechanistic scenarios, shown as three transition states which differ by their coordination environments: **5a**–**c** (Figure 1).[17] In **5a**, transmetalation proceeds through a four-membered transition state without dissociation of a ligand.[13] In **5b**, transmetalation requires prior phosphine dissociation in order to provide an open coordination site at Rh.[18] In **5c**, transmetalation requires prior phosphine dissociation and the resulting open coordination site forms an η^2 complex with the π system of the transmetalating arylgold complex.[19] The involvement of the arylgold π system has been previously implicated in the protodeauration of arylgold complexes (**5d**),[20] raising the possibility that transmetalation and protodeauration proceed through analogous transition states that differ by Rh(III) or proton acting as the electrophile.[20] Interactions with a transmetalation partner's π system have been proposed for other metals (e.g., furylstannane and palladium[19]), producing further interest in this hypothesis. It has been reported that transmetalation between palladium and tin reagents exhibits inverse first-order kinetic dependence on free phosphine ligand;[21] coordination of the tin reagent in place of a dissociated phosphine ligand on palladium has been proposed to account for this observation.[18,22]

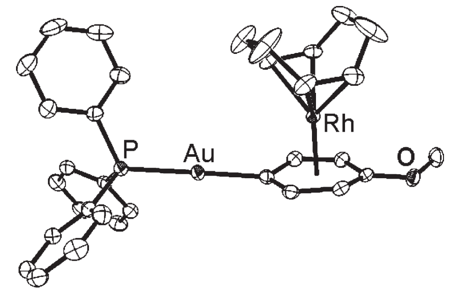
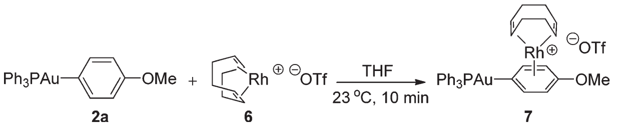


Figure 2. Rh/Au bimetallic π complex **7**, showing π interactions similar to those proposed in transition state **5c**. Thermal ellipsoids are shown at the 50% probability level, and hydrogen atoms and outer-sphere triflate counterion are omitted for clarity.

In order to probe the coordinative nature of the transition state, 10 equiv of PPh_3 was added to **1** prior to addition of **2a** (eq 1). Under these conditions of excess phosphine, no transmetalation product was detected after 24 h. This inhibition suggests that PPh_3 dissociation from coordinatively saturated **1** precedes transmetalation (transition states **5b**,**c** instead of **5a**).

The difference in transmetalation reaction rates between triphenylphosphine complex **1** and trimethylphosphine complex **4** provided additional evidence for ligand dissociation preceding transmetalation. Elevated temperatures (12 min at 80 °C) were required to promote rapid transmetalation with **4** (eq 4); at ambient temperature transmetalation with **4** proceeded significantly more slowly than with **1** (**4**, 2 days at 23 °C; **1**, 15 min at 23 °C). The rate of PMe_3 ligand dissociation has previously been shown to be slower than that of PPh_3 from late-metal complexes;[13] a slower initial ligand dissociation is consistent with the observed slower overall reaction rate with trimethylphosphine complex **4**.

We next considered the plausibility of the bimetallic π-arene interaction proposed in transition state **5c**. We were unable to prepare a complex demonstrating the arene interaction using rhodium(III)/gold; however, switching to the softer rhodium(I) metal center allowed for isolation of a stable bimetallic π-arene adduct.[23,24] Specifically, treatment of the organogold compound **2a** with Rh(cod)OTf (**6**) gave rapid and quantitative formation of complex **7** wherein rhodium was η^6 coordinated to the arylgold π system (eq 6).[23] Structural confirmation of the π-bonding interactions in the bimetallic complex was provided by X-ray crystallographic characterization of **7** (Figure 2). Interestingly, the reaction of **2a** and **6** did not proceed further to give transmetalation products, possibly because the transmetalation products were thermodynamically disfavored relative to the stabilizing soft/soft[23] π interaction present in the rhodium(I)/gold bimetallic complex **7**.[25] While the comparison between rhodium(I) and rhodium(III) bonding is inexact, formation of bimetallic arene complex **7** is consistent with the interaction proposed in transition state **5c**. Nevertheless, transition state **5b** cannot currently be ruled out.



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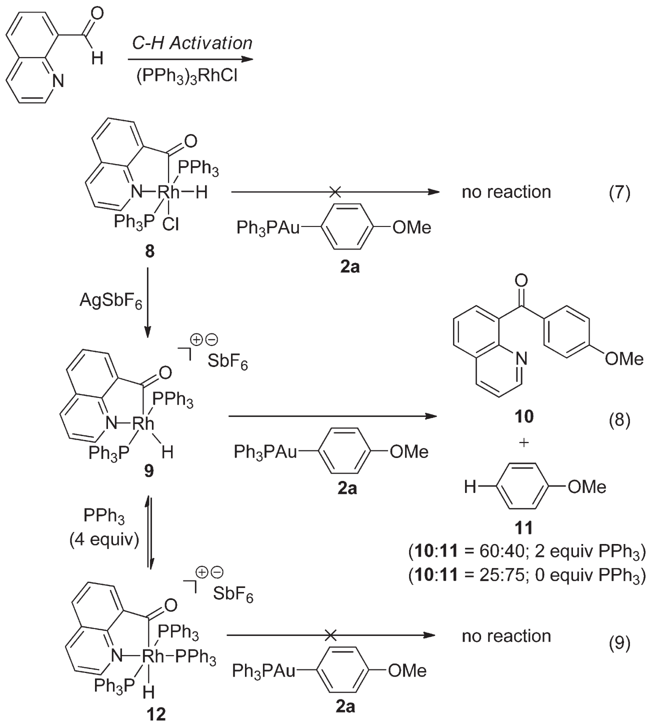
Scheme 1. Rh/Au C−C Bond Forming Transmetalation and Reductive Elimination



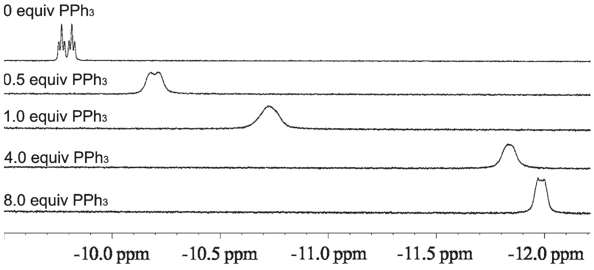


Figure 3. ^{1}H NMR spectra starting from complex **9** with portionwise addition of PPh$_3$. The distinct Rh−H region is shown, as increasing the amount of PPh$_3$ causes the equilibrium to shift toward **12**.

Interestingly, excess PPh$_3$ (10 equiv) also inhibited the transmetalation of sp^3-hybridized methylgold (eq 2). These data supported the operation of a preceding ligand dissociation step even in the absence of a π system that could coordinate to rhodium and facilitate transmetalation. In this case, ligand dissociation could be required to allow formation of a Au−Me/Rh σ complex as an intermediate prior to transmetalation or to allow formation of σ complex character in the transition state, **5e** (i.e., the σ analogue of **5c**); the σ complex depicted in **5e** also could involve metal−metal bonding.[26] The proposed Au−Me/Ru σ interaction is supported by the similar Pt−Me/Cu σ complex transmetalation intermediate characterized by Chen.[1]

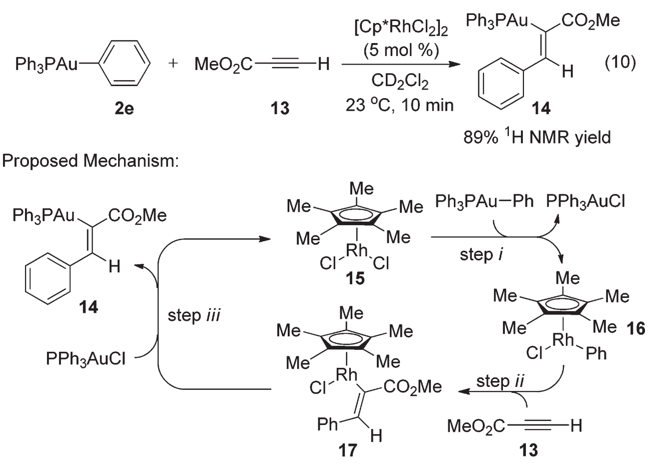
This mechanistic insight permitted the successful linkage of the C−H activation chemistry of rhodium with organogold chemistry, by determining the oxidation state and coordination environment at rhodium that would generate the most successful transmetalation partners. Suggs previously reported that the C−H activation of 8-quinolinecarbaldehyde with Wilkinson's catalyst produced the rhodium(III) complex **8**.[27] On the basis of the coordination environment studies described earlier in this paper, complex **8** was not anticipated to transmetalate with organogold **2a** because it lacked an open coordination site; Suggs demonstrated that the triphenylphosphine ligands in **8** do not dissociate even at elevated temperature.[27] Indeed, no transmetalation reaction with **8** occurred (eq 7, Scheme 1). Abstraction of chloride from **8** by AgSbF$_6$ generated coordinatively unsaturated **9**, which initiated transmetalation reactivity to yield **10** and **11**, the products of transmetalation followed by bifurcation between C−C and C−H reductive elimination pathways at rhodium (eq 8, Scheme 1). The ratio of **10** to **11** could be modified to favor C−C bond formation by addition of a small excess of PPh$_3$ (**10**:**11** = 60:40; 2 equiv of PPh$_3$).[28]

The transmetalation requirement for an open coordination site in both rhodium(III) complex **1** and structurally distinct **9** suggested the broader application of mechanistic knowledge gained from the study of **1**. Further supporting the requirement for an open coordination site, addition of excess PPh$_3$ (4 equiv) to **9** completely inhibited transmetalation from **2a**. When a lesser amount of PPh$_3$ (2 equiv) was premixed with complex **9**, the transmetalation reaction with organogold **2a** was slowed (4 h for 2 equiv of PPh$_3$, <15 min for no added phosphine) but not stopped. Titration of PPh$_3$ to **9** produced a progressive downfield shift of the Rh−H ^{1}H NMR resonance until addition of 8 equiv of PPh$_3$ produced minimal additional change in chemical shift (Figure 3). This spectroscopic data established that the equilibrium favored coordinatively saturated **12** under the same conditions of excess phosphine that fully inhibited transmetalation to **9** (eq 9, Scheme 1). Qualitative line shape analysis verified that a rapid equilibrium existed between complexes **9** and **12** at ambient temperature. From the equilibrium data, K_{eq} for the ligand association reaction could be calculated in the starting presence of 1.0 equiv of **9** and 1.0 equiv of PPh$_3$: $K_{eq} = 60\ M^{-1}$.

Information gained about the optimal oxidation state and coordination environment at rhodium for transmetalation revealed conditions to employ the catalytic conjugate addition reactivity of rhodium(III)[29] as a method to functionalize organogold compounds. The complex [Cp*RhCl$_2$]$_2$ (5 mol %) catalyzed the conjugate addition of phenylgold to methyl propiolate to give **14** (89% ^{1}H NMR yield). The following mechanism is proposed for this rhodium-catalyzed carboauration: (i) transmetalation between **2e** and **15** to give organorhodium complex **16**, (ii) migratory insertion of the alkyne,[30] and (iii) transmetalation between **17** and Ph$_3$PAuCl to regenerate the rhodium catalyst and form the functionalized organogold product **14** (Scheme 2). In this catalytic reaction, dissociation of the dimeric rhodium precatalyst provides the necessary open coordination site required for the complex to participate in transmetalation with organogold complex **2e**.

In conclusion, a new transmetalation reaction between rhodium and organogold(I) complexes was identified. Understanding of the optimal oxidation state, coordination environment, and hybridization of the reacting partners provided fundamental insight useful for reaction design, as highlighted by the development of a rhodium-catalyzed conjugate addition reaction and rhodium-mediated C−H activation/C−C bond forming reaction. This study suggests a future extension of the rhodium/gold dual reactivity that employs catalytic organogold intermediates generated via organic substrate rearrangement instead of stoichiometric organogold reagents.[31] Given the unique transformations available to rhodium, the fundamental understanding of this Au/Rh transmetalation reaction is anticipated to allow the development of rhodium/gold dual catalytic reactions as

Scheme 2. Rh-Catalyzed Conjugate Addition Reaction Employing Au/Rh Transmetalation



methods to functionalize the numerous and easily accessed organogold intermediates reported.[8]

ASSOCIATED CONTENT

Supporting Information. Text and figures giving experimental procedures and compound characterization data and a CIF file giving crystallographic data for 7. This material is available free of charge via the Internet at http://pubs.acs.org.

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