Cross Alkyl-Aryl Versus Homo Aryl-Aryl Coupling in Pd-catalyzed Coupling of Alkyl-Gold(I) and Aryl-X (X = Halide)

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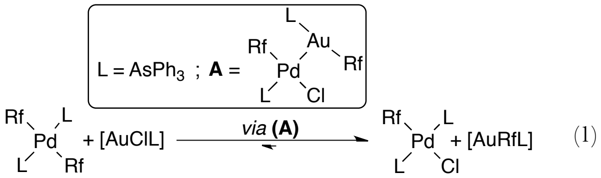
ABSTRACT Experiments on palladium catalyzed cross-coupling of $[AuMe(PPh_3)]$ with aryl iodides show that Ar–Ar homo-coupling products are the main product or an abundant by-product of the reaction. The percentage of cross-coupling product is higher for aryls with larger σ_p Hammet parameter. The scrambling of organic groups *via* bimetallic intermediates explains the formation of these products. This scrambling can be observed and the activation energies partially quantified in some cases using as aryl $C_6Cl_2F_3$, which is relatively reluctant to coupling.

Introduction

In recent years many metal catalyzed processes involving organogold derivatives as stoichiometric reagents or as intermediates have been developed.[1] Transmetalation reactions between organogold and zirconium,[2] iron and ruthenium,[3] rhodium,[4] nickel,[5] or palladium,[6-14] have been reported. The use of gold has been particularly studied in palladium cross-coupling reactions, where gold complexes have been used not only as stoichiometric reagents,[6,7] but also as cocatalysts in the gold-cocatalyzed Stille reaction,[8,9] in Sonogashira-like cross-coupling,[10] in the carbometalation of alkynes, [11] and in processes combining gold-catalyzed cyclizations with cross-coupling processes.[12,13,14]

The kinetics and thermodynamics of the transmetalation involving Au^{I} and Pd^{II}, which should influence the success of the bimetallic process,[8,9,15,16] are only scarcely studied. Our seminal mechanistic studies on the Au^{I}/Pd^{II} aryl transmetalation have shown that the formation of $[PdRf_2L_2]$ ($Rf = C_6Cl_2F_3$) from $[Pd(C_6Cl_2F_3)XL_2]$ (X = Cl; L = $AsPh_3$) and [AuRfL] is an endergonic process that occurs *via* intermediates and transition states stabilized by Pd-Au metallophilic interactions (Eq. 1). In other words, this exchange equilibrium is very shifted towards the formation of $[PdRfCl(AsPh_3)_2]$ + $[AuRf(AsPh_3)]$. The transmetalation occurs *via* replacement of one ancillary ligand in the palladium coordination sphere by the entering gold complex.[17] Similar conclusions have been drawn in a recent computational study of the transmetalation between vinylgold and arylpalladium complexes.[7] This suggests that the participation of intermediates type **A** formed by associative ligand substitution, and also the thermodynamic evolution indicated in Eq. 1 can be fairly general for Au^{I}/Pd^{II} catalytic systems. The displacement of the equilibrium towards the right is expected to be more marked the more nucleophilic the hydrocarbyl groups.



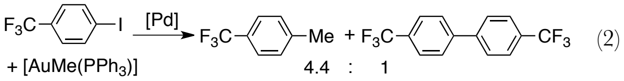
(1)

In spite of the disfavored equilibrium, the cross-coupling processes from $[PdR^1XL_2]$ and $[AuR^2L]$ do work, provided that the irreversible R^1–R^2 coupling is kinetically effective. However, since the transmetalation is a reversible equilibrium, concomitant reactions such as isomerization,[18] or gold mediated ligand scrambling between metal centers (whether involving R, L, or X groups) can occur before the coupling takes place.[9] These side-reactions are a potential complication, more likely to be influential in systems where the reductive elimination at the palladium center is slow, as it is the case for $C(sp^3)$ groups. It is well known that, for common aryl and alkyl groups, the reductive elimination occurs on *cis*-$[PdR^1R^2L_2]$ intermediates at a rate that follows the order C_{Ar}–C_{Ar} > C_{Ar}–C_{sp3} > C_{sp3}–C_{sp3}.[19,20,21] According to this,[22] Me–Ar coupling should be faster than Me–Me, but slower than Ar–Ar.[21]

In spite of this undesired complication, $C(sp^3)$ systems are particularly appealing for gold catalysis because the stability of alkylgold(I) complexes makes them potentially valuable reagents for $C(sp^3)$-$C(sp^2)$ coupling in bimetallic processes.[23] Sarandeses *et al.* have used $[Au(^nBu)(PPh_3)]$ in alkyl-aryl palladium catalyzed cross-coupling experiments, but the results were not good for cross-coupling of $[Au(^nBu)(PPh_3)]$ with 4-iodotoluene, which afforded only 4,4'-dimethylbiphenyl; with 4-Br or 4-TfO-acetophenone the yields in cross-coupling product were low.[6] However, Hashmi *et al.* have reported recently good yields in the cross coupling of $[AuMe(PPh_3)]$ with 4-iodobenzonitrile (83% yield of 4-methyl benzonitrile after three days at 60 °C).[7] Here we report an experimental mechanistic study of the Pd catalyzed Me–Ar coupling of AuMe and ArI systems, trying to better understand the circumstances of this coupling.

Results and discussion

In a typical process, the reaction of $[AuMe(PPh_3)]$ with p-$CF_3C_6H_4I$ catalyzed by *trans*-$[Pd(C_6H_4CF_3\text{-}p)I(PPh_3)_2]$ (5%), NMR monitored in THF-d_8 at 50 °C, led to the competitive formation of the cross-coupling product p-$CF_3C_6H_4Me$ and the homo-coupling product 4,4´-bistrifluoromethylbiphenyl, in 4.4:1 ratio (Eq. 2). Gold mirror was not observed and the products do not fit the expectations in case of redox incompatibility suggested by Webber and Gagné for other cases.[15] Thus, as in a recent study by Blum,[12a] redox incompatibility can be discarded here.



(2)

The results of experiments with other aryl iodides are summarized in Table 1. A reasonable correlation is found between the percentage of cross-coupling product and the σ_p Hammet parameter for the aryls, and aryls with larger σ_p produce less Ar–Ar homocoupling.

Table 1. Table 1. Hetero/ homocoupling ratios versus Hammet σ_p values[a)]

Ar-I	Hammet σ_p	Ar-Me/Ar-Ar
p-$NO_2C_6H_4I$	0.78	6.3
p-$CF_3C_6H_4I$	0.54	4.4
p-FC_6H_4I	0.06	2.4
p-$CH_3C_6H_4I$	-0.17	2.8
p-$CH_3OC_6H_4I$	-0.26	2.4

[a)] Reaction conditions: [AuMe(PPh$_3$)] = 0.021 mmol, [Ar-I] = 0.042 mmol. Catalyst *trans*-[Pd($C_6H_4CF_3$-*p*)I(PPh$_3$)$_2$] (5%). T = 50 °C.

In order to get insight into the mechanism we moved to use $C_6Cl_2F_3$ (Rf) as aryl, which should slow down the different steps of the reaction and facilitate the detection of other possible intermediates or byproducts such as *cis* and *trans*-[PdR^{1}R^2(PPh$_3$)$_2$] (R^1 and R^2 = Rf or Me), or [AuRf(PPh$_3$)]. The study focused on the transmetalations possibly occurring once the concerted oxidative addition to Pd(0) and subsequent *cis/trans* isomerization has formed the *trans*-Pd^{II} intermediate.[24] The same L (PPh$_3$) was used for both metals to avoid observational complications associated to L exchanges that we have studied somewhere else.[9] The reaction of *trans*-[PdRfClL$_2$] (**1**) with excess of [AuMeL] (**2**), in THF at 50 °C, was monitored by ^{19}F NMR (Figure 1). Note that the use of large excess of [AuMeL] does not obscure perfect monitoring by ^{19}F NMR.

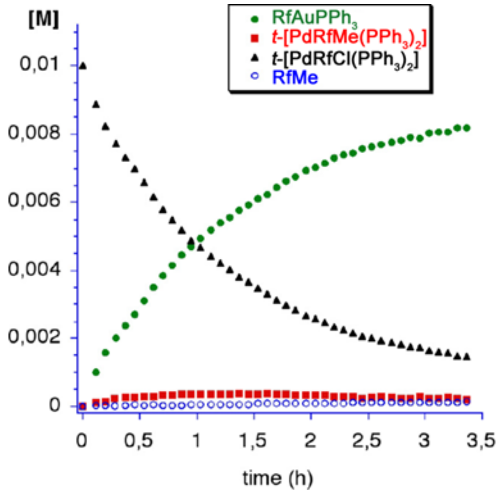
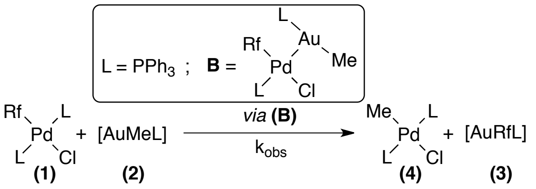


Figure 1. Concentration/time plot of the reaction trans-[PdRfClL$_2$] (**1**) + [AuMeL] (**2**) in THF at 320 K. Initial conditions: [**1**]$_0$ = 0.01 M; [**2**]$_0$ = 0.03 M.

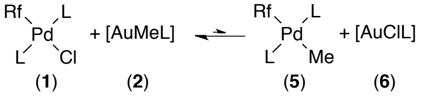
The disappearance of **1** and the formation of [AuRfL] (**3**, L = PPh$_3$) as the main product were observed. The reaction was complete in about 10 h at rt. The presence of the other product, *trans*-[PdMeCl(PPh$_3$)$_2$] (**4**), was confirmed by ^{31}P NMR. It is interesting to note that only a small amount of cross-coupling product RfMe and nothing of the homo-coupling Rf–Rf products was observed, as expected from the reluctance of Rf to participate in reductive elimination. After 17 h a small amount of ethane was also observed in the ^{1}H NMR. The high activation energy of these coupling processes (Rf–Rf, Rf–Me or Me–Me), and the different nature of the two organic groups allow for observation of some exchange processes in solution.

A kinetic study (initial rates method), based on the rate of consumption of **1**,[25] showed that the reaction kinetics is close to first order in gold complex (kinetic order for [**2**] = 0.8), and is retarded by addition of phosphine to the solution (kinetic order for [PPh$_3$] = –1). Moreover, the plot of 1/k_{obs} vs. [PPh$_3$] gives a straight line. Applying the *steady state* approximation to an intermediate **B** (Eq. 3) in which one phosphine has been displaced, a rate constant k_1 $\approx 1.2 \cdot 10^{-3}$ is found, which affords $\Delta G^{\ddagger}_{323}$ = 23.3 kcal.mol^{-1}.[25] The study of the reaction in the temperature range 280–327 K supports an associative phosphine substitution process with $\Delta H^{\ddagger}$ = 63.9 kJ mol^{-1} and $\Delta S^{\ddagger}$ = -95.5 J.K^{-1} mol^{-1}. This fits well the expectations from our previous study on Au(aryl)/Pd(aryl) transmetalation.[17]



(3)

The formation of **3** and **4** indicates the thermodynamic result of group exchange in the absence of coupling, but it does not mean that Eq. 3 is the only pathway from **1** and **2** to **3** and **4**. For instance, the observation of some Rf–Me proves that undetected *cis*-[PdRfMe(PPh$_3$)$_2$] (**7**) must have been formed too during the reaction, but having a high activation energy towards coupling and being high in energy compared to alternative products it never reaches observable concentration. Similarly, a small amount of the exchange product [Au($C_6H_4CF_3$-*p*)(PPh$_3$)] was detected by ^{31}P NMR at early stages of the catalysis in Eq. 2. Overall, the molecules that are known to participate, either because they are observed directly or because they are deduced indirectly through observation of their byproducts, suggest that the reactions in equations 3-7 (L = PPh$_3$) are competitively operating in the process, even if some of them involve undetected products.



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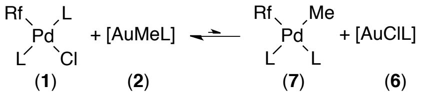

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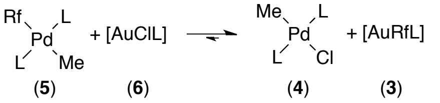

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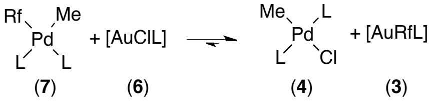
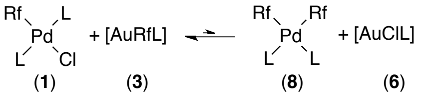


(7)

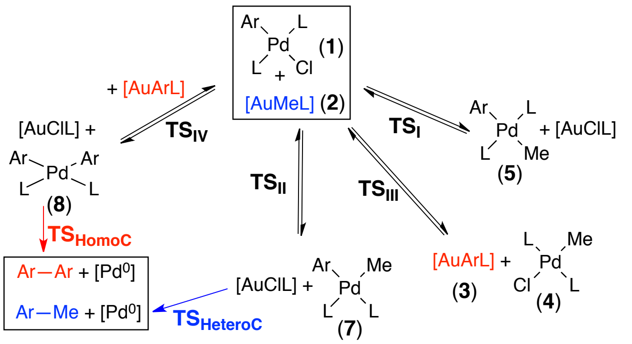
Direct kinetic data can be obtained only for some equations. Thus, complexes **5** and **7** can be prepared by alternative methods,[20] and the reactions in equations 6 and 7 can be studied. The reaction of **5** with [AuCl(PPh$_3$)] (**6**) (Eq. 6) takes place smoothly at 50 °C (for [**5**]$_0$ = 0.01M, k_{obs} = 3.4·10^{-2} Lmol^{-1}s^{-1}; $\Delta G^{\ddagger}_{323}$ = 21.2 kcal mol^{-1}). Not unexpectedly, the reaction is retarded by addition of PPh$_3$ (for [PPh$_3$] = [**5**]$_0$ = 0.01M, k_{obs} = 2.1·10^{-2} Lmol^{-1}s^{-1}). The reaction of the *cis* isomer **7** (Eq. 7) is too fast to be measured by NMR at this temperature, even in the presence of added [PPh$_3$], as in the time required to record a ^{19}F NMR spectrum the reaction is finished. In the context of the reaction of **1** with **2**, this confirms that complex **7**, although formed during the reaction, will not be detected in the experiment due to its very high reactivity with the gold species.

Four other complexes, the precursors of the non-observed homocoupling products Rf–Rf and Me–Me, should be considered in order to have a complete picture of the exchanges. Homocoupling product Rf–Rf was not observed in the experiment in Fig. 1, as expected from the well-known inertness of cis-[PdRf$_2$L$_2$]. In fact this inertness made it possible our previous study using *cis*-[PdRf$_2$(AsPh$_3$)$_2$] and [AuCl(AsPh$_3$)] as reagents.[17] Although that study suggests that the equilibrium [PdRfClL$_2$] + [AuRfL] to give *cis*-[PdRf$_2$L$_2$] (**8**) and [AuClL] (Eq. 8) should not produce NMR detectable concentrations of *cis*-[PdRf$_2$L$_2$], this equilibrium has to be taken into account for aryls less inert than Rf (Ar in place of Rf, such C$_6$H$_4$CF$_3$), because then a faster reductive elimination from the intermediate *cis*-[PdAr$_2$(PPh$_3$)$_2$] will produce biphenyls, as observed (Eq. 1). For the shake of simplicity the pathways leading to PdMe$_2$L$_2$ (similar to Eq. 8, with Me instead of Pf) will be omitted on the reasonable assumption that Me-Me coupling will be slower compared to any other coupling in the systems with conventional aryls and, in addition, the equilibrium for formation of the electron rich [PdMe$_2$L$_2$] should be the most unfavorable one. Note, however that some ethane is observed in our experimental reaction were the fluorinated aryl does not couple fast Finally, isomerization of the [PdRf$_2$(PPh$_3$)$_2$] and [PdR'Rf(PPh$_3$)$_2$] complexes is not considered because these are usually slower processes than transmetalations, as we have previously found in related systems. For instance, under similar experimental conditions the isomerization of cis-[PdRf$_2$L$_2$] is too slow to be measured.[26]



(8)

The previous analysis shows that, in a general case, the Pd catalyzed reaction of aryl halides with alkyl gold complexes is a complicated process involving several competitive transmetalation pathways. This complex system can be simplified as shown in Scheme 1, where the formation of different intermediates *via* Au/Pd transmetalation is represented. From these, coupling should take place according to their respective rates for reductive elimination.[27] All the equilibria have [PPh$_3$] dependent rates. Pathway (**i**) is unproductive as it forms, in a reversible way, *trans*-[PdArMe(PPh$_3$)$_2$] which will not couple (a *cis* arrangement is required for coupling); pathway (**ii**) leads to *cis*-[PdArMe(PPh$_3$)$_2$], producing cross-coupling; pathway (**iii**) produces [AuArL], which eventually leads *via* the fourth pathway (**iv**) to *cis*-[PdAr$_2$(PPh$_3$)$_2$] and explains the Ar–Ar homo-coupling observed in Eq. 1.



Scheme 1. Competitive pathways to homo- and heterocoupling. These equilibria are not necessarily one-step.

In fact the exchanges are more complex than shown in Scheme 1, as the transformations are not direct and involve the formation of bimetallic transition states and intermediates,[28] related to the existence of more than one step. In this intricate scheme the number of unknowns is much larger than the number of parameters that can be experimentally modified, so determining all elementary rate constants from experimental measures on the overall reaction is not possible. However, some reasonable approximations can be made for our model reaction in the light of the kinetic data obtained.

Analysis of the kinetic data. The collection of experimental data was fitted to kinetic models using a non-linear fitting software package.[29]The kinetic models consider a substitution of triphenylphosphine by the incoming [AuMe(PPh$_3$)] consistent with the -1 reaction order on [PPh$_3$] observed above for Eq. 3; otherwise no acceptable fitting is obtained. The activation energy that the non-linear fitting affords for this substitution is 22.5 kcal·mol^{-1}, in good agreement with the experimental values obtained above ($\Delta G^{\ddagger}_{323}$ = 23.3 kcal.mol^{-1}; $\Delta H^{\ddagger}$ = 63.9 kJ mol^{-1} and $\Delta S^{\ddagger}$ = -95.5 J.K^{-1} mol^{-1}) and with similar activation energy values in our previous studies on gold/Pd systems.[8,17] The negative activation entropy for the reaction supports an associative substitution process of PPh$_3$ by the entering gold complex. From intermediate **B**, formed in this step, the reaction may proceed through different competitive pathways, which have different consequences when translated to a catalytic process. The possibilities considered are depicted in Figure 2.[30]

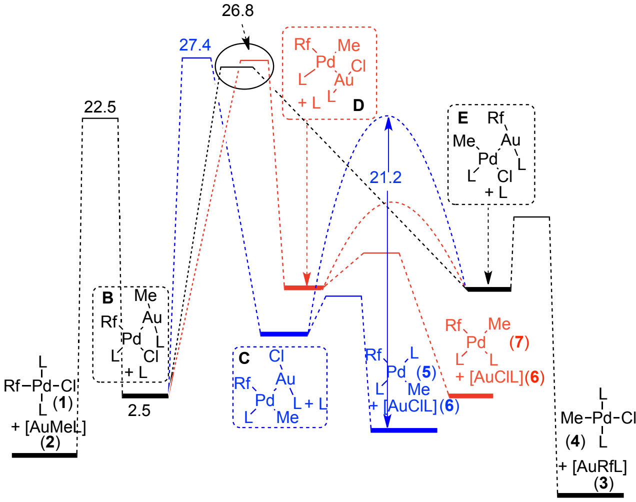


Figure 2. Proposed competitive transmetalations. ΔG_{323} values in kcal mol^{-1}. The three activation energies (22.5, 27.4, and 26.8) are given by the kinetic fitting, taking as zero the stage **1** + **2**. The

value 21.1 is an experimental value, as explained in the text, which is imposed in the fitting as a fixed value.

First of all the transmetalation may produce *trans*-[PdRfMeL$_2$] (**5**) via intermediate **C** . This is an improductive transmetalation since the cross coupling product cannot be formed from this isomer. In addition, since the *cis-trans* isomerization is slow, it cannot re-enter easily the catalytic cycle, except by a reversal transmetalation. Thus **5**, if formed, will react with [AuClL] (**6**) to go back to **C** and eventually produce the byproducts *trans*-[PdMeClL$_2$] (**4**) and [AuRfL] (**3**) (blue lines in scheme 2). In the kinetic model, the known value of the rate constant was assigned to this transformation, with activation energy of 21.2 kcal·mol^{-1}. This pathway is clearly detrimental for cross-coupling purposes since **3** is responsible (*via* transmetalation to **1**; see pathway IV in Scheme 1) for the formation of homocoupling products, and also because **4** further reacts with [AuMeL] (**2**) to produce ethane, consuming unproductively the organogold reagent.

According to the experimental data, a second pathway of reaction has to be proposed to account for a consumption of intermediate **B**, with an activation energy value of 26.8 kcal.mol^{-1}. This second pathway can lead to the unobserved *cis*-[PdRfMeL$_2$] (**7**) through intermediate **D** (red lines in Figure 2). From **7**, the reductive elimination can proceed to the cross-coupling product Rf–Me. However, if the reductive elimination is slow, *cis* aryl-alkyl palladium(II) complexes can alternatively react with [AuClL] (**6**) via intermediate **E**, to produce the undesired aryl gold complex, which eventually gives rise to homocouplings Rf–Rf and Me-Me. This is the case of our model experimental system because fluoroaryls make fluoroary-alkyl coupling particularly difficult. Since the reductive elimination does not take place at a significant rate, almost all our *cis* product is consumed in a very fast reaction with [AuClL] to produce *trans*-[PdMeClL$_2$] (**4**) and [AuRfL] (**3**).

Finally, a third pathway for the evolution of intermediate **B** can be considered: its transformation to intermediate **E** in an aryl/methyl exchange reaction, which eventually produces *trans*-[PdMeClL$_2$] (**4**) and [AuRfL] (**3**) (black lines in Figure 2). Unfortunately, the existence of this pathway cannot be proved or disproved with the experimental data available. In case it effectively exists as a competitive pathway, the experimental activation energy 26.8 kcal mol^{-1} would in fact correspond to the averaged rate of both pathways (red and black).

Thus, the selectivity to the desired cross coupling product Ar–Me depends at least on two critical steps: i) the transmetalation rate from intermediate **B** to produce *cis*-[PdArMeL$_2$], since the other pathways lead to the undesired [AuArL]; and ii) the reductive elimination rate of *cis*-[PdArMeL$_2$], because its accumulation in solution opens the possibility of a fast exchange with [AuClL] to produce again [AuArL].

The model proposed in Figure 2 provides qualitative information to understand why the cross-coupling of alkylgold complexes with aryl halides is difficult. An obvious reason is that the Ar–alkyl reductive elimination has higher activation energy than Ar–Ar coupling for conventional aryls.[19,20,21] This should allow for the formation of *cis*-[PdAr$_2$L$_2$] via successive transmetalations (Eqs. 3, 6–8) with Ar in place of Rf), leading to the precursor on which a faster Ar-Ar homocoupling can occur. The efficiency of this undesired process should depend, in a general case, on the transmetalation rates as compared to the cross-coupling rates. In addition, the preference of palladium for the Me group and gold for the Ar group, remarked in Figure 1 and in equations 5 and 6, suggests that using [Au(^{n}Bu)(PPh$_3$)] or alkyl complexes other than Me should produce alkyl-palladium complexes similar to **4**, allowing for easy β–H elimination. Although the addition of phosphine could help to prevent this and slow down the undesired transmetalation reactions, it should have the same effect on the desired transmetalations, so it does not look that this could help to drive the reaction more selectively.

In summary, the result of the processes should be very much dependent of the compared rates of the reductive elimination for cross-coupling and homo-coupling, and transmetalation steps. The experimental effect of changing the aryl group is as reported in Table 1. In our experience more electronegative aryl groups are slower towards coupling reductive elimination? (an extreme case is Rf, for which Rf–Rf coupling does not occur) and also slower towards transmetalation. Both effects, but specially the first one, should help to do the undesired transmetalation/homo-reductive elimination sequence less competitive for more electronegative groups, somehow protecting the desired homo-coupling reaction. Considering the complexity of the system, the rough correlation between the homo/hetero coupling ratios and the Hammet σ_p supports this qualitative interpretation. The literature case of aryl-vinyl coupling, studied by Hasmi, Blum and Sarandeses groups,[6,7,8,11,13] where the selectivity towards cross-coupling is very high, is also easily understood: Vinyl transmetalations are very fast, and in these conditions the reactions are dominated by the faster coupling rate (aryl-vinyl > aryl–aryl).

EXPERIMENTAL SECTION

All reactions were carried out under argon or nitrogen. Solvents were dried using a Solvent Purification System (SPS). NMR spectra were recorded on a Bruker AV 400 or a Varian 500/MR instrument equipped with a variable-temperature probe. Chemical shifts were reported in ppm from tetramethylsilane (^{1}H), CCl_3F (^{19}F), or 85% H_3PO_4 (^{31}P), with positive shifts downfield, at ambient probe temperature unless otherwise stated. The temperature for the NMR probe was calibrated using ethylene glycol as a temperature standard (T > 300 K) and with a methanol standard (T < 300 K).[31] In the ^{19}F and ^{31}P spectra measured in non-deuterated solvents, a coaxial tube containing acetone-*d$_6$* was used to maintain the lock ^{2}H signal. Combustion CHN analyses were made on a Perkin-Elmer 2400 CHN microanalyzer. Unless specified, all the compounds were used from commercial sources and used without further purification. The compounds *trans*-[PdRfCl(PPh$_3$)$_2$],[26a] [AuRf(PPh$_3$)],[32] *cis*- and *trans*-[PdRfMe(PPh$_3$)] and RfMe, [20] and *trans*-[Pd($C_6H_4CF_3$-*p*)I(PPh$_3$)$_2$],[33] were prepared as reported in the literature.

Synthesis of the complexes

[AuMe(PPh$_3$)]. This synthesis is a modification of the procedure reported in the literature.[34] 1.5 g of [AuCl(PPh$_3$)] (3.03 mmol) were dissolved in THF (20 mL). The solution was cooled to -78 ºC and 7.58 mL of $ZnMe_2$ 2.0 M in toluene (15.2 mmol) were added. The reaction was stirred for four hours. After this time the solution was heated to -20 ºC, the solvent was removed *a vacuo* and 20 mL of cold hexane were added causing the precipitation of the gold complex as a white solid that was filtered, washed with cold hexane and vacuum dried. Yield: 1.30 g. (60 %). ^{1}H NMR (acetone-*d$_6$*): δ 7.62-7.53 (m, 15H, *Ph*), δ 0.42 (d, $^3J_{P\text{-}H}$ = 8.3 Hz, 3H, *Me*). ^{31}P NMR (acetone-*d$_6$*): δ 46.7 (s). Cald. for $C_{19}H_{18}AuP$: C, 48.12; H, 3.83. Found: C, 47.93; H, 3.85.

Reactions of trans-[PdRfCl(PPh$_3$)$_2$] and [AuMe(PPh$_3$)]. Kinetic procedure. The kinetic experiments were studied by ^{19}F NMR. A volumetric NMR tube (5 mm) was charged with weighted amounts of *trans*-[PdRfCl(PPh$_3$)$_2$], [AuMe(PPh$_3$)] and PPh$_3$. The NMR tube was cooled down to -78 ºC and a small amount of THF (about 0.5 mL) was added to dissolve the solids. Then an additional amount of THF was added to reach a fixed volume of 0.6 mL. The tube was charged with an acetone-*d$_6$* capillary for NMR lock, and placed into a thermostated probe. Series of NMR spectra (64 transients) were recorded at fixed time intervals of 5 minutes.

Concentration-time data were obtained from the integrated areas of *trans*-[PdRfCl(PPh$_3$)$_2$], [AuRf(PPh$_3$)], *trans*-[PdRfMe(PPh$_3$)$_2$] and Rf–Me.

Cross-coupling experiments. Typical procedure. A NMR tube was charged with [AuMe(PPh$_3$)] (10 mg, 0.021 mmol), *p*-CF$_3$C$_6$H$_4$I (0.042 mmol), and *trans*-[Pd(*p*-CF$_3$C$_6$H$_4$)I(PPh$_3$)$_2$] as catalyst (0.95 mg, 0.0011 mmol). The solids were dissolved in 0.6 ml of THF-*d$_8$* and the tube was placed in a thermostated bath at 50 ºC. The evolution of the reaction was monitored by ^{31}P NMR and ^{1}H NMR, and by ^{19}F NMR when possible. The relative amount of homo- and cross-coupling products was taken from integrated areas of clean signals. The products were characterized according to the known NMR data: *p*-CF$_3$C$_6$H$_4$-C$_6$H$_4$CF$_3$,[35] *p*-NO$_2$C$_6$H$_4$–C$_6$H$_4$NO$_2$,[36] *and* *p*-FC$_6$H$_4$–C$_6$H$_4$F.[37]

ASSOCIATED CONTENT

Supporting Information

Kinetic data and details about the non-linear-least-squares fitting procedure are included. This material is available free of charge via the Internet at http://pubs.acs.org

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Notes

The authors declare no competing financial interests.

ACKNOWLEDGMENT

We thank the Spanish Comisión Interministerial de Ciencia y Tecnología (Project CTQ2011–25137) and the Junta de Castilla y León (VA256U13) for financial support.

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30 The structures of intemediates **B** and **C** in Figure 2 are proposed with a Pd–Au bond according to the calculated structures found in all DFT studies available. An alternative Pd-X-Au structure with bridging X ligand (X = Cl, Me), which would be kinetically equivalent, has not been found in calculations. Structures with Pd interacting with both components of the X–Au bond have been found in the transition states of the associative substitution of the Pd leaving ligand by the entering complex AuXL: See references 7, 8 and 17.

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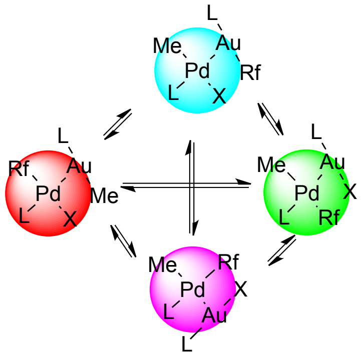

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