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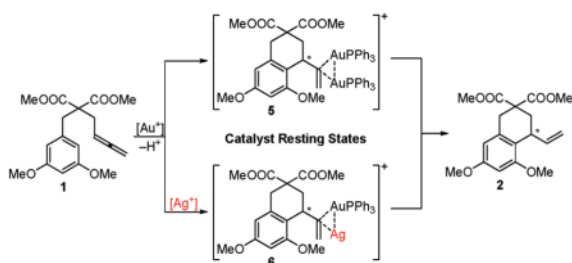
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Dinuclear Gold–Silver Resting States May Explain Silver Effects in Gold(I)-Catalysis

Dieter Weber and Michel R. Gagné*

Caudill Laboratories, Department of Chemistry, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599-3290

Abstract



The resting state of the gold(I)-catalyzed hydroarylation of **1** changes in the presence of Ag^+ , with silver free catalysts resting at the dinuclear gold structure **5** and Ag^+ containing solutions resting at a heteronuclear species like **6**. Adventitious Ag^+ (typically from $LAuCl$ activation) can therefore intercept key organogold intermediates and effect the catalysis even when it does not effect the reaction in Au free control experiments.

Silver salts are commonly used to activate metal halides for catalytic transformations, and this strategy is especially useful in homogeneous gold catalysis.¹ After control experiments demonstrating that the AgX ($X = BF_4, OTf, NTf_2$, etc.) activator does not catalyze the reaction of interest, the silver salts are often used in excess to ensure quantitative activation of the precatalyst.² Despite proving that the silver salts themselves are unreactive, there are examples of gold(I)-catalyzed reactions where Ag^+ effected either activity or selectivity,³ but models for accommodating such observations are not well appreciated in the gold catalysis community. We report herein observations that point to Ag^+ ions intercepting Au(I) catalytic intermediates and subsequently effecting catalyst speciation and reaction kinetics; a structural model is also suggested.

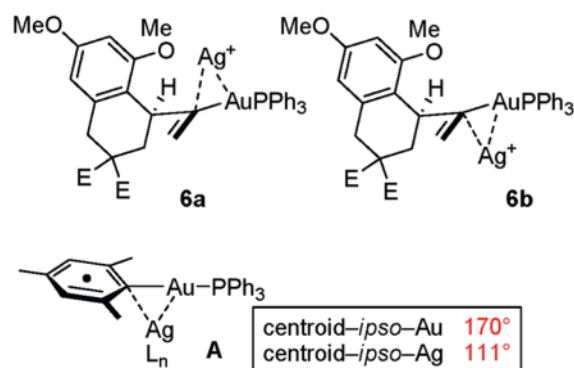
In a recent investigation of the gold(I)-catalyzed hydroarylation of **1** to **2**,⁴ we noted that the catalyst rested at the digold vinyl intermediate **5**,⁵ which could additionally be synthesized by the combination of $Ph_3PAuNTf_2$ (**4**) and the monoaurated vinylgold(I)-complex **3** (Scheme 1). Based on the doubly aurated aryl compounds of Schmidbauer, **5** was formulated as an out of plane Au–C–Au 3-center-2-electron bond with a stabilizing d^{10} closed shell aurophilic interaction.⁶ Motivated by the observation of Ag^+ -effects in gold(I)-catalysis and the known examples of auro-argentophilic closed shell interactions in polymetallic complexes, we examined the effect of Ag^+ on the catalyst speciation.⁷

mgagne@unc.edu.

Supporting Information Available: Synthetic procedures, characterization, and additional spectroscopic data. This material is available free of charge via the Internet at <http://pubs.acs.org>.

As expected, the catalyst generated *in situ* from $\text{Ph}_3\text{PAuCl}/\text{AgNTf}_2$ (5 mol %/25 mol %) was found to be effective for the conversion of **1** to **2**, while the AgNTf_2 activator was much less reactive at RT.⁸ Monitoring the reactions by NMR, however, revealed a significantly different behavior from $\text{Ph}_3\text{PAuNTf}_2$ (**4**) alone.⁹ Instead of **5** being observed using **4**, the Ag^+ -containing catalyst formulations rested at a new structure with a singlet in the ^{31}P NMR at $\delta = 41$ ppm (Figure 1a) and regenerated **4** at the end of the reaction. This compound, **6**, could be independently synthesized by reacting a mixture of **4** and AgNTf_2 with **1** in the presence of 2,6-di-*tert*-butylpyridine, which acts to arrest protodemetalation.¹⁰ The resonances of this new species (Figure 1b) exactly matched those observed in the ^1H and ^{31}P NMR of the *in situ* monitored catalytic reactions. Figure 1c and d additionally display the corresponding spectra for the isolated intermediates **5** and **3**, respectively.

Analysis of the ^1H NMR of **6** indicated a complex with a PPh_3 to carbocyclic framework ratio of one. Both vinyl protons additionally were found to couple to one phosphorus nuclei ($\text{H}_{\text{syn}}: ^4J_{\text{PH}} = 5$ Hz; $\text{H}_{\text{anti}}: ^4J_{\text{PH}} = 14$ Hz), and like **5** and previously reported multimetalated compounds, the quaternary bimetalated sp^2 carbon showed no signal in the ^{13}C NMR, perhaps a result of the quadrupole moment of gold.^{6a} High resolution mass spectrometry showed an m/z of 899.1046 (calcd 899.0966) for the $[\text{M}-\text{NTf}_2]^+$ ion with the isotope pattern expected for a Au–Ag containing compound.



Inspection of X-ray data for numerous simple Au–Ag complexes, e.g. **A**,^{12b} suggests that Ag^+ likely binds to the vinyl carbon and the Au ion without significantly perturbing the gold-vinyl structure.¹² In other words, the 3-center-2-electron interaction is not equal and the stronger C–Au bond dominates the structure. Since only a single diastereomer is observed, one of the diastereofaces must be preferentially populated (i.e. **6a** or **6b**).¹³

Since the putative role of **6** is to react with acid to give **2** and regenerate **4** and AgNTf_2 , the acid stability of **6** was tested. Compound **6** was unchanged in the presence of 5 equivalents of AcOH ,⁵ but did provide traces of **2** with 35 equivalents over 48 h. One equivalent of the stronger acid HNTf_2 (generated *in situ* during catalysis) resulted in a rapid protodeauration to form **2**. When treated with Br^- , precipitation of AgBr drives the conversion of **6** to the monoaurated goldvinyl **3** (Scheme 2).

The rapid and clean reaction of **3**, a putative reaction intermediate, with 2 equivalents of AgNTf_2 to form **6**, suggests that this process may be viable under catalytic conditions, and thus act to trap intermediate Au(I)-compounds. Similarly, the dinuclear gold intermediate **5** reacted with 3 equivalents of AgNTf_2 to provide the mixed metal species **6** showing that even preformed digold structures can be driven to the heterometallic structure.¹⁴

Such a silver-for-gold substitution seems only slightly downhill as it was found in catalytic experiments that the resting state monotonically shifted from **6** to **5** as the Au/Ag ratio was

increased. The change in speciation was especially dramatic when gold was added as Ph_3PAuCl , which simultaneously decreased the Ag^+ concentration by precipitation of AgCl (Figure 2 and 3). Under suitably balanced conditions it is therefore possible to detect both digold and mixed gold/silver resting states.¹⁵

The effect of excess AgNTf_2 on the kinetics of the cyclization was also investigated. At a Au(I) loading of 5 mol %, the rate with a 3-fold excess of Ag^+ was significantly retarded relative to the gold only experiment (Figure 4). Unexpected was the increased rate of **1** consumption as the reaction progressed.

We show herein that even if the reactants are untouched by Ag^+ , silver ions can still influence gold-catalyzed reactions by intercepting key organogold intermediates to form dinuclear intermediates with their own unique reactivity. A structural model based on existing Au/Ag cluster chemistry literature is proposed, which may rationalize known Ag^+ effects.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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References

1. Selected review articles on gold catalysis: (a) Hashmi ASK. *Gold Bull* 2004;37:51. (b) Hashmi ASK, Hutchings GJ. *Angew Chem, Int Ed* 2006;45:7896. (c) Hashmi ASK. *Chem Rev* 2007;107:3180. [PubMed: 17580975] (d) Hashmi ASK. *Catal Today* 2007;122:211. (e) Li Z, Brouwer C, He C. *Chem Rev* 2008;108:3239. [PubMed: 18613729] (f) Widenhofer RA. *Chem—Eur J* 2008;14:5382. (g) Gorin DJ, Sherry BD, Toste FD. *Chem Rev* 2008;108:3351. [PubMed: 18652511] (h) Arcadi A. *Chem Rev* 2008;108:3266. [PubMed: 18651778] (i) Jiménez-Núñez E, Echavarren AM. *Chem Rev* 2008;108:3326. [PubMed: 18636778] (j) Bongers N, Krause N. *Angew Chem, Int Ed* 2008;47:2178. (k) Gorin DJ, Toste FD. *Nature* 2007;446:395. [PubMed: 17377576] (l) Fürstner A, Davies PW. *Angew Chem, Int Ed* 2007;46:3410. (m) Hashmi ASK, Rudolph M. *Chem Soc Rev* 2008;37:1766. [PubMed: 18762826]
2. Selected example of a silver and gold catalyzed reaction: (a) Godet T, Vaxelaire C, Michel C, Milet A, Belmont P. *Chem—Eur J* 2007;13:5632. Selected review articles on silver-catalyzed reactions: (b) Halbes-Letinois U, Weibel JM, Pale P. *Chem Soc Rev* 2007;36:759. [PubMed: 17471400] (c) Weibel JM, Blanc A, Pale P. *Chem Rev* 2008;108:3149. [PubMed: 18616324] (d) Naodovic M, Yamamoto H. *Chem Rev* 2008;108:3132. [PubMed: 18637695] (e) Álvarez-Corral M, Muñoz-Dorado M, Rodríguez-García I. *Chem Rev* 2008;108:3174. [PubMed: 18630971] (f) Yamamoto Y. *Chem Rev* 2008;108:3199. [PubMed: 18611053] (g) Patil NT, Yamamoto Y. *Chem Rev* 2008;108:3395. [PubMed: 18611054]
3. See for example: (a) Li H, Widenhofer RA. *Org Lett* 2009;11:2671. [PubMed: 19514795] (b) Tarselli MA, Chianese AR, Lee SJ, Gagné MR. *Angew Chem, Int Ed* 2007;46:6670.
4. For selected examples of allene activation by Au(I) catalysts, see: (a) Hashmi ASK, Schwarz L, Choi JH, Frost TM. *Angew Chem, Int Ed* 2000;39:2285. (b) Liu L, Xu B, Mashuta MS, Hammond GB. *J Am Chem Soc* 2008;130:17642. [PubMed: 19055329] (c) Zhang Z, Liu C, Kinder RE, Han X, Qian H, Widenhofer RA. *J Am Chem Soc* 2006;128:9066. [PubMed: 16834380] (d) Liu Z, Wasmuth AS, Nelson SG. *J Am Chem Soc* 2006;128:10352. [PubMed: 16895385] (e) Park C, Lee PH. *Org Lett* 2008;10:3359. [PubMed: 18613690] (f) Toups KL, Liu GT, Widenhofer RA. *J Organomet Chem* 2009;694:571. [PubMed: 20305794] (g) Gockel B, Krause N. *Org Lett* 2006;8:4485. [PubMed: 16986931]

5. Weber D, Tarselli MA, Gagné MR. *Angew Chem, Int Ed* 2009;48:5733.
6. These Au–Au interactions are estimated to be worth $\sim 10 \text{ kcal mol}^{-1}$. (a) Porter KA, Schier A, Schmidbaur H. *Organometallics* 2003;22:4922. Selected review articles on aurophilicity: (b) Schmidbaur H, Schier A. *Chem Soc Rev* 2008;37:1931. [PubMed: 18762840] (c) Schmidbaur H. *Gold Bull* 2000;1:33. (d) Schmidbaur H. *Chem Soc Rev* 1995;24:391. See also: (e) Pyykkö P. *Angew Chem, Int Ed* 2004;43:4412. (f) Pyykkö P. *Inorg Chim Acta* 2005;358:4113. (g) Pyykkö P. *Chem Soc Rev* 2008;37:1967. [PubMed: 18762842] (h) Nesmeyanov AN, Perevalova ÉG, Grandberg KI, Lemenovskii DA. *Izv Akad Nauk SSSR, Ser Khim* 1974;5:1124.
7. Selected review on auro-metallophilic interactions: Bardaji M, Laguna A. *Eur J Inorg Chem* 2003;3069. See ref 12 for selected examples of auro-argentophilic interactions.
8. Tarselli MA, Gagné MR. *J Org Chem* 2008;73:2439. [PubMed: 18278940]
9. $\text{Ph}_3\text{PAuNTf}_2$ is a silver-free catalyst: Mézailles N, Ricard L, Gagosz F. *Org Lett* 2005;7:4133. [PubMed: 16146370]
10. In the presence of AgNTf_2 , full conversion of **1** to **6** required only 1 equivalent of **4**. In contrast 2 equivalents of **4** were needed for full conversion of **1** to **5** when no silver salt was present, see ref 5. Resin-bound 2,6-di-*tert*-butylpyridine was used for synthetic applications.
11. We presume that Ag^+ is either coordinated by a weak neutral ligand (e.g. substrate) or by NTf_2^- . ^{19}F NMR data was not indicative. X-ray quality crystals have not been forthcoming.
12. Examples of Au–Ag complexes with a bridging carbon: (a) Contel M, Garrido J, Gimeno MC, Jones PG, Laguna A, Laguna M. *Organometallics* 1996;15:4939. (b) Contel M, Jiménez J, Jones PG, Laguna A, Laguna M. *J Chem Soc, Dalton Trans* 1994:2515. (c) Fernández EJ, Hardacre C, Laguna A, Lagunas MC, López-de-Luzuriaga JM, Monge M, Montiel M, Olmos ME, Puelles RC, Sánchez-Forcada E. *Chem—Eur J* 2009;15:6222. (d) Fernández EJ, Gimeno MC, Laguna A, López-de-Luzuriaga JM, Monge M, Pyykkö P, Sundholm D. *J Am Chem Soc* 2000;122:7287. (e) Fernández EJ, Laguna A, López-de-Luzuriaga JM, Montiel M, Olmos ME, Pérez J, Puelles RC. *Organometallics* 2006;25:4307. (f) Fernández EJ, Laguna A, López-de-Luzuriaga JM, Monge M, Montiel M, Olmos ME, Rodríguez-Castillo M. *Organometallics* 2006;25:3639. (g) Ruiz J, Riera V, Vivanco M, García-Granda S, García-Fernández A. *Organometallics* 1992;11:4077. (h) Vicente J, Chicote MT, Alvarez-Falcón MM, Jones PG. *Organometallics* 2005;24:4666. (i) Schuster O, Monkowius U, Schmidbaur H, Ray SS, Krüger S, Rösch N. *Organometallics* 2006;25:1004. (j) Wei QH, Zhang LY, Yin GQ, Shi LX, Chen ZN. *J Am Chem Soc* 2004;126:9940. [PubMed: 15303866] (k) Xie ZL, Wei QH, Zhang LY, Chen ZN. *Inorg Chem Commun* 2007;10:1206. (l) Wei QH, Yin GQ, Zhang LY, Chen ZN. *Organometallics* 2006;25:4941. (m) Hussain MS, Mazhar-UI-Haque, Abu-Salah OM. *J Cluster Sci* 1996;7:167. (n) Mazhar-UI-Haque, Horne W, Abu-Salah OM. *J Crystallogr Spectrosc Res* 1992;22:421. Other examples: (o) Crespo O, Gimeno MC, Laguna A, Larraz C, Villacampa MD. *Chem—Eur J* 2007;13:235. (p) Catalano VJ, Moore AL. *Inorg Chem* 2005;44:6558. [PubMed: 16156614] (q) Catalano VJ, Etogo AO. *Inorg Chem* 2007;46:5608. [PubMed: 17547393] (r) Catalano VJ, Etogo AO. *J Organomet Chem* 2005;690:6041. (s) Vicente J, Chicote MT, Lagunas MC. *Inorg Chem* 1993;32:3748. (t) Catalano VJ, Horner SJ. *Inorg Chem* 2003;42:8430. [PubMed: 14658896] (u) Rawashdeh-Omary MA, Omary MA, Fackler JP Jr. *Inorg Chim Acta* 2002;334:376. (v) Fernández EJ, Laguna A, López-de-Luzuriaga JM, Monge M, Pyykkö P, Runeberg N. *Eur J Inorg Chem* 2002:750.
13. Alternatively the two diastereofaces could be rapidly interconverting through a doubly argentated intermediate or transition state. Laguna has recently reported a cluster with just such a bonding model, see refs 12e and 12f.
14. Auro-argentophilic interactions are stronger than Au–Au interactions due to the introduction of a dipolar interaction: Catalano VJ, Malwitz MA, Etogo AO. *Inorg Chem* 2004;43:5714. [PubMed: 15332824]
15. After adding $>15 \text{ mol } \%$ **4** some of it was also observed in the NMR, as was $(\text{Ph}_3\text{P})_2\text{AuNTf}_2$, see ref 4b.

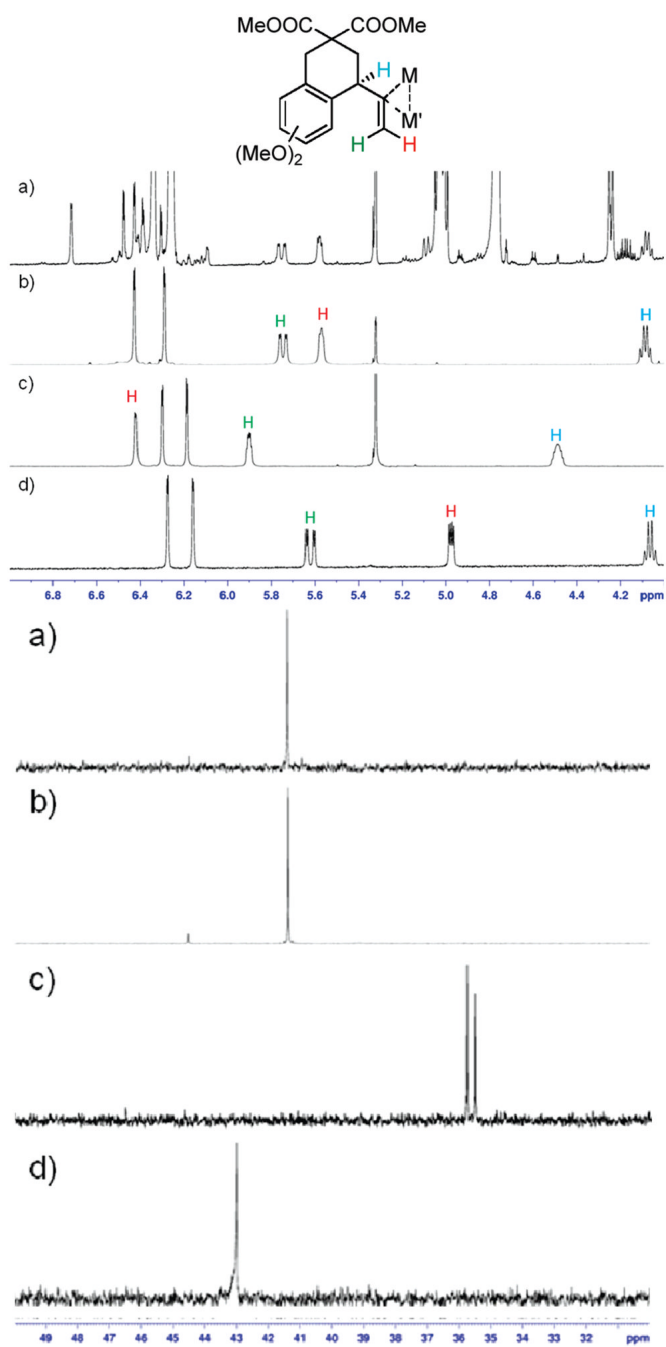


Figure 1. Comparison of ^1H (top) and ^{31}P NMR (bottom) data. (a) Catalysis of **1** with 5 mol % **4** in the presence of 20 mol % AgNTf_2 in CD_2Cl_2 . (b) Compound **6** trapped with 2,6-di-*tert*-butylpyridine in CD_2Cl_2 . (c) Isolated **5** in CD_2Cl_2 . (d) Isolated **3** in CDCl_3 .

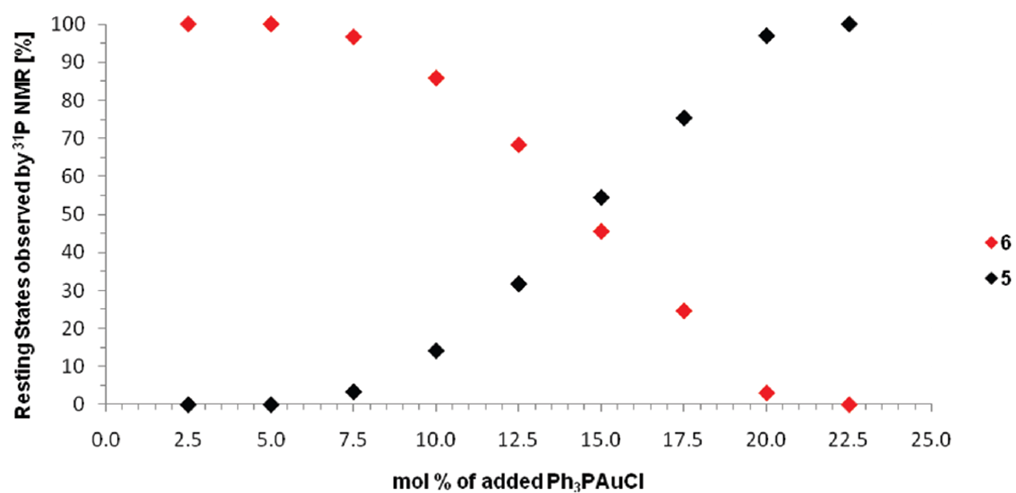


Figure 2. Change in catalyst resting state from **6** (Au–Ag) to **5** (Au–Au) upon additions of Ph_3PAuCl to a solution of **1** and 25 mol % AgNTf_2 in CD_2Cl_2 .

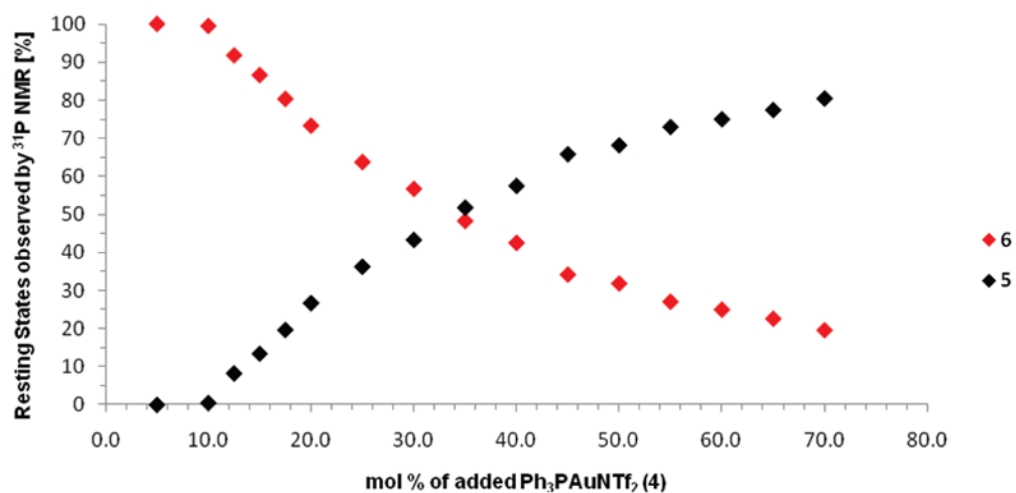


Figure 3. Change in catalyst resting state from **6** (Au–Ag) to **5** (Au–Au) upon additions of **4** to a solution of 0.1 mmol **1** and 15.5 mol % AgNTf₂ in CD₂Cl₂.

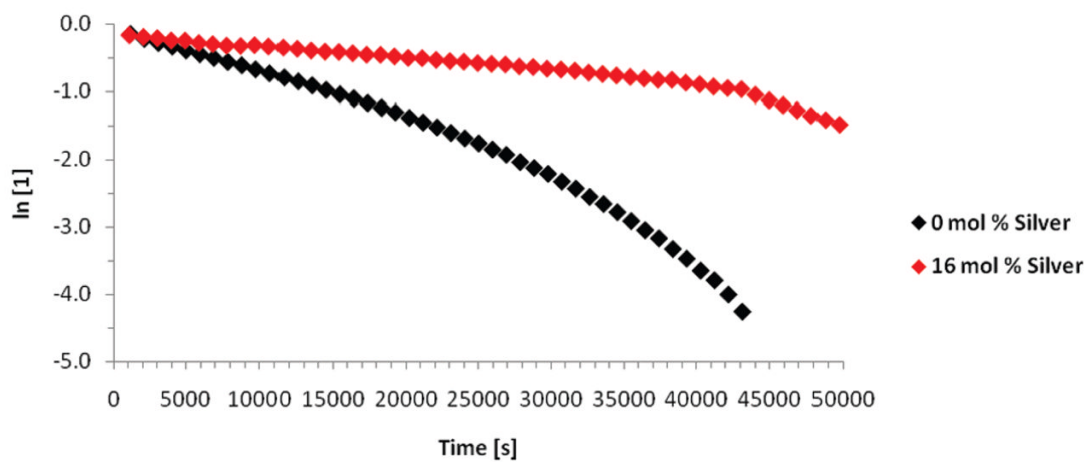
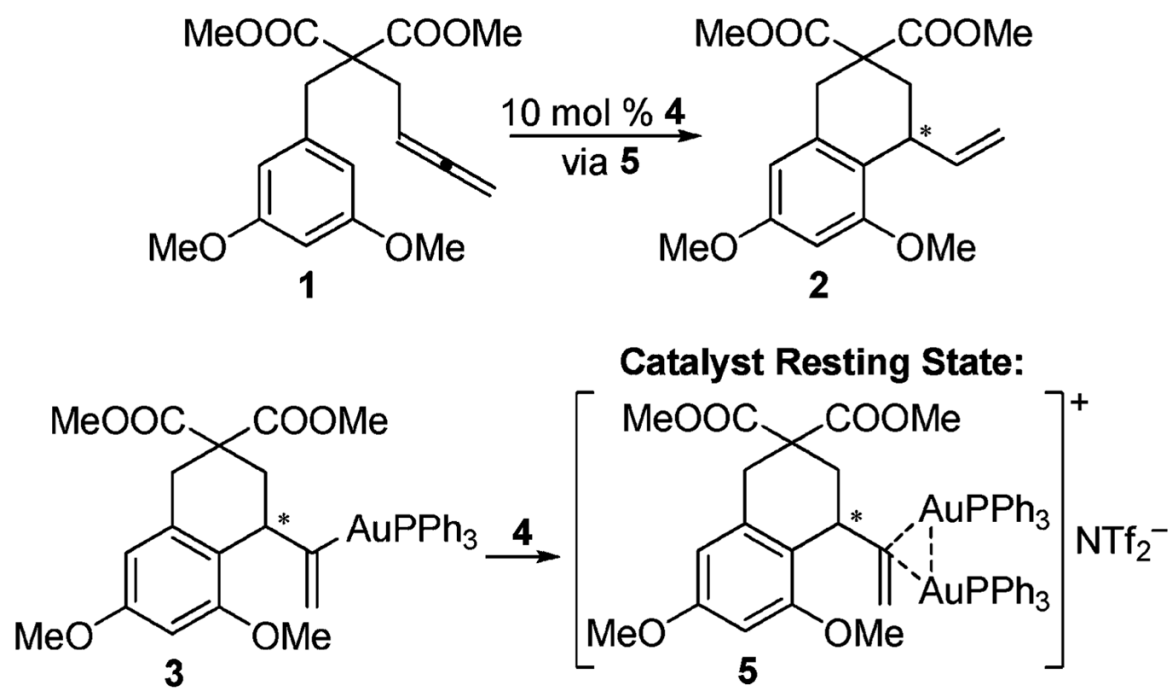


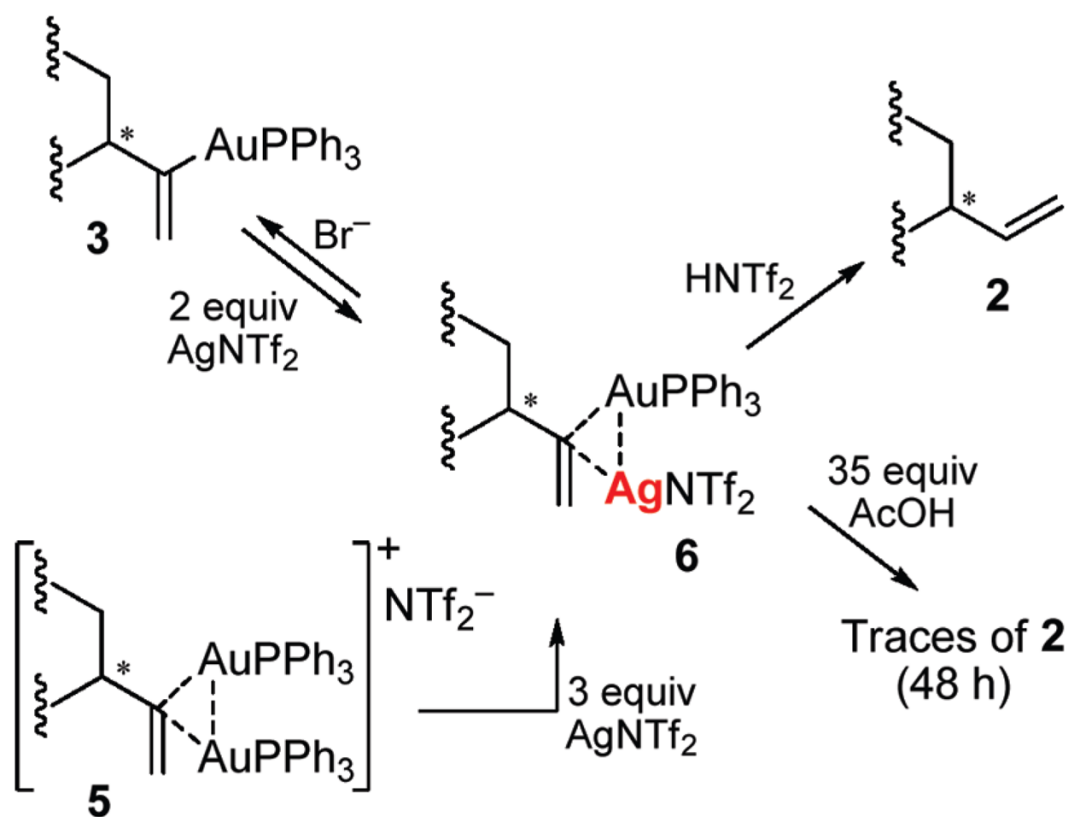
Figure 4.

ln [1] versus time [s] for the conversion to 2 by ^1H NMR; 0.1 mmol 1, 5 mol % $\text{Ph}_3\text{PAuNTf}_2$ (4), and 0.05 mmol hexamethylbenzene (internal standard) in 0.5 mL CD_2Cl_2 ; 6.2 mg (16 mol %) AgNTf_2 was added as a solid (see Supporting Information for details).



Scheme 1.

Catalyst Resting State **5** Was Observed for the Gold(I)-Catalyzed Intramolecular Hydroarylation of **1** to **2**



Scheme 2.
Reactions of Intermediate **6^a**

^a For experimental details, see the Supporting Information.