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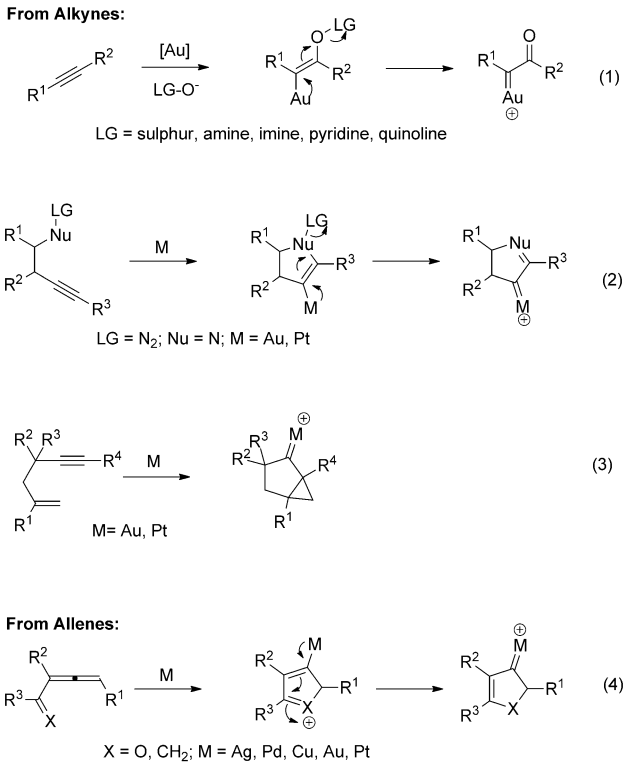
# Studies on $[PtCl_2]$- or [AuCl]-Catalyzed Cyclization of 1-(Indol-2-yl)-2,3-Allenols: The Effects of Water/Steric Hindrance and 1,2-Migration Selectivity

Youai Qiu,[a] Chunling Fu,[a] Xue Zhang,*[b] and Shengming Ma*[a, b]

**Abstract:** The $[PtCl_2]$- or [AuCl]-catalyzed reaction of 1-(indol-2-yl)-2,3-allenols occurred smoothly at room temperature to afford a series of poly-substituted carbazoles efficiently. Compared with the $[PtCl_2]$-catalyzed process, the [AuCl]-catalyzed reaction represents a significant advance in terms of the scope and the selectivity. Selective 1,2-alkyl or aryl migration of the gold carbene intermediate was observed: compared with the methyl group, the isopropyl, cyclopropyl, cyclobutyl, and cyclohexyl groups migrate exclusively; the cyclopropyl group shifts selectively over the ethyl group; the 1,2-migration of a non-methyl linear alkyl is faster than methyl group; the phenyl group migrates exclusively over methyl or ethyl group. DFT calculations show that water makes the elimination of $H_2O$ facile requiring a much lower energy and validates the migratory preferences of different alkyl or phenyl groups observed.

## Introduction

Transformations of metal carbene complexes have been demonstrated to be powerful tools of synthetic organic chemistry in the past several decades.[1] Traditionally, metal carbene complexes have often been generated from organic diazo compounds[2] or the reaction of olefin metathesis.[3] Interestingly, several non-traditional approaches for metal carbene formation have emerged: α-Oxo gold carbenes may be generated from the reaction of $Au^+$-coordinated alkynes with oxygen-centered nucleophiles bearing a protective leaving group, such as sulfur, amine, imine, pyridine, and quinoline [Eq. (1)];[4] gold or platinum carbene may also be generated by such intramolecular reactions with nucleophiles bearing a leaving group [Eq. (2)];[5] in addition, intramolecular alkene unit in 1,5-enynes may also act as the nucleophile to generate cyclopropyl gold or platinum carbene [Eq. (3)],[6] moreover, such reactions may also be observed with allenes: Metal carbene intermediates may be formed through intramolecular nucleophilic attack of carbonyl oxygen lone pair or olefinic double bond on the metal-activated allenic double bond [Eq. (4)].[7–8] However, the 1,2-migration of gold and platinum carbenes is far less understood: despite several reported examples involving 1,2-migration of alkyl, aryl, and halogens, there remains some limitations: 1) The yields are not very good in 1,2-migration of methyl group; 2) It is non-selective with 1,2-migration of the ethyl group versus the phenyl group; 3) The order of 1,2-migration of the alkyl groups has not been established; 4) Various factors on the 1,2-migration of




[a] *Y. Qiu, Prof. Dr. C. Fu, Prof. Dr. S. Ma*
*Laboratory of Molecular Recognition and Synthesis, Department of Chemistry*
*Zhejiang University, Hangzhou 310027, Zhejiang (P.R. China)*
*E-mail: masm@sioc.ac.cn*

[b] *Prof. Dr. X. Zhang, Prof. Dr. S. Ma*
*State Key Laboratory of Organometallic Chemistry*
*Shanghai Institute of Organic Chemistry*
*Chinese Academy of Sciences*
*345 Lingling Lu, Shanghai 200032 (P.R. China)*
*Fax: (+86) 21-626-093-05*
*E-mail: xzhang@sioc.ac.cn*

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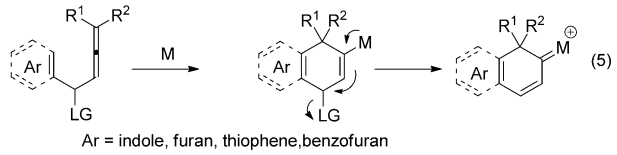
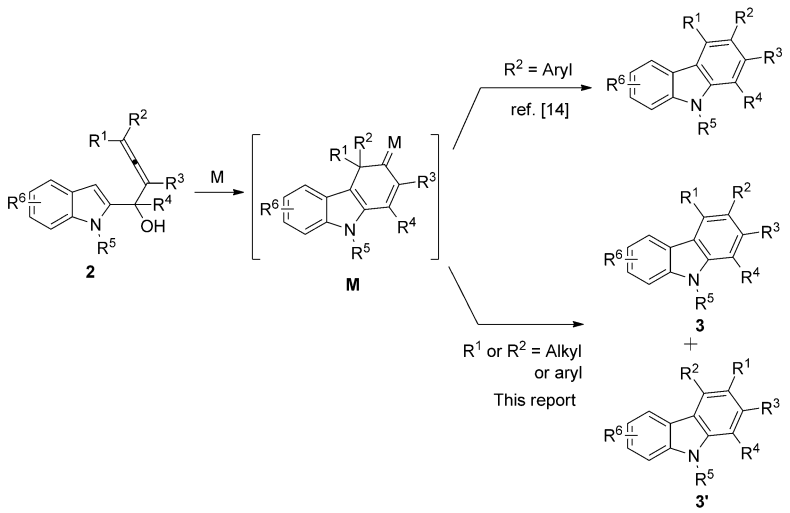
gold and platinum carbene[9] have not been established systematically. Thus, the migratory aptitude in gold and platinum carbene remains to be elucidated.

On the other hand, the tricyclic carbazole ring system is the core structure for a wide range of alkaloids featuring a variety of biological activities.[10] In addition, carbazole derivatives are also widely used as important building blocks for the construction of polymers that exhibit interesting physical properties.[11] The important potentials of these carbazole derivatives have made them attractive targets for organic synthesis.[12] Starting from 2009, we have also observed that cyclic alkyl metal carbene intermediates may be afforded through the reaction of coordinated allene with an indole, furan, thiophene, or benzofuran unit followed by elimination of a leaving group [Eq. (5)].[13]




Ar = indole, furan, thiophene,benzofuran

In the $[PtCl_2]$-catalyzed cycloisomerization of 1-(indol-2-yl)-2,3-allenols, based on deuterium-labeling experiments, the mechanistic assumption involves a 1,2-migration on a Pt–carbene intermediate. Nonetheless, the detailed mechanism of this reaction has not been established. In 2012, we reported the exclusive 1,2-aryl migration over methyl through the Pt-catalyzed cyclization of polysubstituted 1-(indol)-2,3-allenols (Scheme 1).[14] However, the reaction of non-equivalent 4,4-dialkyl-substituted allenols afforded a mixture of regioisomers with very low yields, and the reaction of allenol with phenyl and ethyl groups cannot occur under Pt-catalyzed conditions. These facts promoted us to identify a more efficient catalyst to realize the selective 1,2-alkyl migration of 1-(indol)-2,3-allenols[21]. Herein, we present the results of DFT calculations that support the originally proposed 1,2-migration of the Pt–carbene intermediates, and importantly, provide impetus for the discovery of the more efficient [AuCl] for the selective 1,2-alkyl migration of 4,4-dialkyl-substituted allenols, which show very low reactivities under the $[PtCl_2]$-catalyzed protocol.[14] Finally, the nature of the migratory preferences of different alkyl groups have also been established experimentally and explored by DFT calculations.




**Scheme 1.** Cyclization of 1-indol-2,3-allenols **2**.

## Results and Discussion

### Theoretical studies on mechanisms

To shed light on the mechanism of the above mentioned $[PtCl_2]$-catalyzed cycloisomerization reaction,[14] DFT calculations have been performed first, using the 4-non-substituted 1-(indol-2-yl)-2,3-allenols **2a** as the model substrate.

#### *Computational methodology*

All calculations were performed with the Gaussian 09 program.[15] Geometries have been fully optimized with the density functional theory of B3LYP method.[16,17] The 6-311G (d, p) basis set was used for carbon, hydrogen, nitrogen, and oxygen atoms and LANL2DZ basis set[18] with effective core potential (ECP) for platinum and gold atoms. Harmonic vibration frequency calculations were carried out for all the stationary points to confirm each structure being either a minimum (no imaginary frequency) or a transition structure (one imaginary frequency). The solvent effect has been considered by using the CPCM[19] (UAHF atomic radii) model based on the gas-phase-optimized structures. The reported relative energies are free energies at 298 K ($\Delta G_{298}$) and the zero-point energies corrected electronic energies ($\Delta E_0$), both in gas phase, and free energies ($\Delta G_{sol}$) in toluene (dielectric constant $\varepsilon = 2.37$) for the $[PtCl_2]$-catalyzed process and in 1,2-dichloroethane (DCE) ($\varepsilon = 10.13$) for the [AuCl]-catalyzed process, respectively.

#### *Computational results and discussion*

The computed energy surface for the $[PtCl_2]$-catalyzed cycloisomerization of **2a** is provided in Figure 1. The initial formation of a complex **2a_PtCl$_2$** (selected as free energy reference) involves coordination of $[PtCl_2]$ to the distal allenic double bond, which would be followed by nucleophilic attack of the indolyl C3 to provide the zwitterionic cyclic species **Int1**. This *6-endo-trig* cyclization step is computed to be exergonic ($\Delta G_{298K} =$

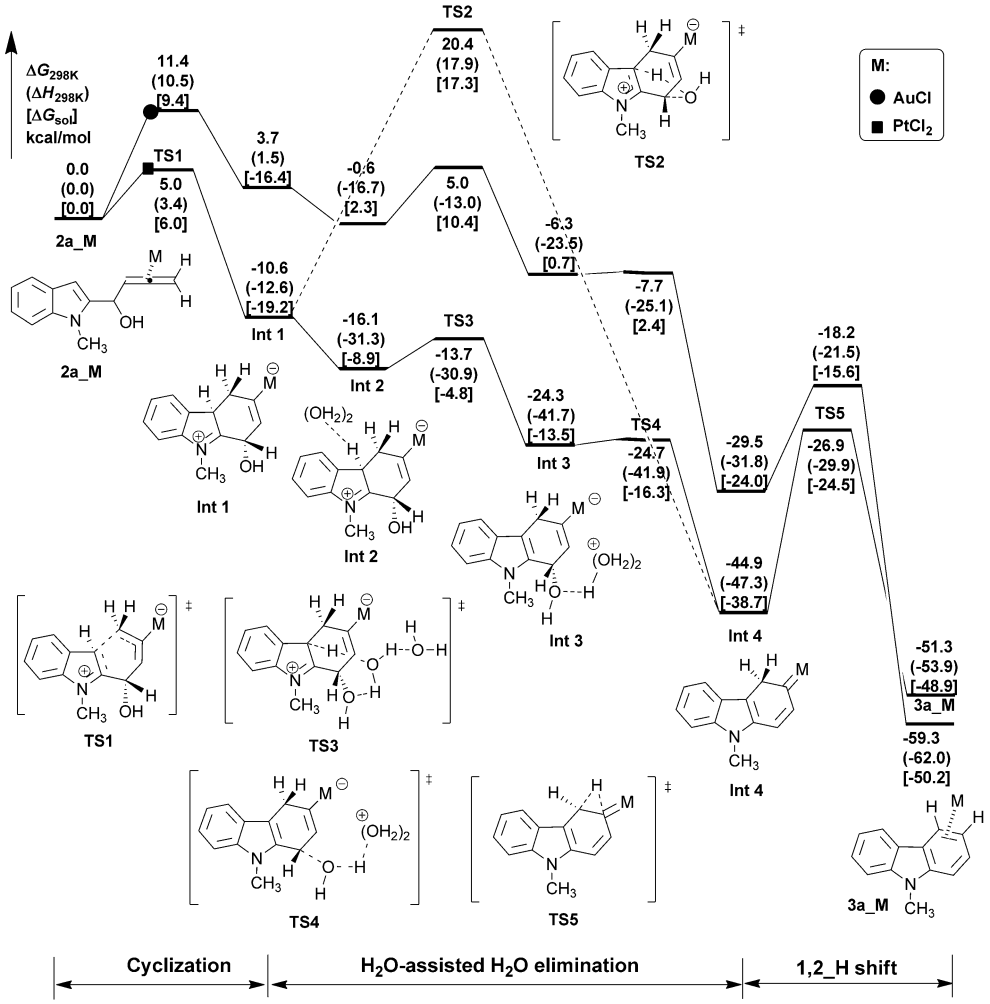



**Figure 1.** DFT-calculated energy surfaces of cycloisomerization of **2a** catalyzed by [$PtCl_2$] and [AuCl].

$-10.6$ kcal mol$^{-1}$) and requires only a 5.0 kcal mol$^{-1}$ activation barrier (**TS1**, Figure 1). The expected platinum carbene **Int4** could be formed by direct elimination of $H_2O$ from the zwitterionic intermediate **Int1**. However, the activation free energy of the elimination of $H_2O$ from **Int1** to **Int4** is computed to be 31.0 kcal mol$^{-1}$ (**TS2**), indicating that this step is not kinetically favorable. Considering the fact that these reactions are usually conducted at room temperature, there should be other possibilities. Interestingly, when water is taken into account, a more kinetically favorable pathway of the elimination of $H_2O$ from **Int1** has been discovered: Abstraction of the proton from **Int2** by water cluster[20] forms the hydroxonium intermediate **Int3**, followed by protonation of the hydroxyl group and elimination of $H_2O$, affording the platinum carbene **Int4**. Calculations show that the presence of water makes the direct elimination of $H_2O$ a reversible stepwise proton–abstraction–donation process, which is highly exergonic by 29.8 kcal mol$^{-1}$ and requires only 2.4 kcal mol$^{-1}$ in total. Thus, the water cluster may act as a proton shuttle in this process, abstracting the proton and subsequent protonating the hydroxyl group. The last step, consisting of a 1,2-H-shift on the resulting carbene with simultaneous coordination of the newly formed C–C double bond to the metal, features the highest relative energy barrier of the profile (18.1 kcal mol$^{-1}$, **TS5**), and may, thus, be rate-determining.

Having established the mechanism for [$PtCl_2$]-catalyzed cycloisomerization, DFT calculations have also been performed for the [AuCl]-catalyzed reaction.[21] The computed potential energy surfaces are qualitatively similar to that of [$PtCl_2$], but less energy demanding especially in the 1,2-H-shift step (11.3 vs. 18.1 kcal mol$^{-1}$ for $PtCl_2$, **TS5**). The Wiberg bond index shows the bond order of C–M in **Int4_PtCl$_2$** is 1.09[22] (Figure 2), much larger than the value in **Int4_AuCl** (0.77). This is in accordance with the well accepted higher ability of Pt compared with Au of forming and stabilizing carbonic C=M bonds.[23] It is due to the formation of a stronger carbene–Pt bond (1.894 Å, Figure 2) compared to carbene–Au bond (1.990 Å, Figure 2) that denotes the relative stability of Pt-carbene intermediate **Int4**, hence, showing lower reactivity for the subsequent 1,2-H-migration.

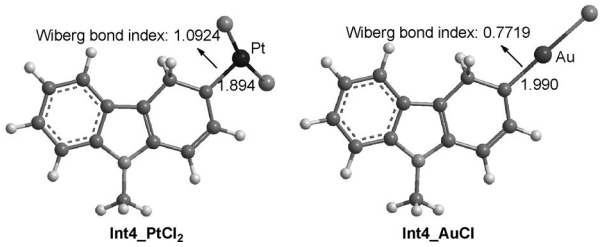
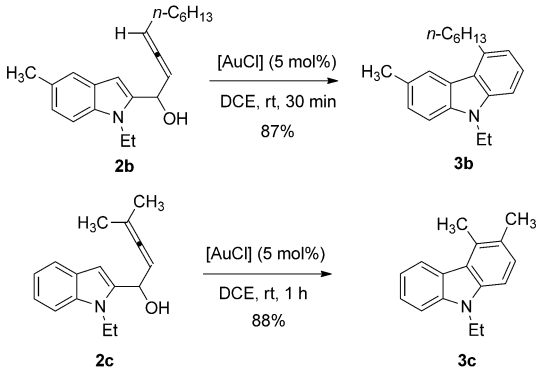



**Figure 2.** Optimized geometries of **Int4_PtCl$_2$** and **Int4_AuCl** with corresponding carbene–metal bond length [Å] and bond order.

## Experimental studies

The DFT calculated results prompted us to investigate the viability of using [AuCl] as the catalyst in this cycloisomerization reaction. Indeed, when allenol **2b** was treated with 5 mol% of [AuCl], the desired carbazole product was obtained in 87% yield after just 30 min in DCE. Furthermore, even the 4,4-dimethyl-substituted 2,3-allenol **2c** could be conducted to 9-ethyl-3,4-dimethylcarbazole in 88% yield within 1 hour under the catalysis of [AuCl], as compared to the reaction catalyzed by [$PtCl_2$] in toluene (Scheme 2).[14]




**Scheme 2.** [AuCl]-catalyzed cyclization reaction of **2b** and **2c**.

### *Optimization of the reaction conditions with [AuCl] as catalyst*

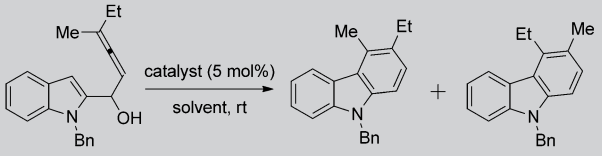
The excellent reactivity profile of [AuCl] led us to test its performance with the substrates that performed very poorly under the standard [$PtCl_2$]-catalyzed conditions. Our initial investigation was focused on the reaction of 1-(1-benzyl-1*H*-indol-2-yl)-4-methylhexa-2,3-dien-1-ol (**2d**). When the reaction was conducted under the catalysis of [$PtCl_2$] (5 mol%) in toluene, the ethyl-migrated carbazole **3d** was formed in 31% yield (analyzed by using NMR spectroscopy), together with the methyl-migrated product **3d′** in 3% yield (entry 1, Table 1). Interestingly, compared with the reaction under the catalysis of [$PtCl_2$], the reaction of **2d** with [AuCl] (5 mol%) in DCE afforded **3d** in a similar yield with a much faster rate (entry 3, Table 1). Fortunately, the combined yield of **3d** and **3d′** was improved to 84% when the reaction was conducted in a diluted solution (entry 5, Table 1). When 1 mol% of [AuCl] was used, the combined yield of **3d** and **3d′** was only 57%, with **2d** being recovered in 24% (entry 6, Table 1). The use of other catalysts such as [$PtCl_4$], [$AuCl(PPh_3)$]/[$AgSbF_6$], or [$AuCl_3$] led to less than 50% of conversion (entries 7–9, Table 1), indicating that the use of [AuCl] as a catalyst is the critical for the success in this reaction.

Furthermore, the effect of temperature and solvent were considered in the reaction of **2d** under the catalysis of [AuCl] (5 mol%). At a lower temperature (10 °C or 0 °C) in DCE, the combined yield of **3d** and **3d′** was slightly lower (entries 2 and 3, Table 2). Several solvents were also tested for the [AuCl]-catalyzed reaction of **2d** at room temperature with DCE still being the best (entries 4–8, Table 2).

### *[AuCl]-Catalyzed cyclization reaction of 4,4-dialkyl-1-(indol-2-yl)-2,3-allenols*

Under the optimized [AuCl]-catalyzed conditions, cycloisomerization of 4,4-dimethyl substituted allenols **2c** and **2e**–**2g** proceeded smoothly to provide better yields of carbazoles **3c** and **3e**–**3g** than the previous [$PtCl_2$]-catalyzed[14] process (entries 1–4, Table 3). In addition to being a methyl group, $R^1$ can also be an ethyl and propyl group (entries 5 and 6, Table 3). It can be easily concluded that the yield was lower as the increasing of steric hindrance of $R^1$. 4,4-Trimethylenelbuta-2,3-dien-1-ol (**2j**) underwent smooth cyclization with ring expansion to afford fused carbazole **3j** in 71% yield (entry 7, Table 3).

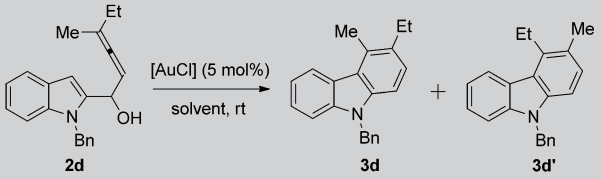
**Table 1.** Optimization of the catalyst and concentration for the reaction of 1-(1-benzyl-1*H*-indol-2-yl)-4-methylhexa-2,3-dien-1-ol.[a]




| Entry | Catalyst | Solvent | *t* [h] | Yield **3d**+**3d′** [%][b] | Ratio **3d**/**3d′** |
|---|---|---|---|---|---|
| 1[c] | [$PtCl_2$] | toluene | 48 | 34 | 91:9 |
| 2 | [$PtCl_2$] | DCE | 42 | 23 | 91:9 |
| 3 | [AuCl] | DCE | 0.5 | 33 | 91:9 |
| 4[d] | [AuCl] | DCE | 0.7 | 73 | 92:8 |
| 5[e] | [AuCl] | DCE | 0.5 | 84 | 92:8 |
| 6[e,f] | [AuCl] | DCE | 48 | 57 | 91:9 |
| 7 | [$PtCl_4$] | DCE | 17 | 18 | 94:6 |
| 8[g] | [$AuCl(PPh_3)$] | DCE | 18 | 8 | – |
| 9 | [$AuCl_3$] | DCE | 18 | 25 | 88:12 |

[a] The reaction was conducted with **2d** (0.2 mmol) and catalyst (5 mol%) in solvent (1 mL). [b] Determined by NMR spectroscopic analysis using dibromomethane as the internal standard. [c] The volume of solvent was 1.5 mL. [d] The volume of solvent was 5 mL. [e] The volume of solvent was 10 mL. [f] [AuCl] (1 mol%) was used, and the recovery of **2d** was 23%. [g] [$AgSbF_6$] (5 mol%) was added.

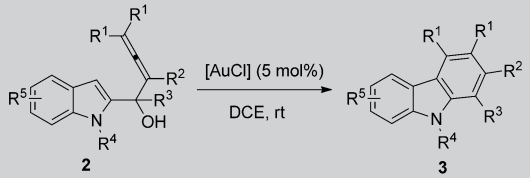
**Table 2.** Effect of temperature and solvent of the reaction of 1-(1-benzyl-1*H*-indol-2-yl)-4-methylhexa-2,3-dien-1-ol.[a]




| Entry | Solvent | *t* [h] | Yield **3d**+**3d′** [%][b] | Ratio **3d**/**3d′** |
|---|---|---|---|---|
| 1 | DCE | 0.5 | 84 | 92:8 |
| 2[c] | DCE | 3.5 | 63 | 92:8 |
| 3[d] | DCE | 16.5 | 58 | 93:7 |
| 4[e] | toluene | 24 | 46 | 91:9 |
| 5 | $CH_2Cl_2$ | 1 | 76 | 92:8 |
| 6 | $CH_3CN$ | 10 | 20 | 85:15 |
| 7 | dioxane | 10 | 52 | 90:10 |
| 8 | THF | 12 | 16 | 88:12 |

[a] The reaction was conducted with **2d** (0.2 mmol), [AuCl] (5 mol%), and solvent (10 mL). [b] Determined by NMR spectroscopy using dibromomethane as internal standard. [c] The temperature was 10 °C, [d] The temperature was 0 °C. [e] The recovery of **2d** was 23%.

**Table 3.** [AuCl]-catalyzed cyclization reaction of 4,4-dialkyl-1-(indol-2-yl)-2,3-allenols.[a]



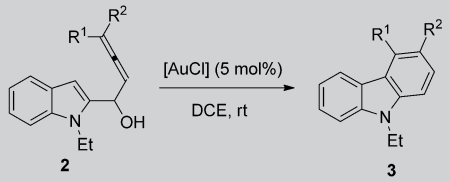

| Entry | $R^1/R^2/R^3/R^4/R^5$ | *t* [h] | Isolated yield (**3**) [%] | Yield/*t* in Ref. [14] [%/h] |
|---|---|---|---|---|
| 1 | Me/H/H/Et/H (**2c**) | 1 | 88 (**3c**) | 73/10 |
| 2 | Me/H/H/Et/7-Me (**2e**) | 1 | 85 (**3e**) | 72/16 |
| 3 | Me/Me/H/Et/H (**2f**) | 1 | 69 (**3f**) | 55/12 |
| 4 | Me/H/Me/Et/H (**2g**) | 1 | 87 (**3g**) | – |
| 5[b] | Et/H/H/Bn/H (**2h**) | 4 | 57 (**3h**) | – |
| 6[b,c] | Pr/H/H/Bn/H (**2i**) | 24 | 34 (**3i**) | – |
| 7[b] | $-(CH_2)_3-$/H/H/Bn/H (**2j**) | 23 | 71 (**3j**) | – |

[a] Reaction conditions: A mixture of **2** (0.2 mmol) and [AuCl] (5 mol%) in DCE (10 mL) under $N_2$. [b] DCE (20 mL) was used. [c] [AuCl] (15 mol%) was used.

### *[AuCl]-Catalyzed cyclization reaction of 4-alkyl-4-phenyl-1-(indol-2-yl)-2,3-allenols*

Furthermore, we have also tested the reaction of 4-alkyl-4-phenyl-1-(indol-2-yl)-2,3-allenols. Selective 1,2-migration of phenyl over methyl group occurred in allenols **2k** to give **3k** in 75% yield (entry 1, Table 4). Electronic effects of substituents on the phenyl ring showed no obvious impact on the yields (entries 2 and 3, Table 4); both *meta*- and *para*-substituted substrates could form the corresponding carbazoles. It is worth noting that the phenyl group migrate exclusively over the ethyl group (entry 4, Table 4), which cannot be realized in previous $[PtCl_2]$-catalyzed process.[14]

**Table 4.** [AuCl]-catalyzed cyclization reaction of 4-alkyl-4-phenyl-1-(indol-2-yl)-2,3-allenols.[a]



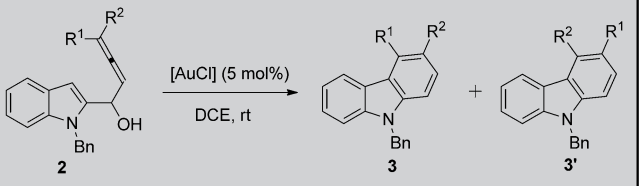

| Entry | $R^1/R^2$ | *t* [h] | Isolated yield (**3**) [%] | Yield/*t* reported in ref. [14] [%/h] |
|---|---|---|---|---|
| 1 | Me/Ph (**2k**) | 1 | 75 (**3k**) | 67/24 |
| 2 | Me/*p*-$FC_6H_4$ (**2l**) | 1 | 88 (**3l**) | 77/25 |
| 3 | Me/*m*-$MeC_6H_4$ (**2m**) | 1 | 79 (**3m**) | 75/12 |
| 4 | Et/Ph (**2n**) | 3 | 53 (**3n**) | NR[b] |

[a] Reaction conditions: A mixture of **2** (0.2 mmol) and [AuCl] (5 mol%) in DCE (10 mL) under $N_2$. [b] No reaction.

### *[AuCl]-catalyzed cyclization reaction of non-equivalent 4,4-dialkyl-substituted-1-(indol-2-yl)-2,3-allenols*

[AuCl] also catalyzes the cycloisomerization reaction of a series of different 4-methyl-4-alkyl-1-(indol-2-yl)-2,3-allenols **2**. The selective 1,2-alkyl migration of non-equivalent 4,4-dialkyl substituted allenols were observed and the results were shown in Table 5. Different carbazoles were formed in moderate to good yields and selectivity, with the longer alkyl group migrating; the structure was confirmed by the X-ray diffraction study of **3p** (Figure 3).[24] In addition to ethyl group (entry 1, Table 5), $R^1$ can also be a propyl, pentyl, and nonyl group (entries 2–5, Table 5). Moreover, from the synthetic view-point, the ratio of **3** and **3′** may be improved to $\geq$97:3 by simple recrystallization (entries 1–5, Table 5). The reaction can be easily conducted in a scale of 3 mmol of **2p** (1.0770 g) in a slightly higher yield (entry 4, Table 5).

**Table 5.** [AuCl]-catalyzed cyclization reaction of 4,4-dialkyl-1-(indol-2-yl)-2,3-allenols.[a]




| Entry | $R^1/R^2$ | *t* [h] | Yield **3** and **3′** [%][b,c] | Yield [%][d] (Ratio) **3**/**3′** |
|---|---|---|---|---|
| 1 | Me/Et (**2d**) | 2 | 75 (92:8) (**3d**/**3d′**) | 46 (98:2) |
| 2 | Me/Pr (**2o**) | 24 | 76 (88:12) (**3o**/**3o′**) | 49 (97:3) |
| 3 | Me/Pent (**2p**) | 4 | 68 (90:10) (**3p**/**3p′**) | 55 (98:2) |
| 4[e] | Me/Pent (**2p**) | 4 | 71 (90:10) (**3p**/**3p′**) | 60 (98:2) |
| 5 | Me/Nona (**2q**) | 4 | 51 (92:8) (**3q**/**3q′**) | 38 (97:3) |

[a] Reaction conditions: A mixture of **2** (0.2 mmol), and [AuCl] (5 mol%) in DCE (10 mL) under $N_2$. [b] Yield of isolated **3** and **3′**. [c] The ratio of **3**/**3′** is reported in the parenthesis. [d] Yield and ratio after recrystallization. [e] The reaction was conducted with a 3 mmol (1.0770 g) scale of **2p**.

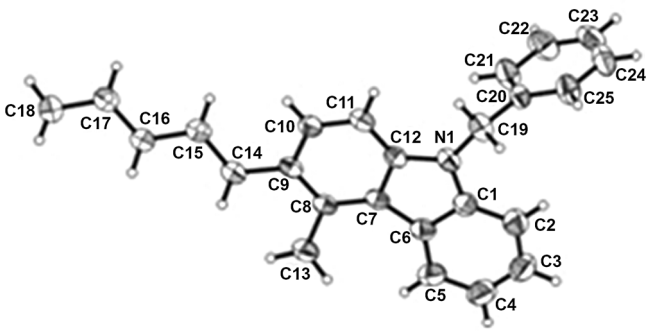
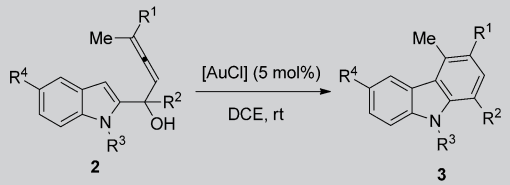



**Figure 3.** ORTEP representation of **3p**.

It is worth noting that exclusive 1,2-isopropyl migration over the methyl group occurred in allenol **2s** to give **3s** in 35% yield (entry 1, Table 6). Cyclopropyl, cyclobutyl, and cyclohexyl

groups have also exclusively migrated in good yields (entries 2–8, Table 6), which was established by the X-ray diffraction study of **3x** (Figure 4).[25] The 1-position of indoles ($R^3$) may be substituted with methyl (entry 8, Table 6), ethyl (entries 1 and 3–7, Table 6), and benzyl groups (Table 6, entry 2). Substituents on the 5 position of indoles ($R^4$) could be methyl (entries 3 and 8, Table 6), or methoxy (entry 5, Table 6) groups. A substituent may also be introduced into the 1 position of the carbazole ring in **3x** by installing $R^2$ groups in the starting allenols.

**Table 6.** [AuCl]-catalyzed cyclization reaction of 4-methyl-4-alkyl-1-(indol-2-yl)-2,3-allenols.[a]




| Entry | $R^1/R^2/R^3/R^4$ | *t* [h] | Yield of isolated **3** [%] |
|---|---|---|---|
| 1[b] | *i*Pr/H/Et/H (**2s**) | 20 | 35 (**3s**) |
| 2 | cyclopropyl/H/Bn/H (**2t**) | 4 | 71 (**3t**) |
| 3 | cyclopropyl/H/Et/5-Me (**2u**) | 2 | 86 (**3u**) |
| 4 | cyclopropyl/H/Et/H (**2v**) | 3 | 70 (**3v**) |
| 5 | cyclopropyl/H/Et/5-OMe (**2w**) | 5 | 86 (**3w**) |
| 6 | cyclopropyl/Me/Et/H (**2x**) | 3 | 76 (**3x**) |
| 7 | cyclobutyl/H/Et/H (**2y**) | 2 | 69 (**3y**) |
| 8[c] | cyclohexyl/H/Me/5-Me (**2z**) | 3 | 31 (**3z**) |

[a] Reaction conditions: A mixture of **2** (0.2 mmol) and [AuCl] (5 mol%) in DCE (10 mL) under $N_2$. [b] DCE (20 mL) and [AuCl] (10 mol%) were used. [c] [AuCl] (10 mol%) was applied.

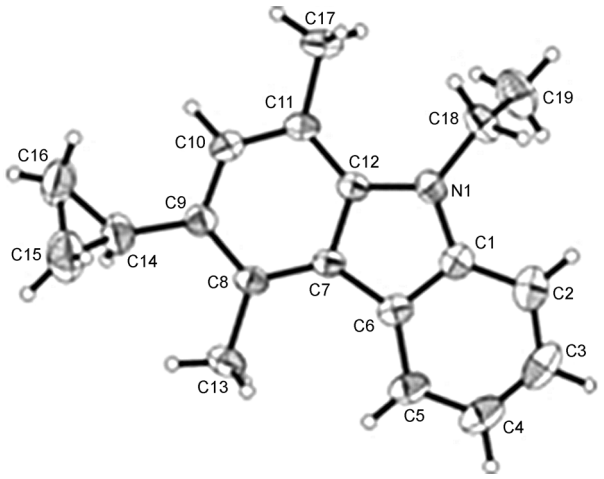
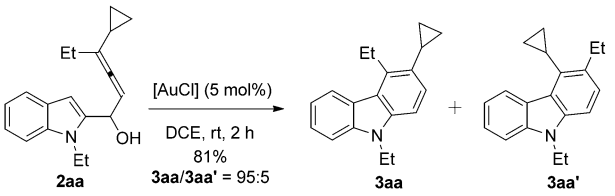



**Figure 4.** ORTEP representation of **3x**.

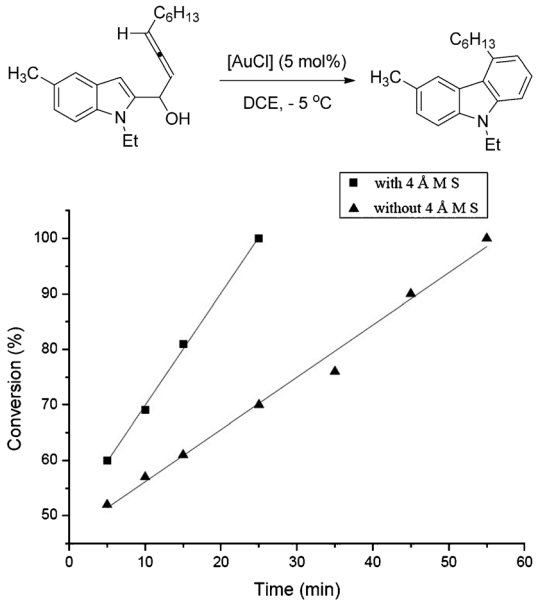
In addition, we observed that the reaction of 1-(1-ethyl-1*H*-indol-2-yl)-4-cyclopropylhexa-2,3-dien-1-ol (**2aa**) in DCE under the catalysis of [AuCl] gave **3aa** and **3aa′** in 81% yield; competing with ethyl group, the cyclopropyl group also migrates highly selectively (95:5) [Eq. (6)].




(6)

### *Experimental study on the effect of the in situ-generated water*

The excellent reactivity of [AuCl] enables us to demonstrate the effect of water experimentally. Molecular sieves (4 Å MS) were added to the reaction mixture of **2b** to remove some of the in situ-generated water. As expected, compared with the reaction in the absence of 4 Å MS, the reaction proceeded in a lower rate (Scheme 3), thus confirming the co-catalytic role of water shown by DFT calculations.



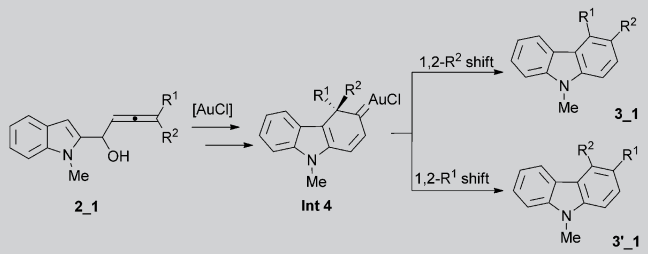

**Scheme 3.** The effect of in situ-generated water on the reaction.

### Theoretical studies on the selectivity

The above mentioned selectivity arises primarily from the preference for either group shift in the gold-stabilized carbene intermediate (**Int4** in Figure 1). To validate the selectivity, the relative activation barriers for the competing migrations have been calculated based on several model substrates 4,4-disubstituted-1-(1-methyl-indol-2-yl)-2,3-allenols **2_1**.

As can be deduced from the energetic data shown in Table 7, the free-energy barrier of phenyl group migration is computed to be lower than that of the competing methyl and ethyl group migration (entries 1 and 2, Table 7). These calculat-

**Table 7.** Calculated free-energy barriers [kcal mol$^{-1}$] for competitive 1,2-migration steps (**TS5** in Figure 1).




| Entry | $R^1/R^2$ | 1,2-$R^1$ shift $\Delta G_{298}$ ($\Delta G_{sol}$) | 1,2-$R^2$ shift $\Delta G_{298}$ ($\Delta G_{sol}$) | $\Delta\Delta G_{298}$ ($\Delta\Delta G_{sol}$) |
|---|---|---|---|---|
| 1 | Me/Ph (**2k_1**) | 19.0 (18.7) | 14.4 (12.6) | 4.6 (6.1) |
| 2 | Et/Ph (**2n_1**) | 17.5 (15.8) | 14.3 (12.6) | 3.2 (3.2) |
| 3 | Me/Et (**2d_1**) | 17.8 (17.2) | 17.0 (14.5) | 0.8 (2.7) |
| 4 | Me/*n*Pr (**2o_1**) | 17.7 (17.0) | 17.2 (14.1) | 0.5 (2.9) |
| 5 | Me/*i*Pr (**2s_1**) | 20.6 (20.7) | 12.4 (8.8) | 8.2 (11.9) |
| 6 | Me/Cyclopropyl (**2t_1** or **2v_1**) | 22.6 (22.0) | 15.7 (9.5) | 6.9 (12.5) |
| 7 | Et/Cyclopropyl (**2aa_1**) | 21.1 (17.1) | 15.4 (9.1) | 5.7 (8.0) |

ed results are in accordance with the generally accepted rate of migratory aptitude to a free carbenic center, H > Ph > Me.[26]

The free-energy barrier of methyl group migration is computed to be higher than that of the competing ethyl, propyl, isopropyl, and cyclopropyl migration (entries 3–6, Table 7). The barrier difference between the migration of regiocompetitive alkyl groups increases roughly with the difference of their steric hindrance, so the bulkier alkyl substituent is calculated to migrate preferentially, thus, capturing the experimental trends, although not quantitatively. The transition structures of the gold carbene 1,2-alkyl migration is responsible for the migratory aptitude. The transition structures of competitive 1,2-isopropyl and 1,2-methyl migrations (entry 5, Table 7), which are denoted as **TS_*i*Pr** and **TS_Me** (Figure 5), respectively, are taken as a typical example. The structures of **TS_*i*Pr** and **TS_Me** largely resemble the planar carbazole products (top view, Figure 5), except that the migrating group bridges the migration original ($C^1$) and terminal ($C^2$) carbon atoms. These two transition states are very late in terms of the C=C bond formation, but are very early in terms of the migration of the alkyl group. As a consequence, the non-migrating isopropyl group in **TS_Me** (side view, Figure 5), roughly in the tricyclic plane, causes a repulsive steric interaction with gold atom (Au···H distance is only 2.558 Å, Figure 5, **TS_Me**, side view) and with the indolyl moiety (H···H distance is only 1.995 Å, Figure 5, **TS_Me**, side view; compare the side view of **TS_Me** with that of **TS_*i*Pr**). The angle $\alpha$ in **TS_Me** (115.8°) is farther from the normal 120° as compared with that of **TS_*i*Pr** (117.9°) (side view, Figure 5) to avoid such steric interactions, resulting in the less stability of **TS_Me** relative to **TS_*i*Pr**. Thus, we reasoned that the release of steric hindrance through the migration of the more sterically hindered group accounts for the migratory preference observed here. In addition, solvent also seems to play a role in enhancing such a selectivity. Of course, there may also be an electronic effect.[27]

## Conclusion

We have reported a simple and mild Au-catalyzed reaction of 1-(indol-2-yl)-2,3-allenols, providing an efficient route to differently substituted carbazoles, which proceeds by a selective 1,2-alkyl or aryl shift via a gold-carbene intermediate. Compared with the previous [$PtCl_2$]-catalyzed process, the [AuCl]-catalyzed reaction represents a big step forward in terms of the scope and the selectivity. Migratory aptitude of 1,2-alkyl or aryl migration has been established: compared with methyl group, the isopropyl, cyclopropyl, cyclobutyl, and cyclohexyl groups migrate exclusively; the cyclopropyl group shifts selectively over ethyl group; the 1,2-migration of a non-methyl linear alkyl is faster than methyl group; the phenyl group migrate exclusively over the methyl or ethyl groups. DFT calculations support the originally hypothesized 1,2-migration on the metal carbene intermediate and discover the co-catalytic role of the in situ-presented water, which makes the elimination of $H_2O$ facile, requiring a much lower energy. Importantly, the calculations suggest that the migratory preference of more bulky

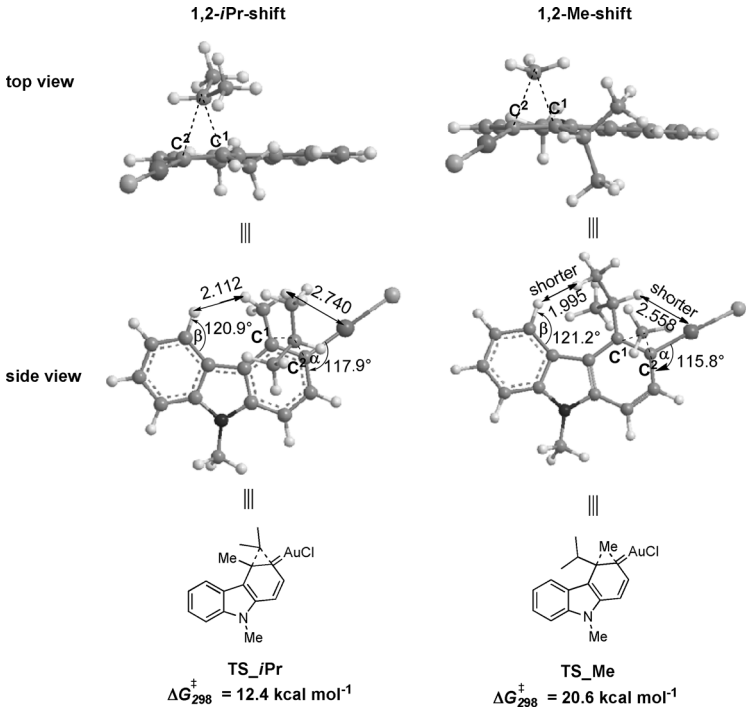



**Figure 5.** The side and top views of the calculated transition structures of competitive 1,2-isopropyl (**TS_*i*Pr**) and 1,2-methyl (**TS_Me**) migrations with selected structural parameters [Å].

alkyl group is a consequence of releasing the steric effect. Further studies in this area are being pursued in this laboratory.

## Experimental Section

### Typical procedure for 3b

[AuCl] (2.5 mg, 0.01 mmol, weighed in a glovebox), compound **2b** (62.0 mg, 0.20 mmol), and DCE (10 mL) were added sequentially to a dry Schlenk tube under $N_2$. After continuous stirring for 0.5 h at RT, the reaction was complete as monitored by TLC. Filtration through a short pad of silica gel (eluent: $Et_2O$ (20 mL×3)), evaporation and column chromatography on silica gel (petroleum ether (30–60 °C)/dichloromethane = 10:1) afforded **3b**[13] (51.1 mg, 87%) as a liquid. $^1$H NMR (300 MHz, $CDCl_3$): $\delta$ = 7.92 (s, 1H, ArH), 7.42–7.13 (m, 4H, ArH), 6.98 (d, $J$ = 7.2 Hz, 1H, ArH), 4.30 (q, $J$ = 7.2 Hz, 2H, $NCH_2$), 3.20 (t, $J$ = 7.8 Hz, 2H, $ArCH_2$), 2.55 (s, 3H, $ArCH_3$), 1.93–1.72 (m, 2H, $CH_2$), 1.62–1.45 (m, 2H, $CH_2$), 1.44–1.27 (m, 7H, 2× $CH_2$ + $CH_3$), 0.91 ppm (t, $J$ = 6.9 Hz, 3H, $CH_3$); $^{13}$C NMR (75 MHz, $CDCl_3$): $\delta$ = 140.4, 138.6, 138.1, 127.8, 126.1, 125.2, 123.0, 122.8, 120.5, 119.2, 107.8, 105.9, 37.4, 34.5, 31.8, 29.7, 29.5, 22.7, 21.6, 14.1, 13.7; IR (neat): $\tilde{\nu}$ = 2954, 2929, 2858, 1598, 1579, 1499, 1477, 1379, 1347, 1331, 1309, 1248, 1150, 1078 cm$^{-1}$; MS (70 ev, EI): *m/z* (%): 294 [$M^+$ + 1] (25.47), 293 (100).

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**Keywords:** allenes · carbenes · density functional calculations · gold · platinum

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