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Preparation of Substituted Cyclopentadienes through Platinum(II)-Catalyzed Cyclization of 1,2,4-Trienes**

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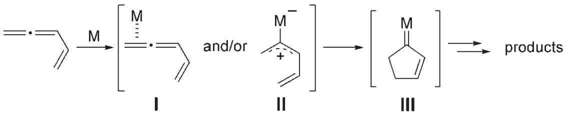
Cyclopentadienes (Cps) are highly useful synthetic intermediates in the field of organic and organometallic chemistry. They are useful not only as a reactive diene component in the Diels–Alder reaction[1] but also as a precursor for the preparation of transition-metal complexes with Cp-type ligands.[2] However, the preparation of well-defined, highly substituted cyclopentadienes is not necessarily easy owing to the absence of general methods[3] and also to the facile migration of the endocyclic double bonds.[4] Herein we describe a novel method for the preparation of highly substituted cyclopentadiene derivatives based on the Pt^{II}-catalyzed cyclization of 1,2,4-trienes in which platinum–carbene intermediates play an important role in determining the reaction pathways.

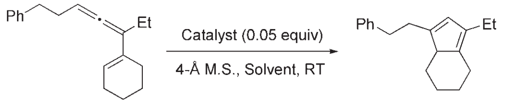
We expected that treatment of 1,2,4-trienes with appropriate electrophilic transition-metal complexes[5] would generate α,β-unsaturated carbene complexes **III** through cyclization of π complex **I**[6] and/or pentadienyl cationic complex **II**, and that the produced carbene complex **III** would further undergo useful transformations to give cyclopentadienes or their derivatives [Eq. (1)].



I II III (1)

On the basis of these considerations, we initiated our study to find optimal conditions for this reaction using 5-(cyclohex-1-enyl)-1-phenylhepta-3,4-diene (**1a**) as a substrate, with a catalytic amount of various electrophilic transition-metal complexes. The expected cyclization of **1a** proceeded most effectively with 0.05 equivalents of $PtCl_2$[7,8] in dichloroethane at room temperature, and the corresponding cyclopentadiene **2a** was obtained in 86% yield with about 95% regioisomeric purity concerning the double bonds (Table 1, entry 5). Other catalysts such as $PtCl_4$ and $AuCl_3$ also showed considerable catalytic activity (Table 1, entries 6 and 7), whereas $PdCl_2$ and $[IrCl(cod)]_2$ did not (Table 1, entries 8 and 9). It was also noted that the reaction with protic acids such as CF_3SO_3H did not yield any cyclopentadiene **2a** (Table 1, entry 10).

Table 1: Cyclization of 1,2,4-triene **1a** to give cyclopentadiene **2a**.



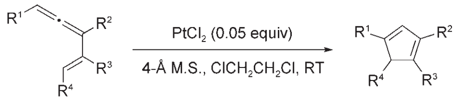
1a **2a**

Entry	Catalyst	Solvent	*t* [h]	Yield [%][a]
1[b]	$[W(CO)_6]$	THF	10	0
2	$PtCl_2$	toluene	24	66
3	$PtCl_2$	THF	48	0
4	$PtCl_2$	CH_3CN	48	0
5	$PtCl_2$	$ClCH_2CH_2Cl$	19	86
6	$PtCl_4$	$ClCH_2CH_2Cl$	20	43[c]
7	$AuCl_3$	$ClCH_2CH_2Cl$	20	60[c]
8	$PdCl_2$	$ClCH_2CH_2Cl$	48	0
9[d]	$[IrCl(cod)]_2$	$ClCH_2CH_2Cl$	48	0
10	CF_3SO_3H	$ClCH_2CH_2Cl$	48	0

[a] Yield of the isolated product. [b] The reaction was performed in the presence of 0.1 equivalents of $[W(CO)_6]$ under direct photoirradiation. [c] The yields were determined by NMR spectroscopy by comparison with an internal standard (dibromomethane). [d] The reaction was performed in the presence of 0.025 equivalents of $[IrCl(cod)]_2$ (cod = cycloocta-1,5-diene).

We then investigated the generality of the reaction using various 1,2,4-trienes (Table 2).[9] Various alkyl groups were used as R^2 in triene **1**, and the corresponding cyclopenta-

Table 2: Platinum(II)-catalyzed cyclization of 1,2,4-trienes **1** to afford cyclopentadienes **2**.



1 **2**

Entry	R^1	R^2	R^3	R^4	*t* [h]	Yield [%][a] (product)
1	$Ph(CH_2)_2$	Et	$-(CH_2)_4-$		19	86 (**2a**)
2	$Ph(CH_2)_2$	*n*Bu	$-(CH_2)_4-$		24	80 (**2b**)
3	$Ph(CH_2)_2$	Bn	$-(CH_2)_4-$		64	81 (**2c**)
4	$Ph(CH_2)_2$	$CH_2{=}CH(CH_2)_2$	$-(CH_2)_4-$		54	54 (**2d**)
5	$Ph(CH_2)_2$	$AcO(CH_2)_5$	$-(CH_2)_4-$		48	88 (**2e**)
6	$Ph(CH_2)_2$	Et	Me	H	44	85 (**2f**)
7	$Ph(CH_2)_2$	Bn	Me	H	48	77 (**2g**)
8	*i*Pr	*n*Bu	$-(CH_2)_4-$		23	77 (**2h**)
9	*i*Pr	Bn	Me	H	60	86 (**2i**)

[a] Yield of the isolated product. Note that a small amount of double-bond regioisomers (≈5%) was found in most cases. Bn = benzyl.

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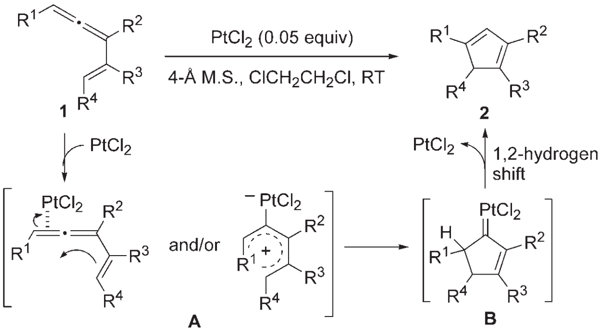
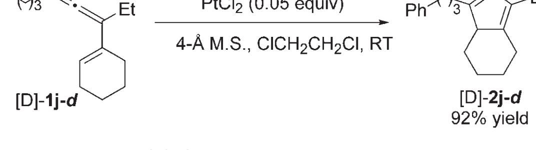
dienes were obtained in high yield (Table 2, entries 1–3). Even 1,2,4-trienes containing a vinyl group (**1d**) or an ester moiety (**1e**) could be employed to give the corresponding tetrasubstituted cyclopentadienes **2** in reasonable yield (Table 2, entries 4 and 5). Furthermore, trisubstituted cyclopentadienes **2f**, **2g**, and **2i** with $R^4 = H$ could be obtained from 1,2,4-trienes **1f**, **1g**, and **1i**, respectively, in high yields (Table 2, entries 6, 7, and 9). Note that in all cases the cyclopentadienes **2** were mostly obtained as a single regioisomer about the double bonds owing to the mildness of the reaction conditions.

A plausible mechanism for this $PtCl_2$-catalyzed cyclization of 1,2,4-trienes is shown in Scheme 1. Intermediates **A**, generated by complexation of 1,2,4-triene **1** with platinum(II), are converted into α,β-unsaturated carbene complexes **B** through intramolecular nucleophilic attack of the olefinic double bond on the $PtCl_2$-π-complexed allenic double bond[10] and/or Nazarov-type 4π electrocyclization of pentadienyl cationic complexes.[11] The platinum–carbene intermediate **B** then undergoes a 1,2-hydrogen shift to give the product **2** with regeneration of the platinum catalyst.



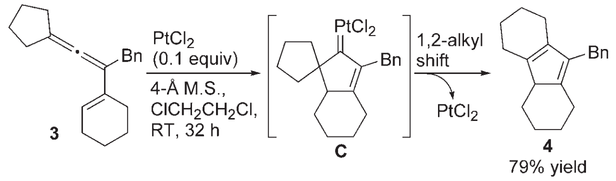
Scheme 1. Proposed reaction mechanism of the platinum(II)-catalyzed cyclization of 1,2,4-trienes.

To examine this proposed reaction mechanism, we carried out a deuterium-labeling experiment (Scheme 2). When deuterated substrate [D]-**1j** was subjected to the same reaction conditions, cyclopentadiene [D]-**2j** with the deuterium label at the vinylic position (> 95% D incorporation) was obtained in 92% yield. This result is consistent with the 1,2-hydrogen migration of the carbene complex intermediate.



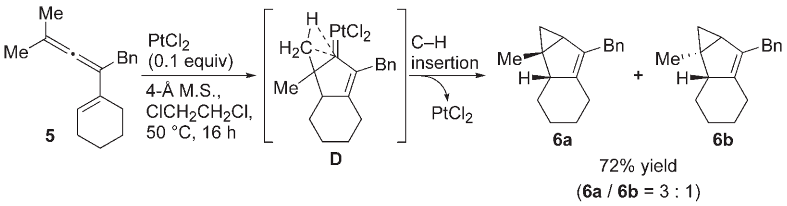
Scheme 2. Deuterium-labeling experiment.

We next applied this cyclization reaction to 1,1-disubstituted 1,2,4-trienes. When 1,2,4-triene **3** was treated with 0.1 equivalents of $PtCl_2$ in dichloroethane at room temperature, a ring-enlargement reaction proceeded smoothly to give the pentasubstituted cyclopentadiene **4** in 79% yield (Scheme 3).[12] The platinum–carbene intermediate **C** was thought to undergo 1,2-alkyl migration[13] to give **4**, and almost no double-bond isomerization was observed in this case also.



Scheme 3. Platinum(II)-catalyzed tandem cyclization/ring-expansion reaction of 1,2,4-triene **3** to give pentasubstituted cyclopentadiene **4**.

Direct evidence of the presence of the carbene intermediate was obtained by the reaction of 1,1-dimethyl-1,2,4-triene **5**. Treatment of this substrate with 0.1 equivalents of $PtCl_2$ at 50 °C gave a tricyclic cyclopropane **6** in 72% yield (Scheme 4). The cyclized product **6** was obtained as a mixture of two stereoisomers (**6a**/**6b** = 3:1), the structures of which were confirmed by measurement of various 1D and 2D NMR spectra (Scheme 4).[14] In this case, the platinum–carbene intermediate **D** inserted into the neighboring carbon–hydrogen bond of the methyl group[15] rather than undergoing 1,2-methyl migration. Formation of the cyclopropane **6** clearly proved the presence of the platinum–carbene intermediate **D**.[13,16]



Scheme 4. Platinum(II)-catalyzed tandem cyclization/C–H insertion reaction of 1,2,4-triene **5** to give cyclopropane **6**.

In conclusion, we have developed a $PtCl_2$-catalyzed preparation of highly substituted cyclopentadiene derivatives from 1,2,4-trienes. This reaction proceeds under mild conditions to afford a variety of well-defined, highly substituted cyclopentadienes, which are key intermediates in organic synthesis and useful ligands in organometallic chemistry. Furthermore, we have succeeded in confirming the presence of α,β-unsaturated platinum–carbene complexes as intermediates by applying this protocol to the tandem cyclization/ring expansion reaction and the tandem cyclization/C–H insertion reaction.

Experimental Section

Typical procedure: Platinum(II) chloride (2.7 mg, 0.01 mmol) was added to a mixture of 1,2,4-triene **1a** (50.5 mg, 0.2 mmol) and 4-Å molecular sieves (200 mg) in 1,2-dichloroethane (2.0 mL) at room temperature. After disappearance of the starting material was confirmed by TLC, the reaction mixture was filtered through Celite using diethyl ether as eluent. The filtrate was washed with an aqueous saturated solution of $NaHCO_3$ and then brine, dried over $MgSO_4$, and filtered. The resulting filtrate was concentrated under reduced pressure, and the residue was purified by preparative TLC (hexane) to give the cyclopentadiene **2a** (43.3 mg, 0.17 mmol) in 86 % yield as a colorless oil.

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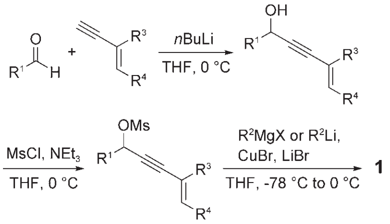
[9] 1,2,4-Trienes **1** were readily prepared in three steps [Eq. (2); Ms = methanesulfonyl]. See Supporting Information for details.



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