Radical Additions to a Coordinated Hydrocarbyl Ligand. Synthesis of Titanacyclobutane Complexes via Regioselective Free Radical Addition to a Ti(III) Allyl Complex†

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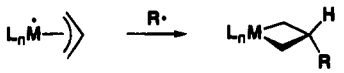
The reactivity of coordinated hydrocarbyl ligands toward nucleophilic and electrophilic reagents has been extensively investigated, leading to the development of numerous synthetically important transition metal-mediated organic transformations.[1] The addition of organic free radicals to organometallic hydrocarbyl ligands, however, remains far less developed. One direct investigation, into the addition of the isobutyrylnitrile radical to cobaltocene,[2] provides strong support for the involvement of analogous free radical additions in the reactions of halocarbons with 19- and 20-electron metallocene and bis(η^6-arene) complexes[3] and in the migration of the benzyl ligand observed upon photolysis of $(C_5H_5)Fe(CO)_2(CH_2Ph)$.[4] Radical addition pathways have also been defined for reactions of radicals with the free olefin moiety of α,β-unsaturated carbene,[5a] η^2-alkenyne,[5b] η^1-allyl,[5c] and η^1-cyclopentadienyl ligands.[5c] Most common, however, are various ligand-to-ligand dimerization reactions observed for a range of odd-electron metal complexes.[6]

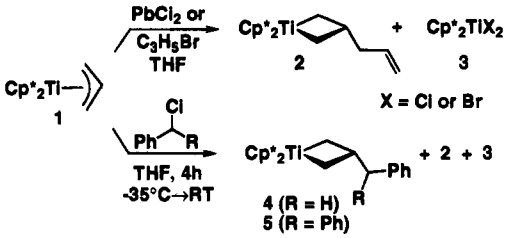
In this Communication, we report the general, highly regioselective addition of organic free radicals to an odd-electron η^3-allyl complex (eq 1). With the neutral, 17-electron complex



(1)

$Cp^*_2Ti(\eta^3\text{-}C_3H_5)$ (**1**,[7] $Cp^* = C_5Me_5$), radical addition takes place exclusively at the central carbon of the allyl ligand, providing a novel entry into the titanacyclobutane structural class. In addition, this efficient radical process may provide mechanistic insight into the recently reported rearrangements of Zr(IV) bis(allylic) complexes[8] and nucleophilic additions to cationic Ti(IV) and Zr(IV) η^3-allyl complexes.[9] When compared to these latter reactions, the greatly reduced electrophilicity associated with the neutral Ti(III) template considerably raises the potential for the development of synthetic methodology based on this reactivity pattern.

Scheme 1



The potential for effecting direct radical coupling was recognized during the oxidative chlorination of allyl complex **1** using $PbCl_2$[10] (0.5 equiv, 20 °C). This reaction unexpectedly leads to the formation of β-allyltitanacyclobutane **2**[11] (47%) and $Cp^*_2TiCl_2$ (53%) rather than $Cp^*_2Ti(allyl)Cl$ (Scheme 1). Although the titanacyclobutane can, in principle, arise from a number of mechanistic schemes, *most* hypotheses incorporate a coupling reaction involving the allyl radical and allyl complex **1**.[12] Treatment of allyl complex **1** with allyl bromide[13] (0.5 or 1.0 equiv, −35 °C → 20 °C) similarly gives complex **2** and $Cp^*_2TiBr_2$. In this reaction, however, the yield of titanacyclobutane reproducibly exceeds 50%, demanding that at least some of the metallacycle is formed via direct addition of allyl radical to complex **1**.[14]

With benzylic chlorides, the intermolecular radical trapping reaction becomes more efficient. Thus, oxidation of allyl complex **1** with benzyl chloride or chlorodiphenylmethane (THF, ~0.05 M) leads to the formation of titanacyclobutane complexes **4** and **5**,[11] respectively, along with complex **2** and $Cp^*_2TiCl_2$ in close to the theoretical ratio of 2:1:1 (Scheme 1).[15,16] The procedure is limited to activated organic halides: the use of *tert*-butyl chloride results in a low yield of *β-tert*-butyltitanacyclobutane **7**,[11] and neither primary nor secondary alkyl halides react with starting allyl complex **1**.

The unproductive consumption of the allyl complex can be avoided by using one of several alternative approaches to radical generation (Table 1). Titanacyclobutane complexes **4**, **5**, and

† Dedicated to Professor Gilbert Stork, his uniquely inspirational presence, and his unsurpassed creativity.

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(11) Complete experimental data are given as supporting information.

(12) The oxidation of $Cp^*_2TiCH_2Ph$ with $PbCl_2$ yields Pb, Cp^*_2TiCl, and bibenzyl, proposed to arise from homolysis of the Ti−benzyl bond of $Cp^*_2Ti(CH_2Ph)Cl$.[10] For complex **1**, we *speculate* that $Cp^*_2Ti(\eta^3\text{-}C_3H_5)Cl$ may be formed slowly, at a rate competitive with decomposition to Cp^*_2TiCl and the allyl radical, which is trapped efficiently by residual **1**. A radical-mediated disproportionation mechanism starting from $Cp^*_2Ti(\eta^3\text{-}C_3H_5)Cl$ is also plausible. Only a trace of 1,5-hexadiene is detected.

(13) Radical dehalogenation of activated alkyl halides by Cp_2TiX. (a) X = crotyl: Sato, F.; Iida, K.; Iijima, S.; Moriya, H.; Sato, M. *J. Chem. Soc., Chem. Commun.* **1981**, 1140. (b) X = Cl, Br: Yanlong, Q.; Guisheng, L.; Huang, Y.-Z. *J. Organomet. Chem.* **1990**, *381*, 29.

(14) An unquantified amount of 1,5-hexadiene is also produced.

(15) The yields of the inseparable titanacyclobutane complexes were determined by ^1H NMR integration. The products were identified by comparison to authentic materials prepared independently.

(16) The ratios of products are dependent on both the reaction concentration and the stoichiometry.

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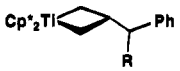
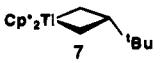
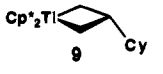
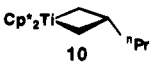
Table 1

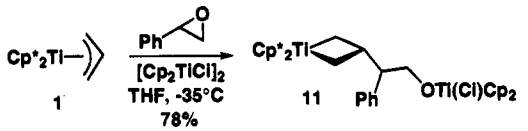
entry/addend	product/procedure[a]	time (h)	yield[b] (%)
			
	R = H, **4**		
1	A	6	94
2	B	1	92
	R = Ph, **5**		
3	A	6	88
4	B	1	70[c]
	R = Me, **6**		
5	B	1	95[d]
			
	7		
6[e]	A	6	90
7	B	0.7	83[f]
			
	8		
8	B	1	90[f]
			
	9		
9	B	5	73[f]
			
	10		
10	B	2	66[f]

[a] All methods used 1 equiv of $Cp^*_2Ti(\eta^3\text{-allyl})$ and THF. Procedure A: Cp^*_2TiCl (1 equiv), −35 °C. Procedure B: SmI_2 (1 equiv), −35 °C → 20 °C (entries 2, 4, 5) or 40 °C (entries 7−10). [b] Chemical yields were determined by ^{1}NMR spectroscopy. [c] About 13% 1,1-diphenylbut-3-ene formed as a byproduct. [d] Yield of isolated pure product. [e] *t*-BuCl is equally effective. [f] Minor amounts of complexes **2** and **3** also detected.

7[11] are isolated in high yield by incorporation of equimolar Cp^*_2TiCl[17,18] into the reaction mixture (entries 1, 3, 6). Although this reagent is significantly more halophilic than allyl complex **1**, the procedure remains limited to activated or tertiary radical precursors. A marginal extension in scope is gained by replacing the organic halides with alkyl mercuric salts,[11] allowing the isolation of β-isopropyltitanacyclobutane **8**,[11] albeit in low yield. Titanacyclobutane complexes **8** and **9** derived from the addition of secondary radicals are accessible in good yield by photolysis of the alkyl halide in the presence of $(Ph_3Sn)_2$,[11,19] but this procedure too is not general, failing for tertiary and benzylic halides, which give product mixtures containing β-allyltitanacyclobutane **2**.

General, synthetically practical methodology for the preparation of titanacyclobutane complexes **4**−**10**[11] is realized using SmI_2·THF[20] for dehalogenation (entries 2, 4, 5, 7−10). For the benzylic cases, the use of low temperature and the less reactive chloride is preferred, inhibiting both SmI_2-induced radical dimerization[20] and reaction of the halide with the Ti(III) allyl complex. For alkyl halides, the use of the iodide and higher temperature are required, a procedure that invariably leads to the formation of β-allyltitanacyclobutane **2** as a minor byproduct. For the diphenylmethyl radical (entry 4), the free alkene from coupling with the terminal allyl carbon is observed as a minor reaction product.[21] In all cases, the Sm(III) byproduct(s) are conveniently separated from the titanacyclobutane complexes by trituration with pentane.

Radical generation using Ti(III)-mediated epoxide-opening[22] is also compatible methodology, providing access to functionalized titanacyclobutanes from trapping the intermediate β-oxyalkyl radical. Thus, treatment of Cp^*_2Ti(allyl) (**1**) and styrene oxide (which do not themselves react at room temperature) with $[Cp_2TiCl]_2$ in THF leads to clean formation of the crystalline titanacyclobutane complex **11**[11] in 78% yield (eq 2).



(2)

The regioselectivity of the radical addition is attributed to the same molecular orbital considerations that govern nucleophilic addition in the isostructural cationic series, $[Cp^*_2M(\eta^3\text{-allyl})]^+BPh_4^-$ (M = Ti, Zr).[9,23] That the reaction proceeds by kinetic attack on the allyl ligand and not via attack at the metal and subsequent rearrangement[8] is supported by the clean formation of titanacyclobutane products using nonstabilized radicals, where initial addition to the metal would presumably lead to release of the more stable allyl radical.[10] Despite the low activation barriers for radical coupling to odd-electron metal complexes,[24] the efficiency of this addition is nonetheless surprising, perhaps reflecting significant delocalization of radical density to the allyl central position. In this context, it is noteworthy that radical addition to the less electron-rich complex $(C_5H_5)_2Ti(\eta^3\text{-allyl})$[25] is generally unsuccessful, although this observation, together with other fundamental issues, remains under investigation.

Notwithstanding the unusual regioselectivity observed in the present system, it is reasonable to propose a more general context for organometallic radical alkylation reactions, extended to other ligands and metal templates, including even-electron systems capable of sustaining radical chain processes.

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Supporting Information Available: Experimental procedures and complete data for all new compounds (8 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, can be ordered from the ACS, and can be downloaded from the Internet; see any current masthead page for ordering information and Internet access instructions.

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(18) $[(C_5H_5)_2TiCl]_2$ (Manzer, L. E. *Inorg. Synth.* **1982**, *21*, 84) can be used in place of Cp^*_2TiCl to initiate the reaction,[13b] but ligand exchange and competitive halide abstraction by complex **1** occur in some cases, leading to the coproduction of small quantities of complex **2**.

(19) Tin hydride/AIBN procedures are incompatible in the present context: allyl complex **1** reacts rapidly with AIBN.

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