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Review

Chemistry of the electrophilic Cp^*Ru^+ fragment. Activation of C–H, C–O, C–C, C–Cl and C–S bonds and some applications

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Summary – The fragment Cp^*Ru^+ is prepared by protonation of $[Cp^*Ru(OMe)]_2$ by triflic acid and shows a high electrophilicity and a very large affinity for aromatic hydrocarbons. The combination of these two properties leads to a very high activity towards the aromatization of C6 hydrocarbons through C–H, C–O, C–C and C–Cl bond activation. The most spectacular reactions are those involving activation of C–C bonds such as the selective aromatization of the A- or B-ring of steroids. In addition Cp^*Ru^+ catalyzes the transformation of acyclic unsaturated hydrocarbons, such as the isomerization of *t*-butyl ethylene into 2,3-dimethylbutenes.

Introduction

Cyclopentadienyl ligands, and in particular the fully methyl-substituted pentamethylcyclopentadiene (Cp^*H) represent one of the most important classes of stabilizing ligands in organometallic chemistry [1]. Hence, these ligands have shown remarkable coordination properties with virtually all transition metals and a number of main group elements. The most interesting property of these ligands is their ability to stabilize high valent species (viz Cp^*ReO_3) [2], strongly Lewis acidic derivatives (Cp^*_2ScX [3], Cp^*_2LuX [4]), and electron-rich low valent compounds ($Cp^*Ir(CO)_2$) [5]. The ruthenium chemistry of this ligand includes $[Cp^*Ru(CO)_2]_2$ [6] and $[Cp^*Ru(\eta^6\text{-}C_6H_6)]^+$ [7], which do not allow a general access to new pentamethylcyclopentadienyl derivatives and $[Cp^*RuCl_2]_n$ (**1**), as was reported almost simultaneously by Bercaw *et al* [8] and Suzuki *et al* [9], and which found a broad use as starting material. This compound could be reduced by $LiBHEt_3$ to give the tetramer $[Cp^*RuCl]_4$ (**2**) [10] or by K_2CO_3 in methanol to give the μ-methoxo derivative $[Cp^*Ru(OMe)]_2$ (**3**) [11]. Both compounds have found a wide use as starting materials for the preparation of new ruthenium derivatives. Another very interesting complex is the tetrahydrido-bridged $[Cp^*Ru(\mu\text{-}H)_2]_2$ (**4**) [12], which can activate a C–H bond of ethylene. It is noteworthy that using **1** as a starting material, several groups prepared the trihydrides $Cp^*RuH_3PR_3$ (**5**) [13-14] shown to exhibit quantum mechanical exchange couplings.

It became rapidly apparent that complexes **1-3** could lead to interesting unsaturated fragments containing 3 vacant coordinating sites. Fagan *et al* prepared $[Cp^*Ru(MeCN)_3]OTf$ (**6**) from **2** and used it for coordinating various aromatic molecules [10]. The purpose of this work was the study of the three-dimensional arrangement of these complexes in the solid state and the possible cooperative properties of these novel materials.

Lewis acidic platinum metal cations display a high reactivity towards hydrocarbons. In the case of unsaturated hydrocarbons, catalytic oligomerization [15, 16] or rearrangements through methyl migration [16] have been observed whereas the activation of methane occurred in the presence of platinum [17] or palladium [18] salts in trifluoroacetic acid. In a parallel approach, we have studied the reactivity of the Lewis acidic fragment Cp^*Ru^+ (**7**) prepared in our hands by protonation of **3** with triflic acid.

Our strategy was to study first the coordination of **7** to polyfunctional systems or heterocycles containing aromatic rings in order to define the affinity of this fragment for aromatics and the selectivity of the coordination to the π-arene ring in the presence of other functions. In a second step, we studied the activation properties of **7** in the presence of C_6 rings, quinoid systems and acyclic compounds. Finally, we investigated some applications of these processes in steroid, terpene or polymer chemistry.

In this review article we present the most conclusive results of these investigations.

Preparation of the Cp^*Ru^+ fragment

In order to undergo reactions involving activation and transformation of hydrocarbons we needed new electrophilic ruthenium fragments containing only Cp^* and

very weakly coordinated ligands. Our first attempt involved the zinc reduction of $(Cp^*RuCl_2)_n$ in THF or CH_2Cl_2 [19]. The transitory complex formed showed a good activity towards complexation of π-rings including heterocycles. However, a more electrophilic fragment was needed to undergo activation reactions. We prepared this by reaction of **3** with HOTf in CH_2Cl_2 or THF at room temperature. The reaction yields a complex mixture of derivatives, which all react with benzene or acetonitrile to give respectively $[Cp^*Ru(\eta^6\text{-}C_6H_6)](OTf)$ (**8**) and **6**. In this review, when we refer to Cp^*Ru^+ (**7**) we will refer to this procedure.

Before investigating the reactions of **7** with various hydrocarbons, it was necessary to examine possible deactivation processes and the reactivity of this fragment with different solvents. Hence, **7** reacts at 80°C in a closed vessel with CH_2Cl_2 to yield a 6:3:1 mixture of $[Cp^*Ru)_3(\mu\text{-}Cl)_3(\mu^3\text{-}CH)](OTf)$ (**9**), $[(Cp^*Ru)_3(\mu\text{-}Cl)_2(\mu\text{-}CO)(\mu^3\text{-}CH)](OTf)_2$ (**10**) and an unidentified paramagnetic cluster [20, 21]. Compound **9** was characterized by X-ray diffraction (see fig 1) and was also obtained by Suzuki *et al* [22] upon reacting **1** with $AgBF_4$ and acetaldehyde in THF.

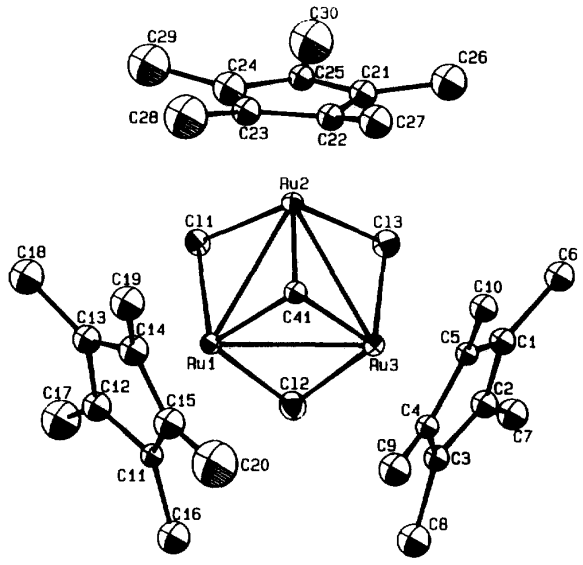


Fig 1. Molecular structure of $[Cp^*Ru)_3(\mu\text{-}Cl)_3(\mu_3\text{-}CH)](OTf)$ (**9**).

Another deactivation process of **7** could involve oxidation reactions. Thus, for example, **1** reacts with dioxygen to give the oxo-bridged complex $(Cp^*RuCl_2)_2O$[23]. The reactivity of **7** was anticipated to be higher. It was reacted with oxygen and several oxidizing agents. In each case intriguing NMR spectra were obtained. Crystals of the oxidized complex were obtained upon reacting **7** with $KHSO_5$, which contains both an acidic proton and a transferable oxygen atom. The X-ray structure of the resulting product $Cp^*_2Ru_3\{\mu^3\text{-}\mu^7C_5Me_3(CH_2)_2\}(\mu^3\text{-}O)(\mu^2\text{-}H)_2(SO_4)$ (**11**) is shown in figure 2 [24]. Compound **11** is an unusual trinuclear cluster resulting formally from the condensation of a high valent ruthenium moiety on a dinuclear low valent moiety. Two adjacent methyl groups of the Cp* ring located on the high valent ruthenium, Ru(3), have been activated by the two other ruthenium atoms to give methylene groups and hydrides. Compounds **11** and similar complexes are extremely stable and do not show any reactivity.

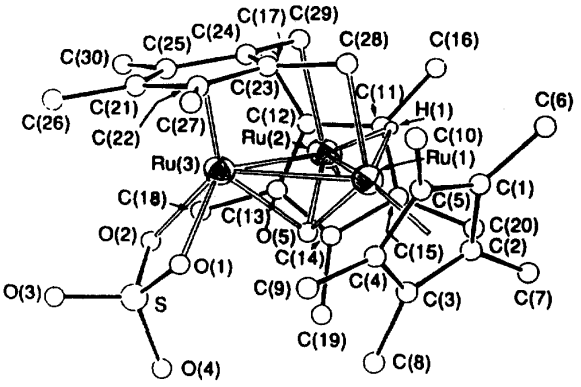
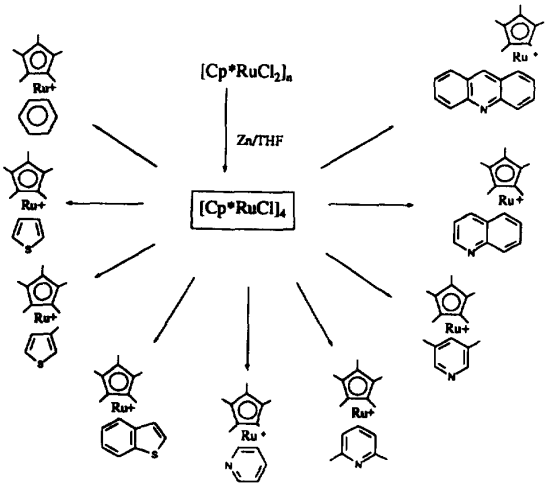


Fig 2. Molecular structure of $Cp^*_2Ru_3(\mu_3\text{-}\eta^7C_5Me_3(CH_2)_2](\mu_3\text{-}O)(\mu_2\text{-}H_2)(SO_4)$ (**11**).

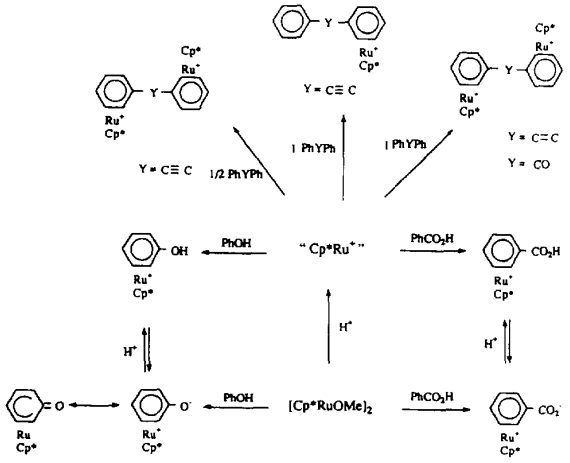
Reactions of coordination

Prior to our work, Angelici *et al* studied several π-complexes of thiophene as possible models for the adsorption step of the hydrodesulfurization (HDS) process [25]. This includes the π-thiophene derivative $[Cp^*Ru(\eta^6\text{-}C_4H_4S)]^+$ (**12**) [26]. We have widely studied the coordination of different heterocycles to **7** in order to determine the stability of these adducts. The results are shown in scheme 1 [19]. Several conclusions were made from this study. First, in fused ring systems, the coordination of **7** was observed on the arene ring rather than on the heterocyclic one. The π-thiophene derivatives are very stable whereas the stability of the π-pyridine adducts depends upon the substitution of the heterocyclic ring. π-adducts of 2,6- and 3,5-lutidine were found to be stable and recrystallized unchanged, whereas in the same conditions the reaction with pyridine led to $[Ru(\eta^1\text{-pyridine})_6](PF_6)_2$ (**13**). This suggests that electronic rather than steric factors are important for the stabilization of π-complexes of substituted pyridines. If the reaction with pyridine is carried out by reducing **1** by zinc in THF, a precipitate of $[Cp^*Ru(\eta^6\text{-pyridine})]Cl$ (**14**) is obtained. The ^1H NMR spectrum of **14** can be recorded rapidly in CD_2Cl_2 but the compound slowly decomposes in this medium and rapidly in other polar solvents, such as THF or acetone. Attempts to prepare π-adducts of other heterocycles such as furan led to extremely unstable species, which could only be observed in solution [27].

Before investigating the reactivity of **7** towards C_6 rings, we carried out a study of the coordination of this fragment to various functional arenes. The purpose of this study was to determine the selectivity of coordination to arenes when other functional groups are present. Compound **7** was therefore reacted with olefins, acetylenes, ketones, phenols, acids and nitriles [28] (see scheme 2).



Scheme 1. Coordination of the Cp^*Ru^+ fragment to selected heterocycles.



Scheme 2. Coordination of the Cp^*Ru^+ fragment to selected functional arenes.

The reactions of **7** with diphenylacetylene are selective and lead to the mono- or di-ruthenium adduct according to the reaction conditions. The structure of the bis-adduct, namely $[(Cp^*Ru)_2(\eta^6,\eta^6$ Ph–C≡C–Ph)](OTf)$_2$ (**15**), is shown in figure 3. This result contrasts with that obtained upon reacting **7** with stilbene or benzophenone, which only leads to the bis-adducts, even in the presence of 1 equivalent of **7**. This difference of behavior could be explained by the better transmission of electronic effects in the sp^2 systems than in the *sp* system as a result of a better conjugation. Since **7** will preferentially coordinate to electron-rich rings, this observation suggests a surprising electron-releasing effect of the Cp^*Ru^+ fragment.

The reactions of **7** with phenol or benzoic acid lead exclusively to the π-coordinated complexes $[Cp^*Ru(\eta^6$-$C_6H_5OH)](OTf)$ (**16**) and $[Cp^*Ru(\eta^6$-$C_6H_5COOH)](OTf)$ (**17**), whereas the direct protonation of **3** with these compounds yields the zwitterionic species $Cp^*Ru(C_6H_5O)$ (**18**) and $Cp^*Ru(\eta^6$-$C_6H_5COO)$ (**19**);

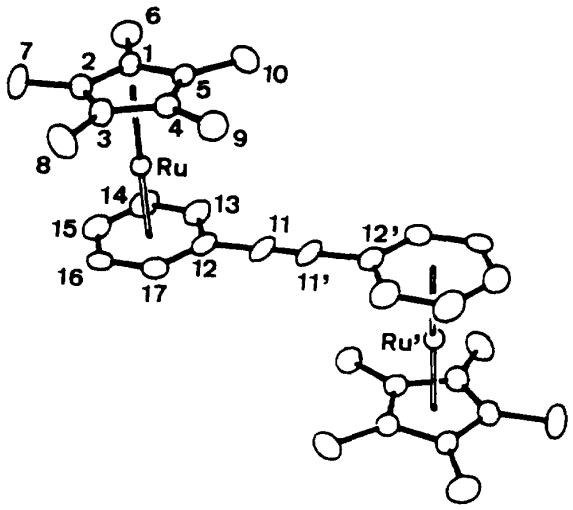


Fig 3. Molecular structure of $[Cp^*Ru)_2(\eta^6,\eta^6$ Ph–C≡C–Ph)](OTf)$_2$ (**15**).

the latter were characterized by X-ray crystallography (fig 4). Interconversion between **16** and **18** and between **17** and **19** is possible through protonation/deprotonation reactions [28].

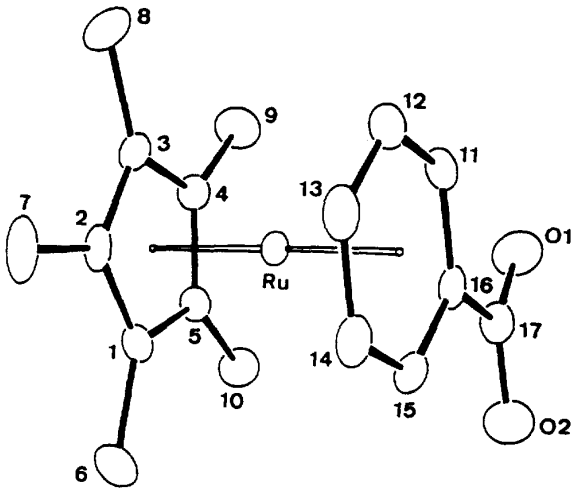


Fig 4. Molecular structure of $Cp^*Ru(\eta^6$-$C_6H_5COO)$ (**19**).

In contrast to these results, no clean reaction was observed between **7** and benzonitrile or phenylacetylene. In the case of phenylacetylene, a reaction occurs with **6** to yield a curious paramagnetic dimer (**20**) (see fig 5) in which one ruthenium is bound to a Cp^* ligand and a ruthenacyclopentadienyl moiety.

Aromatization of C_6 rings

Quinoid systems

Quinones are non-aromatic conjugated systems. The coordination of **7** to such species was anticipated to lead to

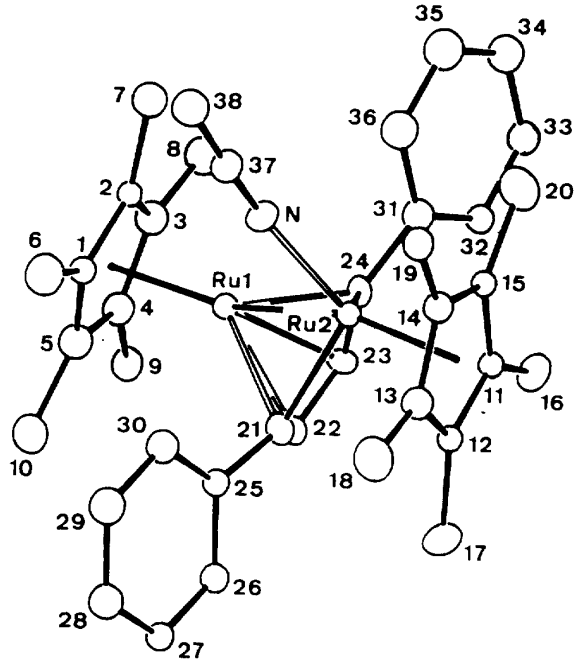


Fig 5. Molecular structure of $[Cp^*(MeCN)Ru(\mu^2\text{-}\eta^2,\eta^4\text{-}C_4H_2Ph_2)RuCp^*](OTf)$ (**20**).

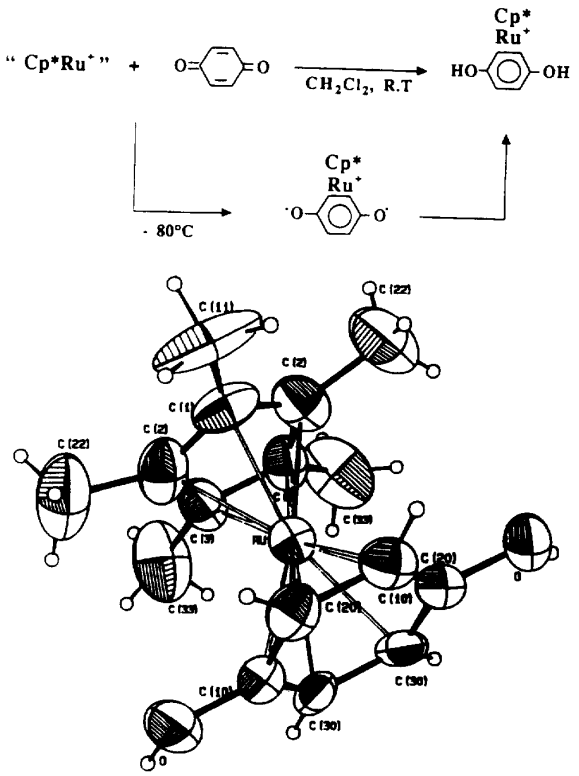
biradical systems. We observed the formation of the hydroquinone derivative $[Cp^*Ru(\eta^6\text{-}HO\text{-}C_6H_4OH)](OTf)$ (**21**) [29], but EPR monitoring of the reaction shows the transient formation of a biradical compound (see scheme 3). In order to extend the lifetime of the biradical species, **7** was reacted with TCNQ. The reaction was immediate and led to a green radical species, which was unfortunately not fully characterized due to its very low solubility.

Activation of C–H bonds

After the demonstration that **7** will preferably coordinate to the arene ring of a given molecule, even if other functionalities are present in the molecule, we examined the reaction of the Cp^*Ru^+ fragment with functional hydrocarbons containing non-aromatic C_6 rings in order to determine whether aromatization is possible after activation of C–H, C–O and C–C bonds.

Prior to our work, Singleton *et al* had shown that the complexes CpRuX(1,5-COD) (X = Cl, Br) could react with cyclohexadiene or bromocyclohexane in refluxing conditions to give $[CpRu(\eta^6\text{-}C_6H_6)]$ [30].

We carried out our activation reactions in closed vessels (Fischer-Porter-type bottles) which allow an analysis of the evolved gas by GC. Thus, **7** reacts at 80°C with cyclohexene in dichloromethane to give quantitatively $[Cp^*Ru(\eta^6\text{-}C_6H_6)](OTf)$ (**8**) and two moles of dihydrogen [31]. The same reaction occurs at room temperature, but slowly since only *ca* 60% cyclohexene was converted into benzene over a period of 72 h. Longer reaction times lead to completion of the reaction (see

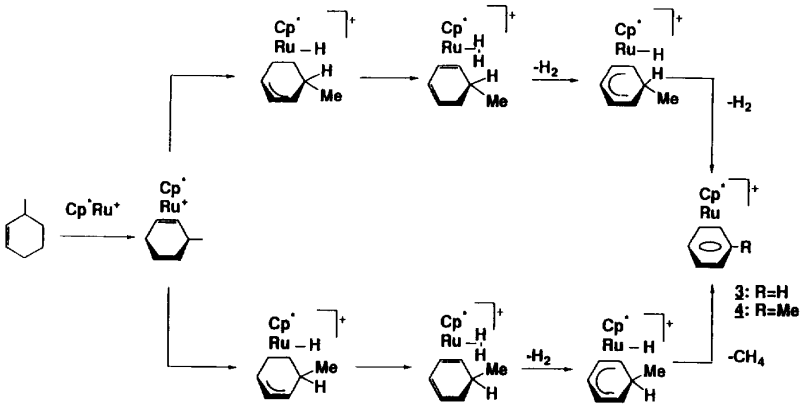


Scheme 3. Reaction of the Cp^*Ru^+ fragment with quinones.

scheme 4). It is noteworthy that no reaction was observed here between **7** and CH_2Cl_2, probably as a result of the much higher rate of cyclohexene transformation. The reaction between **7** and 1,3-cyclohexadiene is instantaneous even at −80°C to give **8**. When using methylcyclohexene, the reaction proceeds to completion at 80°C but produces a 9:1 ratio of $[Cp^*Ru(\eta^6\text{-}C_6H_5CH_3)](OTf)$ (**22**) and **8**. The gas phase of the reaction was shown to contain *ca* 5% methane compared to dihydrogen. This result therefore demonstrates the possibility for **7** to activate carbon-carbon bond in mild conditions. This point will be developed later in this review.

In order to have an insight into the mechanism of the C–H bond activation reaction, **7** was reacted with 1,3-cyclooctadiene. The reaction yields $[Cp^*Ru(1,3\text{-}C_8H_{12})](OTf)$ (**23**) displaying an agostic interaction between a proton of a methylene groups adjacent to a double bond and the metal (see scheme 5). This complex is fluxional down to 183 K and was previously obtained upon protonating Ru(COD)(COT) in the presence of Cp*H [32]. The agostic proton is acidic since the reaction of **23** with NEt_3 leads to $Cp^*Ru(\eta^5\text{-}C_8H_{11})$ (**24**). Furthermore, gentle heating of **23** in THF produces a clean evolution of dihydrogen and formation of $[Cp^*Ru(\eta^6\text{-}C_8H_{10})](OTf)$ (**25**) (scheme 3). This sequence of reaction is probably representative of the mechanism of the dehydrogenation of cyclic alkenes.

Finally, **7** was also shown to dehydrogenate cyclopentenone to give the triple-decker derivative $[Cp^*Ru(\eta^5\text{-}C_5Me_4OH)RuCp^*](OTf)$ (**26**) (see fig 6).



Scheme 4. Reaction of the Cp^*Ru^+ fragment with methylcyclohexene.

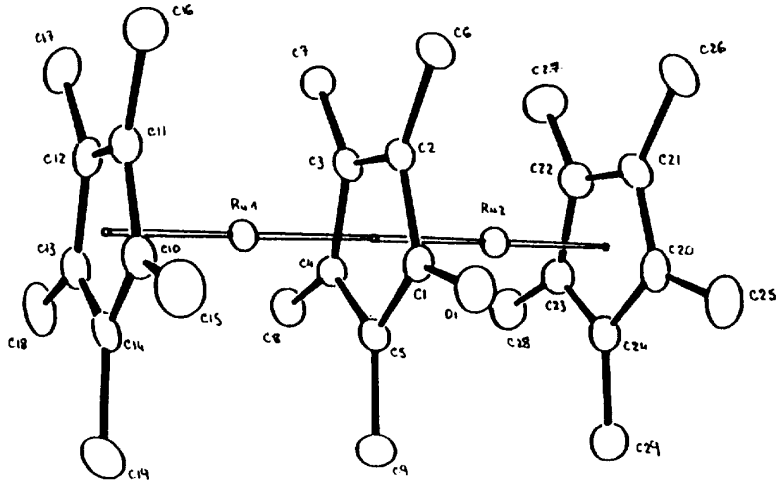
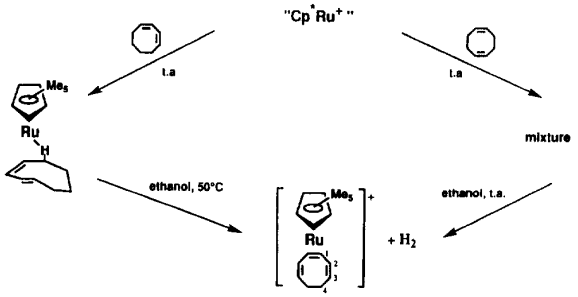


Fig 6. Molecular structure of $[Cp^*Ru(\eta^5\text{-}C_5Me_4OH)RuCp^*](OTf)$ (**26**).



Scheme 5. Activation of C–H bonds of cyclooctadienene by the Cp^*Ru^+ fragment.

Activation of C–O bonds

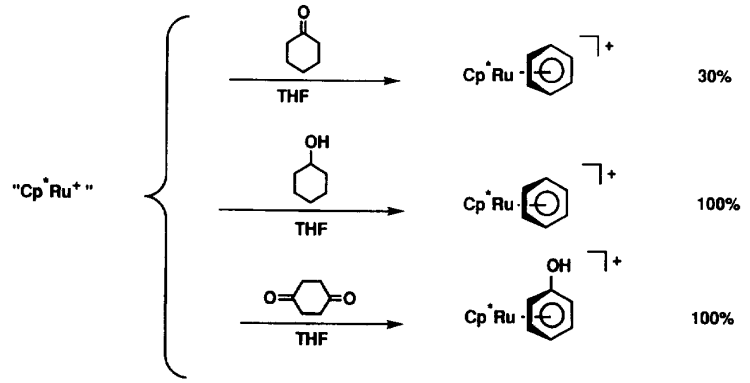
Surprisingly, the reactions of **7** with cyclic enones do not lead to the expected phenol but to aromatic hydrocarbons [31]. No dihydrogen is produced during this reaction but water could be detected by GLC. The reaction is facile and quantitative at room temperature. The spectroscopic detection of an intermediate allows us to propose a mechanism such as that shown on scheme 6. 1,4-Cyclohexadione is dehydrated at 80°C to produce the π-phenol derivative $[Cp^*Ru(\eta^6\text{-PhOH})](OTf)$ (**16**).

The combined dehydrogenation and dehydration of cyclohexanone and cyclohexanol lead in both cases to **8**. However, a solvent dependence was observed, since the reaction with cyclohexanone is more facile in CH_2Cl_2, whereas that with cyclohexanol is preferred in THF. This dependence results from competitive reactions observed in CH_2Cl_2 (activation of CH_2Cl_2) and THF (coordination of THF to ruthenium), which favors the most unsaturated species in the first case, and the best ligand in the second.

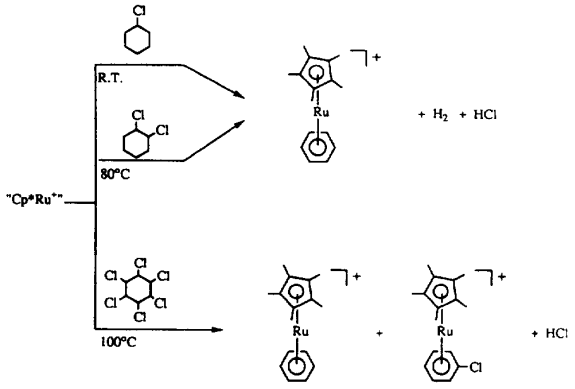
Activation of C–Cl bonds

We have previously discussed the reaction of **7** with CH_2Cl_2. It was therefore of interest to study the reactivity of this fragment with cyclic chlorocarbons (see scheme 7) [20, 21].

The reaction of **7** with chlorocyclohexane proceeds at room temperature and yields **8** in 60% yield after 15 h. The same reaction with 1,2-dichlorocyclohexane only occurs at 80°C to give quantitatively **8** and



Scheme 6. Activation of C–O bonds of cyclohexyl derivatives by the Cp^*Ru^+ fragment.



Scheme 7. Activation of C–Cl bonds of cyclohexyl derivatives by the Cp^*Ru^+ fragment.

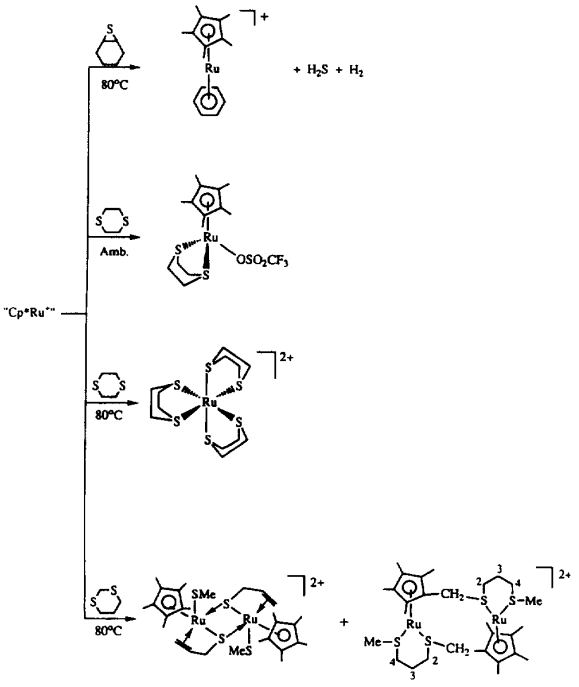
HCl. This effect could result from the initial chelation of dichlorocyclohexane to the ruthenium center. More stable compounds, such as lindane (1,2,3,4,5,6-hexachlorocyclohexane), react with **7** at 100°C in THF to give a 30% conversion to a 9:1 mixture of **8** and $[Cp^*Ru(\eta^6\text{-}C_6H_5Cl)](OTf)$ (**27**).

Competitive C–O and C–Cl bond activation were studied using successively (i) 2-chlorocyclohexanone, (ii) 2-chlorocyclohexanol and (iii) 2,2′-6,6′-tetrachlorocyclohexanol. Reaction (i) produced rapidly **8** in quantitative yield. Surprisingly, reaction (ii) led to the trinuclear cluster $[(Cp^*Ru)_3(\mu_2\text{-}Cl)_2(\mu_2\text{-}CO)(\mu_3\text{-}Cl)](OTf)_2$ (**28**). Reaction (iii) at 80°C in THF gave a 1:7:1 mixture of **8**, **16** and **27**, therefore demonstrating the large preference for C–Cl bond activation in the presence of C–O bonds.

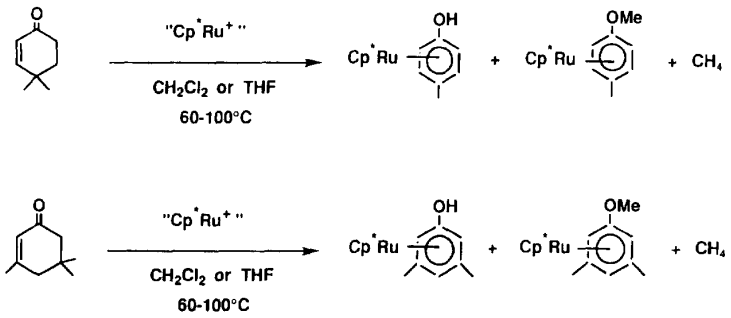
Activation of C–S bonds

The activation of carbon-sulfur bonds is related to a very important industrial process, namely HDS [25]. Two mechanistic hypotheses have been proposed, one involving hydrogenation of the sulfur heterocycle followed by desulfurization, the other direct cleavage of carbon sulfur bonds. We have previously shown that aromatic heterocycles such as thiophene or benzothiophene will coordinate to **7** but not lead to any activation reactions (see above *Reactions of coordination*). We therefore examined the reactivity of several saturated cyclic compounds containing sulfur in the ring or α to the ring [21]. The compounds investigated were cyclohexylmercaptan, cyclohexene sulfide, pentamethylene-sulfide tetrahydrothiophene, 1,4- and 1,3-dithiane.

No conclusive result was obtained with cyclohexylmercaptan, whereas pentamethylene sulfide, tetrahydrothiophene and 1,4-dithiane coordinate to ruthenium, in some cases with elimination of Cp*H but without any C–S bond activation. The only interesting results were obtained with cyclohexene sulfide, the reaction of which leads to **8**, H_2 and H_2S, and with 1,3-dithiane, in which, a facile cleavage of the C–S bond occurred to give two compounds, one containing a bridging thioallyl fragment and the other in which a sulfur atom has migrated to a methyl group of a Cp* ring to form a dimer containing two bridging $C_5Me_4CH_2SCH_2CH_2CH_2SMe$ ligands (see scheme 8).



Scheme 8. Reaction of the Cp^*Ru^+ fragment with sulfur heterocycles. Activation of C–S bonds.



Scheme 9. Activation of C–C bonds of enones by the Cp^*Ru^+ fragment.

Activation of C–C bonds

The reactions described above are interesting, but a few precedents are known for each type of activation. However, the activation of carbon-carbon bond is highly unusual and has previously been limited to strained hydrocarbons. After the demonstration that **7** reacts with methylcyclohexene to give *inter alia* **8** and methane, we looked at the reactions between **7** and C_6 rings containing 2-*gem*-methyl substituents to see whether the C–C bond activation could be rendered selective [31].

Compound **7** reacts with 4,4′-dimethylcyclohexenone in CH_2Cl_2 at 80°C to give a 8:2 mixture of [Cp*Ru(η^6-pCH$_3$-C$_6$H$_4$OH)](OTf) (**29**) and [Cp*Ru(η^6-pCH$_3$-C$_6$H$_4$OMe)](OTf) (**30**), and with isophorone in CH_2Cl_2 at 80°C to give a 5:4 mixture of [Cp*Ru(η^6-3,5Me$_2$-C$_6$H$_3$OH)](OTf) (**31**) and [Cp*Ru(η^6-3,5Me$_2$-C$_6$H$_3$OMe)](OTf) (**32**). The first reaction is quantitative whereas the yield of the second is only *ca* 50%; in both cases methane was evolved together with *ca* 10% ethane. It is remarkable that the C–C bond cleavage is facile in the presence of **7**. The reaction is not selective since together with the expected π-phenol derivatives **29** and **31**, we observe the formation of the corresponding methyl ether derivatives **30** and **32**.

The mechanism of this reaction was studied by NMR (^{1}H and ^{13}C) spectroscopy. At room temperature, the reaction proceeds rapidly to give hydrido cyclohexadienyl species, which then lose methane very slowly at room temperature to give the π-arene derivatives **29**, **31** or **30**, **32** (see scheme 9). Two important findings arise from this study. First, the C–C bond activation reaction occurs at room temperature. This demonstrates that in contrast to other systems found to activate C–C bonds, the kinetic barrier of this reaction is low. The second point is that we observe the formation of two hydrido cyclohexadienyl species, one containing a hydroxo substituent and the other a methoxo substituent. The integration ratio between these two types of species does not vary after the activation process. This indicates that the formation of complexes **31** and **32** does not arise from a transfer of a methyl radical but rather from an etherification process at the early stage of the reaction with methanol present in the reaction mixture.

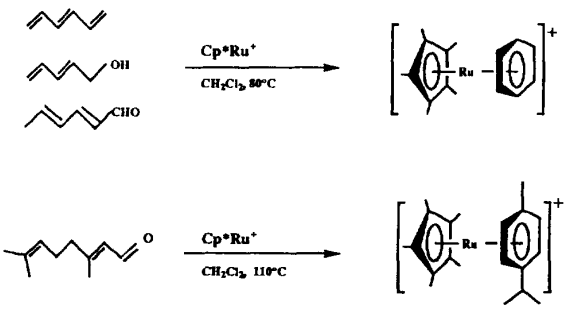
If we could follow the reaction by ^{1}H NMR, we did not observe any intermediate between the hydrido cyclohexadienyl and arene species. No definitive mechanistic path can be proposed for the C–C bond-breaking step. Nevertheless, the presence of *ca* 10% ethane together with methane in the gas phase suggests a radical pathway. Furthermore, the demonstration in steroid chemistry (*vide infra*) that the Cp^*Ru^+ fragment is coordinated on the face opposite to the methyl group to be eliminated, and that the metal fragment cannot change position during the activation process, greatly support the existence of homolytic cleavage of the C–C bond.

Cyclizations

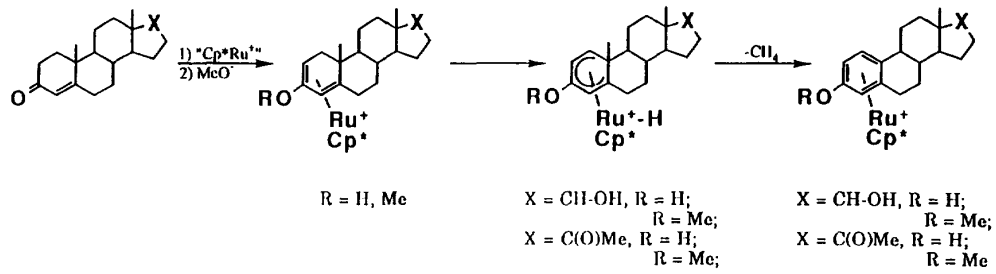
In the preceding sections, we have explored several pathways leading to the aromatization of cyclic hydrocarbons, but which all involve the breaking of a chemical bond. It was then of interest to determine whether bond-forming reactions and in particular cyclizations could be induced by coordination to **7** [33].

The reactions were first attempted with polyunsaturated molecules, such as hexatriene, 2,4-hexadienal and 3,5-hexadienol (see scheme 10). In the first two cases, a clean reaction was observed to lead quantitatively at 80°C in CH_2Cl_2 or THF to **8**. The reaction with 3,5-hexadienol was more complex and led to a *ca* 30% yield of **8** and unidentified polymeric species. Finally, in order to extend the scope of these reactions, we reacted **7** with citral. A clean dehydration was observed at 110°C to give the *p*-cymene complex {Cp*Ru[η^6-pCH$_3$-C$_6$H$_4$CH(CH$_3$)$_2$]}(OTf) (**33**).

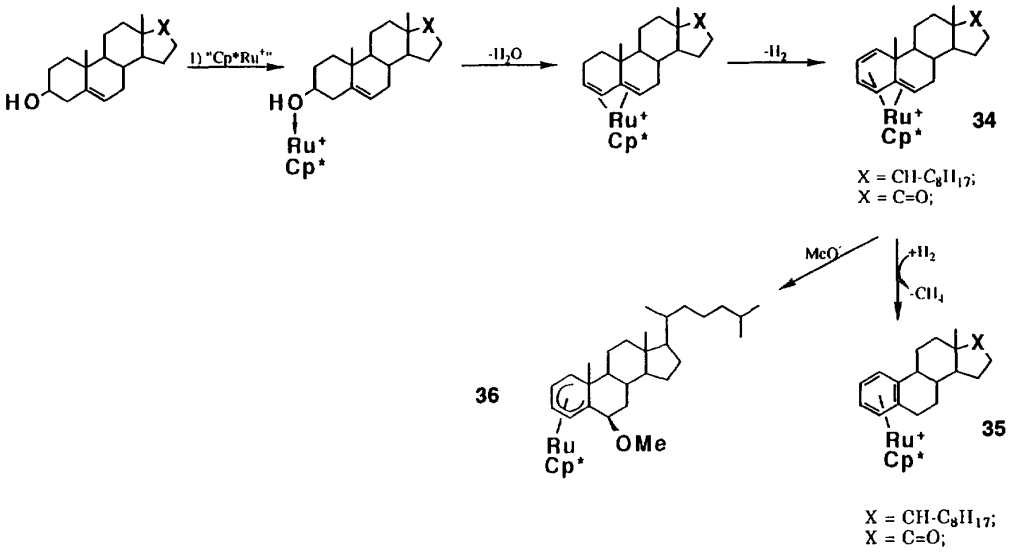
The cyclization reactions were shown to be effective for compounds containing three unsaturations or two unsaturations and one functional group. However, for less unsaturated species, such as dienes, a more complex reactivity was observed (*vide infra*).



Scheme 10. Reactions of cyclization induced by the Cp^*Ru^+ fragment.



Scheme 11. Aromatization of the A-ring of testosterone and progesterone.



Scheme 12. Aromatization of the A-ring of cholesterol and dehydroisoandrosterone.

Some applications of the reactivity of the Cp^*Ru^+ fragment

In view of the unprecedented reactivity of the Cp*Ru fragment, we looked for various applications of the new hydrocarbon transformation processes described above in selected areas of organic chemistry. We considered three areas where the coordination and transformation of C_6 rings could be important, namely steroids, terpenes and polymers. In addition, we investigated the catalytic activity of **7** towards acyclic alkenes and dienes and compared it to that of other electrophilic fragments such as Pd^{2+}.

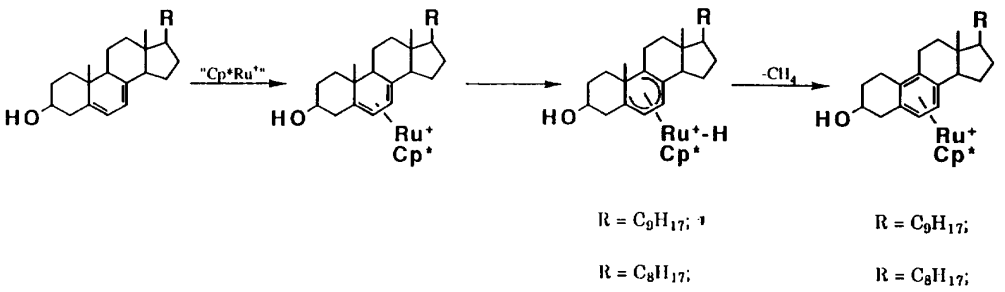
Aromatization of steroids by the Cp^*Ru^+ fragment

Steroids are large multifunctional molecules of great biological importance, since many animal sex hormones (for example testosterone, estrone and progesterone), cell constituents (cholesterol) or vitamins belong to this class of molecules. Prior to our work, a few reports on the complexation of the arene ring of aromatic steroids have appeared in the literature [34].

After demonstrating that **7** could selectively coordinate to the arene rings of such aromatic steroids, we considered the case of steroids for which the A-ring contains an enone functionality and a quaternary carbon atom [35]. In these compounds, for example, testosterone or progesterone, the aromatization process requires the activation of a C–C bond (C(10)-C(19)). Such an aromatization is potentially important for the preparation of estrogens. It occurs in nature by a cytochrome P-450 enzyme through successive oxidation steps [36] and is difficult in classical organic chemistry.

The reaction of **7** with testosterone and progesterone proceeds very cleanly in THF at 100°C to give essentially quantitative yields of the aromatized product. In addition, over 90% of these aromatized products contain the ruthenium fragment coordinated on the α-ring of the steroid (see scheme 11). As for simple enones, the presence of methane could be detected in the gas phase of the reaction mixture together with some ethane. The reaction also proceeds via the formation of a hydrido cyclohexadienyl moiety, as monitored by ^1H and ^{13}C NMR. It is interesting to note that the reaction is easier than in the case of simple enones and transforms in one step testosterone into estradiol.

A more challenging compound to consider is cholesterol, in which the unsaturated is carried by the B-ring (scheme 12), and the aromatization process is anticipated to be more complex. However, we found in this case that the reaction was facile at relatively low temperatures (90°C) and led to 100% spectroscopic yield



Scheme 13. Aromatization of the B-ring of dehydrocholesterol and ergosterol.

of a single isomer in which the ruthenium was coordinated to the A-ring on the α-face. In contrast to the case of enones, the hydroxy group born by the A-ring is lost during the aromatization process. GC analysis indicates as previously the presence of methane in the gas phase. A detailed mechanistic analysis (scheme 8) shows however that the mechanism of the aromatization process is complex. There is rapid formation of the triene complex **34**, which is accompanied by the evolution of dihydrogen. In a second step, dihydrogen is cleaved heterolytically by **34** to give a transient hydride species from which methane is eliminated to give the aromatized product **35**. These steps were demonstrated by initially forming **34** and letting it react with or without dihydrogen. Pure **34** could not be isolated, but was trapped by its reaction with NaOMe which leads to the neutral cyclohexadienyl species **36** in which the methoxo group is borne by C(6) (see fig 7).

An extension of these reactions was performed with dehydroisoandrosterone, which led to similar results albeit at higher temperature. The aromatization reaction is possible with androsterone, which does not contain any unsaturation, but requires temperatures of 140°C and occurs via an unknown mechanism.

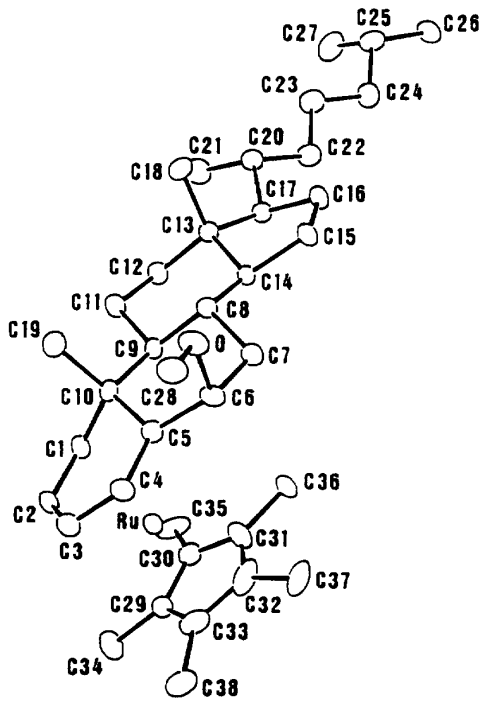


Fig 7. Molecular structure of **36**.

The scope of these reactions was also extended to the unfavorable case of prednisolone, which contains both a quinoid A-ring and oxygenated functions on the D ring. The reaction then needs two equivalents of **7** to proceed; the first is linked to the oxygen groups of the D-ring, and eventually leads to a degradation of the steroid.

After demonstrating the selectivity of Cp*Ru for the aromatization of the A-ring of different steroids, we investigated the possibility of **7** selectively attacking another site of the steroid and considered the B-ring first. Dehydrocholesterol is readily available by classical organic chemistry from cholesterol. It was therefore interesting to study this compound because it could display a B-ring-based selectivity [37]. Hence the reaction of **7** with dehydrocholesterol or ergosterol first leads to a hydrido cyclohexadienyl complex (see scheme 13), which upon heating evolves methane and gives the aromatized product.

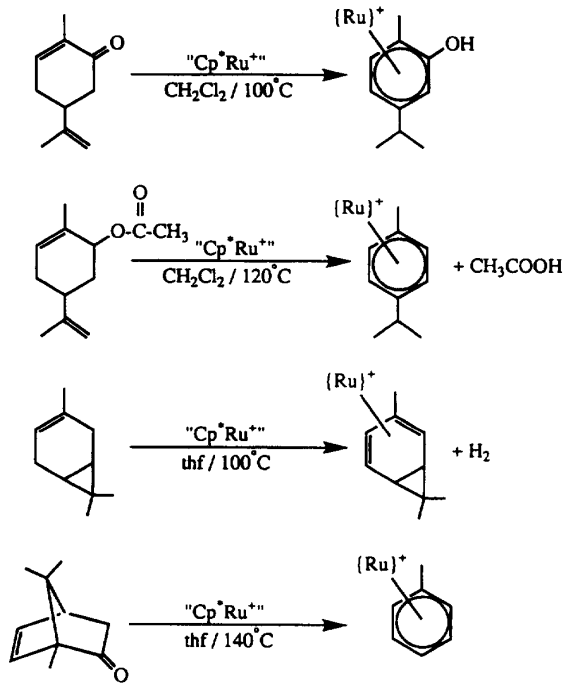
The reaction is totally similar to those described above, except that this time the initial coordination of **7** and the aromatization process occur on the B-ring.

Reactions with terpenes

After steroids, terpenes represent a class of organic compounds containing C_6 rings and various types of C–C bonds needing to be activated to lead to aromatic products. Scheme 14 summarizes different type of reactions carried out [36]. Surprisingly, during reaction (3) with carene, which contains a strained C_3 ring, no clean C–C bond activation was observed but rather a simple dehydrogenation. In the case of camphor the C–C bond activation does proceed, but a high temperature, which is surprising in view of the preceding reactivity observed with steroids.

Reactions with polymers

The preparation of metal-containing polymers could lead to a novel class of polymers exhibiting interesting mechanical or electrical properties. As a first test, **7** was reacted with polystyrene (PST). It was possible, probably for steric reasons, to coordinate 50% of the phenyl rings of PST to **7** [38]. The result was a change in solubility since the metallated polymer was soluble

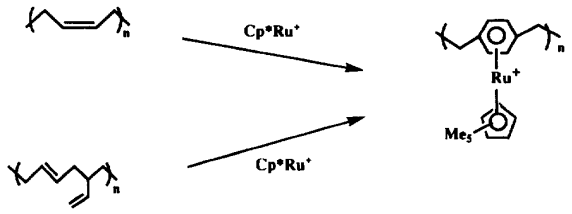


Scheme 14. Reaction of the Cp^*Ru^+ fragment with selected terpenes.

in acetone and methanol but not in dichloromethane, in contrast to free PST.

Coordination was also attempted with potentially conducting polymers like polydimethylphenylene oxide (PPO) and polyphenylenesulfide (PPS). In the case of PPO it was again possible to coordinate **7** to each second ring of the polymer, whereas the reaction with PPS was not clean, probably because of the insolubility of this polymer.

Finally, we considered the formation of new types of polymers by modification of polybutadiene containing pendant olefinic groups [39]. It was possible to observe a cyclization reaction and the formation of new polymers containing phenyl rings and C_2H_4 fragments acting as spacers (see scheme 15). The properties of these polymers are being explored.



Scheme 15. Reaction of the Cp^*Ru^+ fragment with selected polymers.

Reactivity of Cp^*Ru^+ with unsaturated acyclic molecules

In view of the interesting reactivity displayed by electrophilic fragments such as Pd^{2+} or Cp^*Rh^{2+} for the transformation of unsaturated hydrocarbons, or even in certain cases saturated hydrocarbons, we investigated the reactivity of **7** in these reactions. Scheme 16 shows some of these reactions [40]. With 1-hexene we observe oligomerization reactions, which are typical of Lewis acid catalysts. With 1,4-pentadiene a catalytic dimerization proceeded, the catalyst being the ruthenium (IV) complex **37** (scheme 16) which contains a branched pentadiene dimer acting as a bis-(allyl) ligand. In the case of 1,5-hexadiene, the reaction was more complex leading to dimerization into C_{12} hydrocarbons, cyclization to give **8** and metathesis to give ethylene and C_{10} hydrocarbons. The intermediate of the dimerization was found to be complex **38** (scheme 16), which contains a linear dimer of hexadiene coordinated through its three double bonds. The most surprising reaction here is metathesis, unusual for ruthenium complexes. We checked that this reaction occurred by reacting **7** with 1,7-octadiene, which leads to **8** and ethylene.

However, the most novel aspect of the reactivity of **7** was observed upon reacting it with *t*-butylethylene. A catalytic isomerization was first identified. This reaction converts *t*-butylethylene into a mixture of 2,3-dimethylbutene-2 and 2,3-dimethylbutene-1 and therefore involves the migration of a methyl group (scheme 16). The turnover number of this reaction after 12 h at 100°C (not optimized) is 92. However, a side reaction was observed which leads to C_{17} hydrocarbons and methane after oligomerization and cracking (*ca* 4%). This is the first such cracking reaction in homogeneous medium and could be of interest for hydrocarbon chemistry.

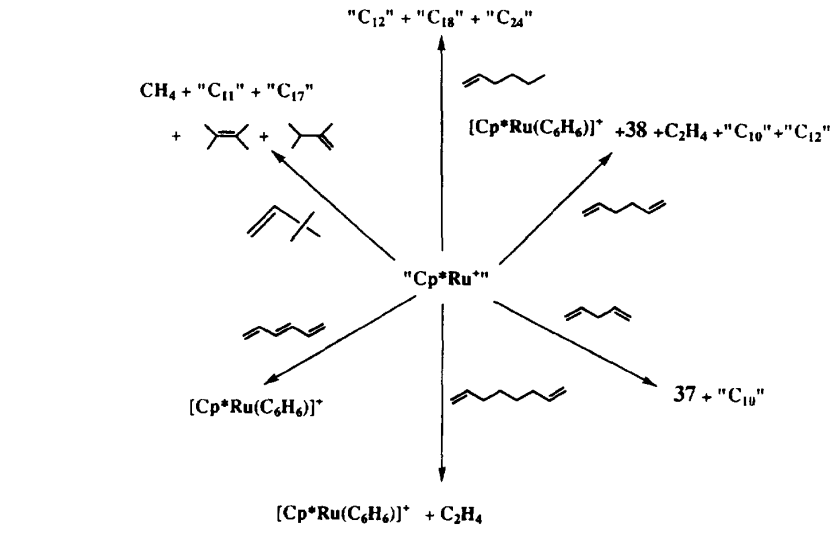
Perspectives

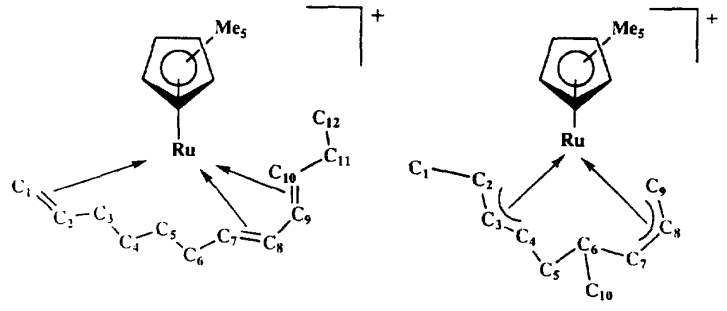
It is clear from the preceding chapters that the Cp^*Ru^+ fragment shows an exceptional reactivity, in particular for C–C bond activation reactions. However, we found at least two important limitations to this reactivity. The first is the strength of the ruthenium-arene bond which probably favors the activation reactions, but has so far limited the catalytic applications of the ruthenium fragment. It is therefore necessary to look for new fragments which could be as electrophilic as **7**, but which could release coordinated arenes more readily. The recent synthesis of $TpRuH(H_2)_2$ (Tp = various hydrido tris(pyrazollyl) borate ligands) could open the route towards new Tp ruthenium fragments [41].

Another problem is the absence of solubility of **7** in saturated hydrocarbons, which prevented an extensive study of C–H activation in alkanes. In order to circumvent this problem we investigated the synthesis of a new neutral electrophilic fragment $Cp^*RuSnCl_3$ (**39**) [42]. The adduct of **39** with 1,5-cyclooctadiene (**40**) is shown in figure 8. The study of the reactivity of this fragment which is soluble in alkanes is presently in progress.

Conclusion

The reactivity of the simple fragment Cp^*Ru^+ was found to be highly unusual in many respects. First, it shows a very high affinity for aromatic hydrocarbons which, although no direct comparison has been established, is probably higher than the affinity of $CpFe^+$ and





Scheme 16. Reactions of the $Cp^*Ru(\eta^6\text{-}C_{10}H_{16})](OTf)$ (**37**) and $[Cp^*Ru(\eta^6\text{-}C_{12}H_{20})](OTf)$ (**38**).

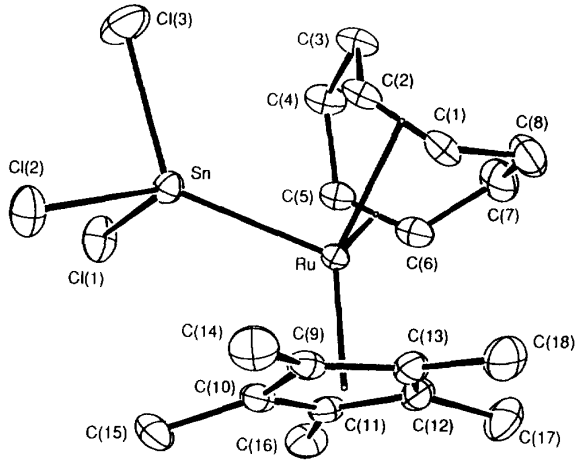


Fig 8. Molecular structure of $Cp^*Ru(SnCl_3)(\eta^4\text{-}C_8H_{12})$ (**40**).

$Cr(CO)_3$ for such fragments. This leads to new complexation reactions such as those with aromatic carboxylic acids or polymers.

The second aspect of the reactivity of Cp^*Ru^+ is its unique ability to aromatize cyclic hydrocarbons, while breaking virtually all types of bonds involving carbon. The most spectacular results in this respect are the very high (and total in certain cases) selectivity of the transformations involving carbon-carbon bond cleavage. Hence C–C bond activation has only rarely been observed and the reactions are often difficult. The catalytic cracking reaction observed in the presence of *t*-butylethylene is in this respect also entirely novel.

The limitations of Cp^*Ru^+ have been described above and are presently under investigation in our laboratory.

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