Ruthenium catalysts bearing *N*-heterocyclic carbene ligands in atom transfer radical reactions

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Abstract—The catalytic activity of ruthenium-*p*-cymene complexes bearing *N*-heterocyclic carbene ligands in atom transfer radical addition (ATRA) or polymerisation (ATRP) strongly depends on the substituents of the carbene ligand, thereby providing a nice illustration of the importance of organometallic engineering and ligand fine tuning in homogeneous catalysis.
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Atom transfer radical polymerisation (ATRP) is one of the most versatile controlled radical polymerisation techniques. Indeed, it allows to polymerise a wide variety of monomers, while offering excellent control of both molecular weight and molecular weight distribution of the resulting polymers. ATRP is an extension of the atom transfer radical addition (ATRA) also known as the Kharasch addition. Both processes involve the generation of active radicals from 'dormant' halogenated derivatives by a reversible redox process catalysed by transition metal compounds (Scheme 1). If the olefin is introduced in a proportion close to stoichiometry compared to the halogen compound, formation of the single addition product is favoured and the reaction is referred to as ATRA. In the presence of a large excess of olefin compared to the haloalkane, multiple insertion of the unsaturated monomer leads to a macromolecular chain and the whole process is now known as ATRP. The polymerisation is controlled by maintaining a low concentration of active radical species, thereby reducing the probability of termination and establishing a fast dynamic equilibrium between active and dormant species. Following the key observation by Sawamoto[1] and Matyjaszewski[2] that ruthenium(II) and copper(I) complexes afford highly efficient ATRP catalysts, a number of different metal ligand combinations have been investigated.[3]

With the discovery of ATRP, the Kharasch addition of polyhalogenated compounds across a C=C bond has experienced a rejuvenation.[4] Recently, we reported on the exceptional efficiency of various ruthenium complexes,[5] including $RuCl_2(p\text{-cymene})(PCy_3)$.[6,7] We also
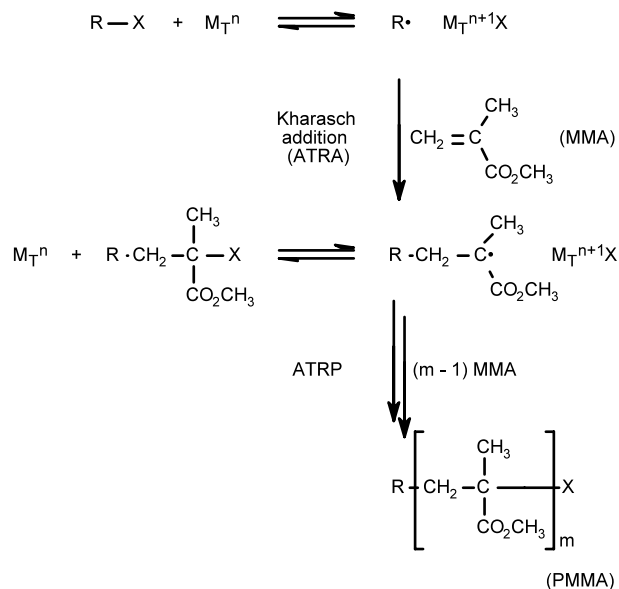

where X = Cl, Br, ... and M_T^n is a transition metal in the oxidation state n

Scheme 1. Kharasch addition versus ATRP of methyl methacrylate.

demonstrated that the Grubbs' ruthenium benzylidene complexes, $RuCl_2(=CHPh)(PR_3)_2$, were efficient catalyst precursors for both ATRP[6,8] and Kharasch addition,[8] and then expanded our investigations towards N-heterocyclic carbene-containing ruthenium benzylidene complexes.[9]

Nowadays, N-heterocyclic carbenes constitute a promising new class of ligands available for catalyst engineering and fine tuning. They behave as phosphine mimics, yet they are better σ-donors and they form stronger bonds to metal centres than most phosphines.[10] In addition, their electronic and steric properties are liable to ample modification simply by varying the substituents on the nitrogen and the carbon atoms. We have recently launched a detailed investigation on the role of NHC ligands in ruthenium-p-cymene catalyst precursors for the ring-opening metathesis polymerisation of cyclic olefins.[11] We now report on the use of new ruthenium catalysts bearing various NHC ligands for the Kharasch addition of carbon tetrachloride to olefins, and for the ATRP of vinyl monomers.


	R^1	R^2
1	Mes	Me
2	Mes	H
3	Mes	Cl
4	Cy	Me
5	Cy	H
6	Cy	Cl
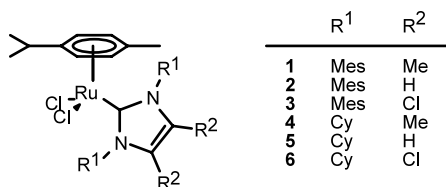
Mes = 2,4,6-trimethylphenyl; Cy = cyclohexyl

In a first set of experiments, the Kharasch addition of CCl_4 across the vinylic double bond of styrene was investigated using the ruthenium complexes **1–5** as catalysts. The reactions were carried out in toluene under inert atmosphere. Carbon tetrachloride was introduced in small excess compared to the olefin and the catalyst loading was 0.3 mol%. Under these conditions, a quantitative conversion of styrene into (1,3,3,3-tetrachloropropyl)benzene was obtained in the presence of complex **3** ($R^1=Mes$, $R^2=Cl$). Complex **5** bearing a rather different carbene ligand ($R^1=Cy$, $R^2=H$) was the second best choice and afforded the Kharasch adduct in 62% yield after 24 h of reaction at 90°C

(Table 1). Other substituent combinations on the imidazolylidene ring led to catalysts that were less efficient and selective. It should be pointed out, however, that stilbene formation did not contribute to more than 1 or 2% of the styrene consumption, indicative that ATRA was strongly favoured over olefin metathesis under the experimental conditions adopted yet (Scheme 2).

Thus, with styrene, subtle modifications of the R^1 and R^2 substituents led to dramatic changes in the ability of the corresponding ruthenium complexes to promote efficient Kharasch additions. At first sight, electronic effects seem to be more important than steric factors in governing reactivity. For instance, the reactivity order within the series of the N-mesityl-substituted NHC-ruthenium complexes was ($R^2=$) Cl (**3**)>H (**2**)>Me (**1**), clearly demonstrating the beneficial influence of electron-withdrawing chloro substituents compared to the electron-donating methyl groups. To further probe the structure–activity relationship in operation within the series of N-cyclohexyl-substituted ruthenium–NHC complexes, we planned to prepare complex **6** with R^2 chloro substituents for testing it in the Kharasch addition of CCl_4 to styrene. However, our attempts to synthesise the required free carbene ligand ($R^1=Cy$, $R^2=Cl$) using the same experimental procedure[12] that afforded the NHC with $R^1=Mes$ and $R^2=Cl$ met with failure.[13]
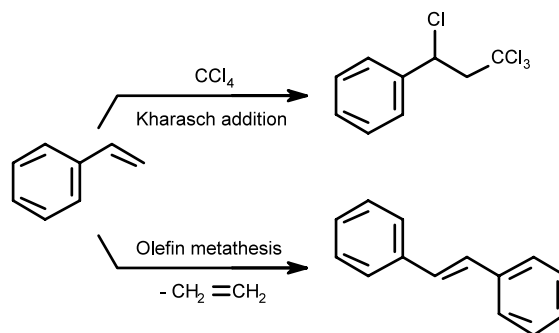
Scheme 2. Kharasch addition versus olefin metathesis of styrene.

Table 1. Reaction of styrene with carbon tetrachloride catalysed by complexes **1–5**[a]

Complex	Temperature					
	60°C			90°C		
	Conversion (%)[b]	Kharasch addition (%)[b]	Olefin metathesis (%)[b]	Conversion (%)[b]	Kharasch addition (%)[b]	Olefin metathesis (%)[b]
1	1	m	m	47	27	0.5
2	11	7	2	70	48	1
3	95	89	3	100	97	1
4	10	1	m	38	8	m
5	22	11	0	88	62	0

[a] *Reaction conditions*: styrene (9 mmol), carbon tetrachloride (13 mmol), ruthenium complex (0.03 mmol), toluene (4 mL), dodecane (0.25 mL), under nitrogen atmosphere. Reaction time, 24 h.
[b] Conversions and yields are based on styrene and determined by GC using dodecane as internal standard. m stands for minute amounts.

In order to get a better picture of the reaction course, the Kharasch addition of carbon tetrachloride onto styrene mediated by complexes **3** and **5** was monitored by gas chromatography (GC) at regular time intervals. The results are illustrated in Figure 1.
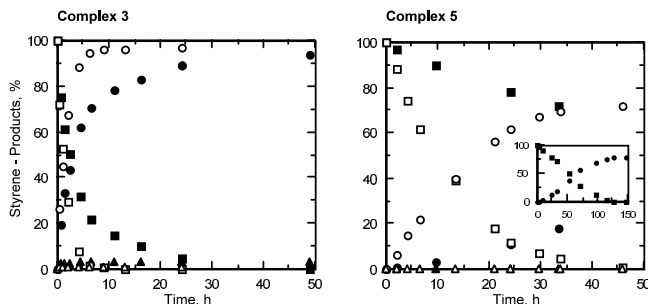

Figure 1. Time dependence of styrene (□, ■), Kharasch adduct (○, ●), and stilbenes (△, ▲) for reactions carried out at 60 (■, ●, ▲) and 90°C (□, ○, △). Reaction conditions are the same as in Table 1.

At 90°C, the difference of activity between the mesityl- and cyclohexyl-substituted derivatives, although clearly noticeable, was not striking (cf. Table 1). When the temperature was decreased to 60°C, the substrate and product evolution curves recorded with complex **3** were inflected, but not markedly affected (Fig. 1, left). Indeed, this catalyst still afforded a 95% styrene conversion and a 89% yield of Kharasch adduct after 24 h. The activity of complex **5**, on the other hand, almost completely collapsed when the reaction temperature was lowered (Fig. 1, right). After 24 h at 60°C, the conversion remained limited to 22%, and only half of the monomer consumed led to the Kharasch reaction (11% yield from styrene).
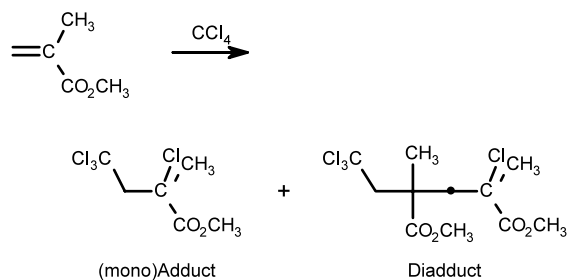

Table 2. Reaction of methyl methacrylate with carbon tetrachloride catalysed by complexes **1–5**[a]

Complex	Conversion (%)[a]	Kharasch addition (%)[a]	
		Monoadduct	Diadduct
1	10	*m*	0
2	7	*m*	0
3	7	*m*	0
4	19	1.5	1
5	20	4	1.5

[a] Experimental conditions are the same as in Table 1 (90°C, 24 h).

Under the same experimental conditions, at 90°C, methyl methacrylate displayed a disappointingly low reactivity, whichever NHC ligand was present on the ruthenium centre (Table 2). Conversion remained below 20% and only minute amounts of the addition product were detected by gas chromatography. Only when the dicyclohexyl complexes **4** and **5** served as catalysts, was the diadduct resulting from the insertion of two olefinic units within the activated carbon–halogen bond visible in the chromatograms. In all cases higher oligomers also formed and accounted for the mass balance, but their high molecular weights prevented a satisfactory GC analysis.

n-Butyl acrylate was more prone to undergo the atom transfer radical addition of carbon tetrachloride than MMA using the series of ruthenium–NHC complexes under study. Indeed, complex **3** afforded a 99% conversion and a 80% yield of the Kharasch adduct after 24 h at 90°C. 1-Decene, on the other hand, was much less reactive than styrene and *n*-butyl acrylate (Fig. 2). With complex **3**, some 60 h were needed to achieve the complete conversion of the substrate. The desired product (1,1,1,3-tetrachloroundecane) was obtained in 85% yield, together with a small amount (7% yield based on 1-decene) of 9-octadecene (*cis/trans* = 0.75) resulting from olefin metathesis. In addition, isomerisation of 1-decene into internal olefins (mostly 2-decene) also occurred and accounted for the mass balance.

The close similarity of structure between complexes **1–5** and $RuCl_2$(*p*-cymene)PCy_3 prompted us to assess the formers as possible catalysts for ATRP (Table 3). In a series of preliminary experiments, methyl methacrylate (MMA) and styrene (S) served as prototypical monomers for screening the most efficient catalysts. ATRP was initiated by carbon tetrachloride (2 equiv. compared to the ruthenium complex) and conducted at either 85°C (MMA) or 110°C (S).[14]

With MMA as the monomer (Table 3), complex **4** gave the highest polymer yield (96%), but the polymerisation was not controlled and the molecular weight distribution was very broad ($M_w/M_n = 2.5$). Complex **3**, on the other hand, displayed a lower activity (44% yield of PMMA) together with some level of control, as indicated by the narrower polymer distribution ($M_w/M_n = 1.4$). As already observed with polyhalogenated
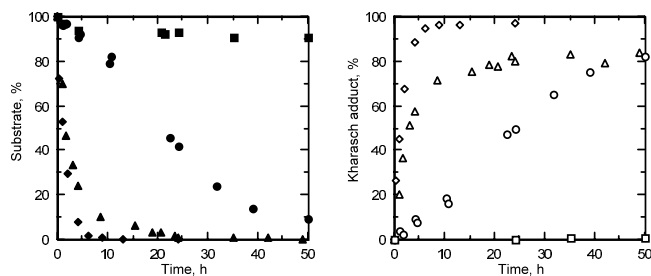

Figure 2. Time dependence of styrene (◆), 1-decene (●), *n*-butyl acrylate (▲), methyl methacylate (■), and their respective Kharasch adducts (◇, ○, △, □) for reactions carried out at 90°C in the presence of complex **3**. Reaction conditions are the same as in Table 1.

Table 3. Polymerisation of methyl methacrylate and styrene in the presence of carbon tetrachloride, catalysed by complexes **1–5**[a]

Complex	Methyl methacrylate			Styrene			
	PMMA yield (%)[b]	M_n[c]	M_w/M_n[c]	PS yield (%)[b]	M_n[c]	M_w/M_n[c]	Stilbenes (%)[b]
1	10	33000	1.8	78	36000	1.85	3
2	76	26000	1.9	74	28000	1.85	4
3	44	6000	1.4	34	12000	1.25	46
4	96	90000	2.5	94	30000	1.7	*m*
5	51	53000	2.05	89	22000	1.5	*m*

[a] Reaction conditions: $[MMA]_0:[CCl_4]_0:[Ru]_0 = 800:2:1$; temperature, 85°C. $[Styrene]_0:[CCl_4]_0:[Ru]_0 = 750:2:1$; temperature, 110°C. Reaction time, 16 h.[6,9]

[b] Based on the monomer. *m* stands for minute amounts.

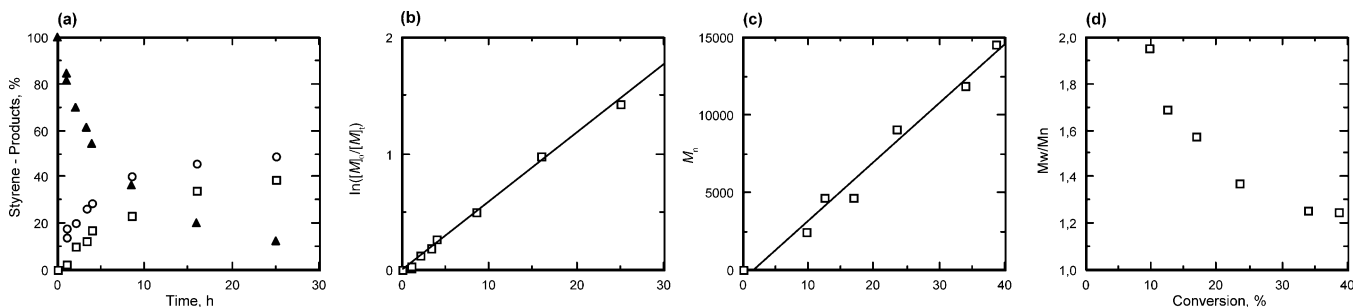[c] Determined by size-exclusion chromatography (SEC) with PMMA and polystyrene calibration, respectively.

Figure 3. Experimental data for the polymerisation of styrene catalysed by ruthenium complex **3**. (a) Time dependence of styrene (▲), polystyrene (□), and stilbenes (○). (b) Time dependence of $\ln([M]_0/[M]_t)$ where $[M]_0$ and $[M]_t$ are the styrene concentrations at times 0 and t.[17] (c) Dependence of the PS molecular weight M_n on monomer conversion.[17] (d) Dependence of the polydispersity M_w/M_n on monomer conversion.[17] Experimental conditions are the same as in Table 3.

initiators such as CCl_4,[5a,8,15] the molecular weight ($M_n = 6000$) was lower than the value calculated assuming that one molecule of initiator generates one living polymer chain, indicating that additional polymer chains are generated through transfer reactions.[16]

Complex **3** also provided the highest level of control for the polymerisation of styrene, with a polydispersity M_w/M_n around 1.25 (Table 3). Noteworthy, with complexes **1–3** bearing *N*-mesityl-substituted NHC ligands, metathesis of styrene occurred competitively with polymerisation. *trans*-Stilbene and minute amounts of *cis*-stilbene were formed in varying quantities according to the substituents of the NHC ligand. With complex **3** ($R^1 = Mes$, $R^2 = Cl$), olefin metathesis was predominant (49% yield based on styrene, after 25 h of reaction (Fig. 3a)), whereas with the parent *N*-mesityl-substituted derivatives **1** ($R^2 = Me$) and **2** ($R^2 = H$) stilbene formation reached only 3–4%. Interestingly, complexes **4** and **5** bearing *N*-cyclohexyl-substituted NHC ligands were devoid of any significant activity for the metathesis of styrene.

From the results shown in Tables 1 and 3, it also appeared that carbon tetrachloride had a detrimental effect on olefin metathesis. Indeed, a rough comparison of the ability of complex **3** to promote the metathesis of styrene revealed that, despite the experimental conditions were quite different, higher yields of stilbenes were

obtained under ATRP conditions (375 equiv. of styrene compared to CCl_4: 46% yield of stilbenes) than under ATRA conditions (0.69 equiv. of olefin compared to CCl_4: 1–3% yield of stilbenes). In light of these observations, a systematic investigation of the competitive reactions of styrene (olefin metathesis, ATRA, and ATRP) has been undertaken to allow for proper comparative analysis. The results shown in Table 4 confirmed our expectations. First, in the absence of carbon tetrachloride, complex **3** was an excellent catalyst precursor for the metathesis of styrene. A 70% yield was achieved at 90°C, with a turnover number of 210 after 10 h. Second, in the presence of CCl_4, styrene underwent radical reactions in addition to olefin metathesis. In accordance with our preliminary results, upon addition of an increasing amount of CCl_4, the metathesis activity decreased significantly for the benefit of the Kharasch addition. Thus, for 1.5 equiv. of CCl_4 compared to styrene, the ATRA went to 91% yield, whereas styrene metathesis dropped to 6%.

Finally, the ability of complex **3** to control the polymerisation of styrene was investigated.[17] The semilogarithmic plot of $\ln([M]_0/[M]_t)$ versus time was linear (Fig. 3b: $y = -4.6298 \times 10^{-3} + 5.8793 \times 10^{-2} \, x$; $r^2 = 0.996$) with a pseudo-first order rate constant (k_{app}) of $1.63 \times 10^{-5} \, s^{-1}$, indicating that the radical concentration remained constant throughout the polymerisation run. In addition, the molecular weights M_n increased lin-

Table 4. Competitive reactions of styrene in the presence of carbon tetrachloride, catalysed by complex **3**[a]

Carbon tetrachloride	None	0.01[b]	0.1[b]	0.5[b]	1.5[b]
Styrene conversion (%)[c]	71	68	49	78	99
Stilbenes (%)[c]	70	58	27	10	6
Kharasch adduct (%)[c]	–	0	6	40	91
(Oligo-) polystyrene (%)	0	10	16	28	2

[a] Reaction conditions: styrene (9 mmol), ruthenium complex (0.03 mmol), toluene (7.5 mL), dodecane (0.25 mL), under nitrogen atmosphere. Temperature, 90°C. Reaction time, 10 h.

[b] Addition of CCl_4 (equiv. of CCl_4 compared to styrene).

[c] Conversions and yields are based on styrene, and determined by GC using dodecane as internal standard.

early with conversion (Fig. 3c: $y = -572 + 378.71 \, x$; $r^2 = 0.980$), thus demonstrating good control over M_n. Polydispersities (M_w/M_n) were quite low (typically ca. 1.25) and decreased with monomer conversion (Fig. 3d). By contrast, the other ruthenium complexes tested led to poorly controlled or uncontrolled polymerisations of styrene.

To conclude, it should be pointed out that neither the yields, nor the R^1–R^2 substituent combinations within the NHC ligand were optimised. Thus, room for improvement certainly exists. Nevertheless, this study provides a glimpse of the synthetic possibilities arising from the use of ruthenium *N*-heterocyclic carbene complexes in radical reactions, and illustrates how the fine tuning of the steric and electronic parameters of this class of ruthenium complexes affects their catalytic activity. Further work in this field is in progress.

Acknowledgements

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