Journal of Molecular Catalysis A: Chemical 386 (2014) 86–94

Contents lists available at ScienceDirect

Journal of Molecular Catalysis A: Chemical

journal homepage: www.elsevier.com/locate/molcata

Catalytic activity and selectivity of a range of ruthenium complexes tested in the styrene/EDA reaction system

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ARTICLE INFO

Article history:
Received 18 October 2013
Received in revised form 1 February 2014
Accepted 8 February 2014
Available online 17 February 2014

Keywords:
Cyclopropanation
N-heterocyclic carbenes
Schiff bases
Ruthenium complexes
C—C coupling

ABSTRACT

The complex ensemble of competing chemical processes (cyclopropanation, metathesis, dimerisation) involved in the reaction of ethyl diazoacetate with styrene is examined in the presence of a panel of ten ruthenium complexes. Our results, focusing on the catalysts' activity and selectivity, showcased the new NHC-containing complex **10** and the Fischer carbene **7** as leading to best chemoselectivities for cyclopropanation while the bidentate Schiff-base complexes **3** and **4** provided highest stereoselectivity. The traditionally metathesis-active Grubbs I catalyst (**5**) could be manipulated, by working under high dilution, to display moderate activity in cyclopropanation whereas the Grubbs II catalyst (**6**) totally promoted metathesis. Data obtained with the above set of Ru complexes strongly support the premise that ligand structure and configuration in the Ru coordination sphere are essential factors in controlling the reaction pathways.

1. Introduction

Many natural or unnatural compounds incorporate cyclopropane as a basic structural motif that often confers them biological activity, frequently also therapeutic properties [1]. In addition, the propensity of cyclopropane to induce conformation constraints promotes the use of this highly strained carbocycle as a synthetic building block in more complex structures demanding a particular stereoconfiguration. Starting from these premises, an enabling construction of the useful cyclopropane entity by metal-catalyzed [2] or organocatalyzed [3] intermolecular cyclopropanation has always been an attractive research area for synthetic organic chemists. To date, a substantial number of excellent reviews on different aspects of cyclopropanation reactions have been published [4].

Of the plethora of methods published for stereoselective cyclopropanation starting from alkenes [4b], the transition-metal mediated transfer of carbene (*in situ* delivered through decomposition of aliphatic diazo compounds) is the most developed and used protocol [4e,h]. Several traditional transition metal catalysts for cyclopropanation are presently enjoying a revived interest, *e.g.* those based on copper [5a], gold [5a,b], rhodium [5c,d] palladium [5e,f], cobalt [5g,h] and ruthenium [2a,b, 4a–d, 6a–h]. Owing to the various oxidation states that ruthenium can assume, with easy redox transitions between them during catalytic cycles, as well as to the flexible coordination abilities of ruthenium, large libraries of mononuclear and dinuclear ruthenium complexes have been created for various applications. In contrast to rhodium- and copper-based catalysts leading to either *cis*- or *trans*-substituted cyclopropanes, depending on the structure of the catalyst employed, ruthenium catalysts provide mostly *trans*-cyclopropanated products [4]. Currently cyclopropanation employs an array of ruthenium catalysts based on arene and/or NHC [3a–c, 7] or more complicated ligands such as pybox, salen, porphyrin [4b,c,h,i]. Previous research unequivocally evidenced that some catalysts with established activity for alkene metathesis could also

Abbreviations: ATRP, atom transfer radical polymerization; EDA, ethyl diazoacetate; Grubbs I catalyst, Grubbs first generation catalyst; Grubbs II catalyst, Grubbs second generation catalyst; NHC, N-heterocyclic carbene; Pybox, pyridinebis(oxazoline); rt, room temperature; Ru, ruthenium; Salen, 2,2'-ethylenebis(nitrilomethylidene)diphenol,N,N'-ethylenebis(salicylimine).

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http://dx.doi.org/10.1016/j.molcata.2014.02.009
1381-1169/

be valorized in alkene cyclopropanation [8]. However, rigorous control of the reaction conditions can favour either reaction pathway.

As part of our ongoing programme to extend the utility of ruthenium catalytic systems [9], we have previously reported on cyclopropanation catalyzed by bidentate N,O-Schiff base ligated precursors [10]. This class of catalysts also proved good activity in metathesis, ATRP, enol-ester synthesis, vinylation [11]. In olefin cyclopropanation with diazo compounds, Ru(II)–arene catalysts bearing Schiff base ligands were found to be moderately active producing, as expected, higher proportions of cyclopropanated products with activated olefins than with non-activated counterparts [10]. On optimizing reaction conditions, cyclopropanation could overcome side reactions (dimerisation and metathesis). It was concluded that the electronic properties of the Schiff base ligand influence the decomposition rate of the diazo compound, hence generation of the carbene. With more donating Schiff bases higher yields (max. 76%) and *trans*/*cis* ratios (dr: 2.8/1) in cyclopropanated products were recorded. For practical purposes such yields are, however, not satisfactory.

We were prompted therefore to investigate a whole range of structurally diverse Ru precursors and determine their performance, for the first time under uniform conditions and in the same reaction, of styrene with ethyl diazoacetate (EDA), generally accepted as standard. The primary goal of this work is to extend the scope of several commercial and known or new Ru catalysts to prevailingly cyclopropanation. A secondary focus has been on rationalizing the effect that ligands within the Ru coordination sphere play on the selectivity in cyclopropanation, relative to that in concurrent metathesis or dimerisation. These new findings could provide fresh insights into this intricate transformation.

2. Results and discussion

Intermolecular transition metal-catalyzed carbenoid cyclopropanation of alkenes with diazo compounds has been extensively studied, in particular the reaction between styrene and ethyl diazoacetate (EDA) [12]. Ethyl diazoacetate generates *in situ* a carbene species which undergoes chemoselective insertion yielding *cis* and *trans* cyclopropanes (Scheme 1, Eq. (1)). However, as mentioned above, the overall process also commonly involves different side-reactions resulting in products observed for all types of transition metal catalysts (Scheme 1): metathesis (Eq. (2)), cross-metathesis styrene-diazoester (Eq. (3)), homocoupling (dimerisation) of EDA to a mixture of diethyl maleate and fumarate, usually strongly favouring the former (Eq. (4)).

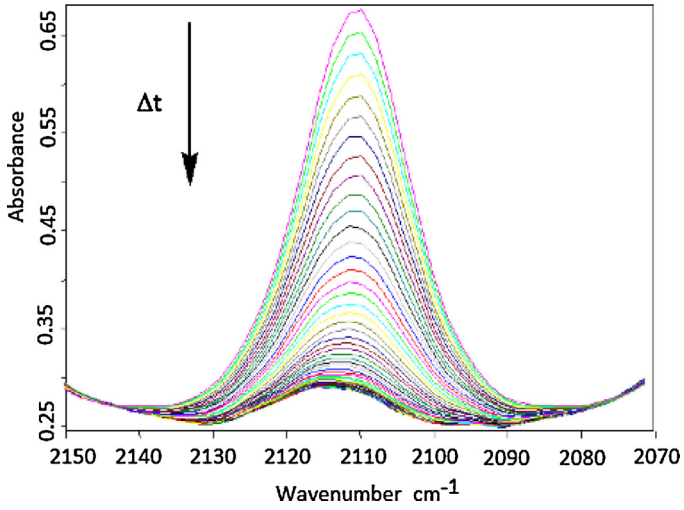


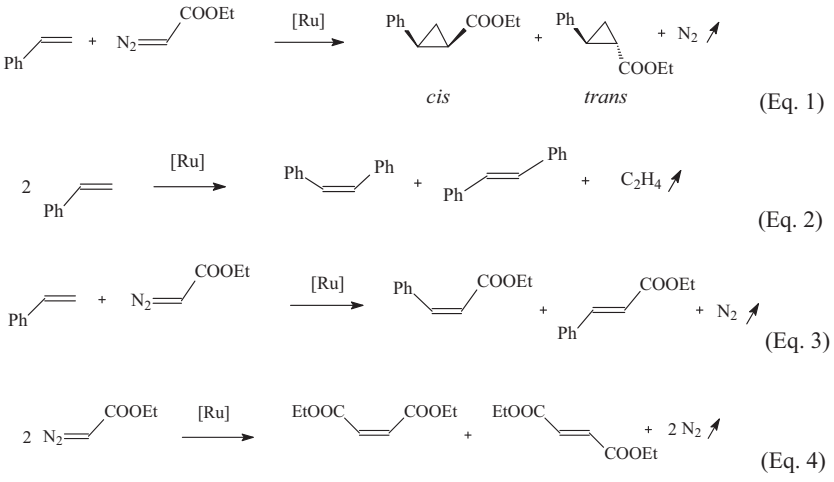
Fig. 1. EDA decomposition induced by Ru catalysts followed by FTIR spectroscopy in the presence of catalyst **7** (at 40 °C).

By modulating the reaction conditions a certain control on undesired reactions can be exerted. To enhance cyclopropanation we decided to minimize dimerisation by slowly adding a diluted solution of the diazoacetate to the mixture of styrene and catalyst and also by using a large excess of styrene. Working under high substrate:catalyst loadings we expected a subdued metathesis, thus enhancing cyclopropanation.

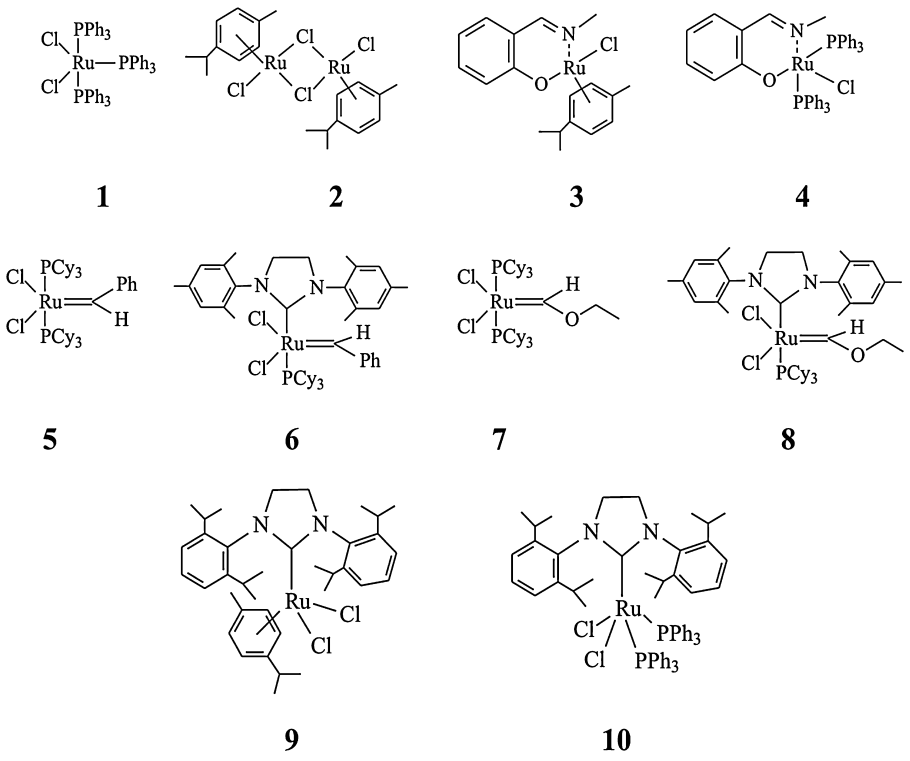
Progress of the reaction of styrene with EDA as proceeding under promotion of our Ru catalysts (Scheme 2) was examined using FTIR and GC methodologies.

Due to release of nitrogen gas, EDA decomposition in the presence of Ru catalysts is an irreversible process. To determine the influence of EDA decomposition on the overall catalytic process, advantage was taken of the characteristic stretching vibration of the N=N double bond (2110 cm^{-1}) from EDA whose decrease in time at the reaction temperature was followed by FTIR spectroscopy, in the presence of each catalyst; a typical example is shown in Fig. 1, for the catalyst **7** (at 40 °C). Since above 80 °C a very rapid thermal decomposition of EDA in toluene could be observed, our catalytic tests were run at lower temperatures (30–60 °C).

In order to evaluate the effect of the ligands in the four- and five-coordinate complexes we have synthesized and applied in cyclopropanation quite structurally different 16- or 18-electron ruthenium complexes selected so as to bear diverse ligands



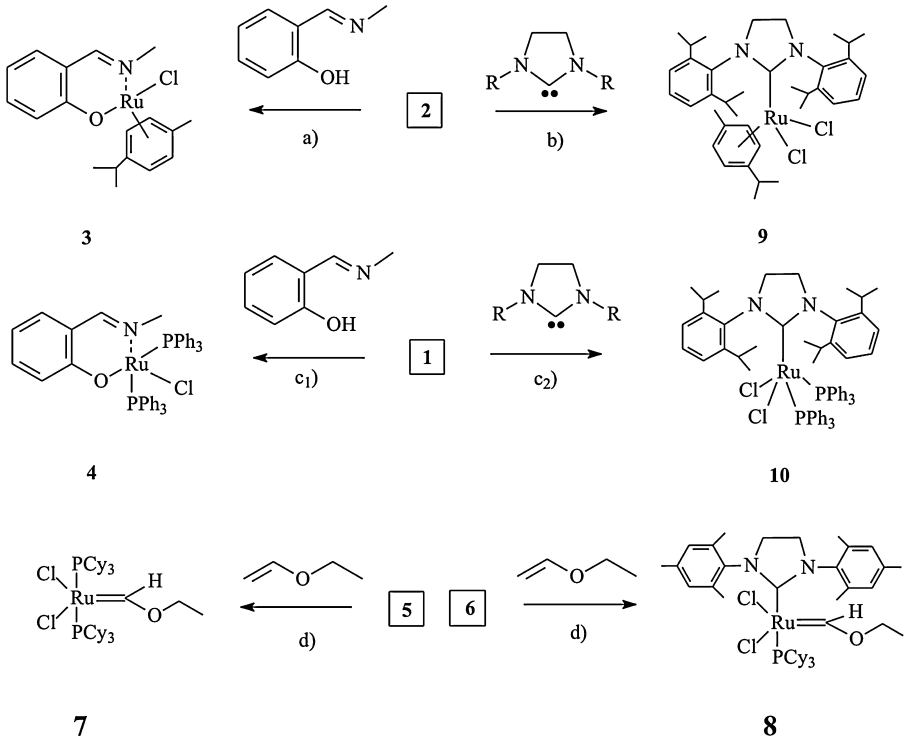
Scheme 1. Concurrent reactions in cyclopropanation of styrene with diazoesters (Eqs. (1)–(4)).



Scheme 2. Ruthenium catalysts employed in reaction of styrene with EDA.

attached to the metal core (Scheme 2) including the, to our knowledge, not yet reported Ru complexes (**4**, **10**), several known (**3**, **7**–**9**) and some commercial (**1**, **2**, **5**, **6**) catalysts. Synthesis of the non-commercial complexes was carried out using established procedures as indicated in Scheme 3 (see also Section 3).

Previous investigations in our group have already shown that catalysts **2** and **3** are adequate promoters for styrene cyclopropanation with ethyl diazoacetate as the carbenoid source [10]. It is worth mentioning that in the present work catalysts **4**, **7**, **8** and **10** are being used for the first time in cyclopropanation *via* the carbene



Scheme 3. Syntheses of new and known catalysts used in cyclopropanation: (a) Ref. [10]; (b) Ref. [2b,c]; (c) This work; (d) Ref. [13].

Table 1
Product distribution in the reaction of styrene with EDA (in toluene, at 60 °C, 4 h).[a,b]

		Reaction selectivity				Yield[c] in cyclopropa-nated products (%)
Entry	Catalyst	Cyclopropanation (%)	*trans*/*cis*	Metathesis (%)	Dimerisation (%)	
1	**1**	77	1.81	12	11	87.5
2	**2**	58	1.49	13	29	66.6
3	**3**	73	2.3	8	19	79.3
4	**4**	72	2.7	21	7	91.1
5	**5**	35	1.02	59	6	85.4
6	**6**	–	–	100[d]	–	–
7	**7**	84	0.98	8	8	91.3
8	**8**	50	1.38	33	17	74.6
9	**9**	44	1.21	13	43	50.6
10	**10**	85	1.47	5	10	89.5
11	**5**[e]	82	2.0	9.5	8.5	90.6
12	**7**[e]	75	–	5	20	78.9

[a] Based on ethyl diazoacetate. Determined by GC by comparison with authentic samples (internal standard diethyl adipate). Ratio of the dimerisation products: diethylmaleate/diethylfumarate ~2/1.
[b] Molar ratios: catalyst/EDA/styrene = 1/125/2500; toluene/styrene = 10.
[c] Based on EDA. EDA was totally consumed.
[d] Determined by GC by comparison with authentic samples.
[e] Molar ratios: catalyst/EDA/styrene = 1/400/8000. Reaction temperature: 50 °C. Reaction time: 4 h.

transfer approach. Results are compiled in Table 1 and graphically highlighted in Fig. 2.

Of the catalysts examined for reactions performed under high dilution in toluene, at 60 °C and molar ratios catalyst/EDA/styrene = 1/125/2500, the best chemoselectivity for asymmetric intermolecular cyclopropanation yielding 1-carbethoxy-2-phenylcyclopropane has been observed for the *IPr*-containing promoter **10** (85%) and the ethoxy Ru-carbene **7** (84%) (Table 1). Besides, cyclopropanation is still the main reaction pathway in the case of catalysts **1**–**4** and **8**. Under these conditions the Grubbs I catalyst (**5**) displays just a moderate selectivity for cyclopropanation with metathesis prevailing. In contrast to its congener, the Grubbs II catalyst (**6**) gives neither cyclopropanation nor dimerisation, while metathesis reaction is entirely favoured. Regarding now the competing processes, dimerisation and metathesis, results evidence them as balanced in the case of catalysts **1** and **7**, whereas nearly a twice as much dimerisation is recorded with catalysts **2**, **3** and **10**. An exceptionally sharp increase of dimerisation is found for catalyst **9** (43%), quite close to the extent to which cyclopropanation occurs (44%). Though pretty good promoters for cyclopropanation, the ethoxy Ru-carbene **8** and our new Schiff-base bidentate-Ru catalyst **4** favour metathesis over dimerisation. Remarkably, while best diastereoselectivities in cyclopropanation were attained with the bidentate Schiff-base Ru complexes **3** and **4** all other catalysts investigated here directed more towards the *trans* diastereomer, with the exception of **7** (Table 1, Entry 7). These data on diastereoselectivity comply with literature reports on a variety of ruthenium catalysts that also exert *trans* control. The same is true for the *trans*/*cis* stereoselectivities of the metathesis products found to be roughly 2/1. The divergent behaviour of catalysts **1**–**10** in the reaction of styrene with diazoester is more suggestively illustrated in Fig. 2.

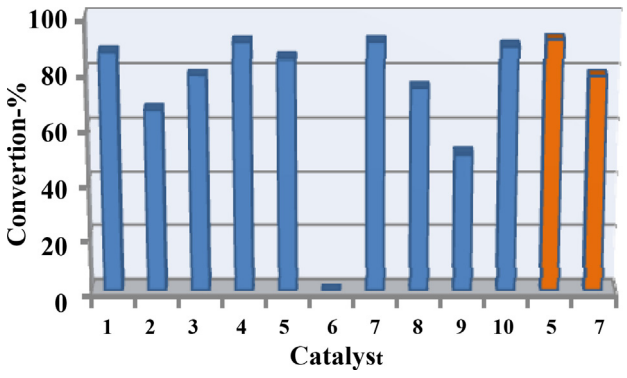


Fig. 2. Conversion (%; based on EDA) of styrene into the cyclopropanation product (1-carbethoxy-2-phenyl cyclopropane), in the reaction with EDA (60 °C, 4 h). Conditions for experiments with catalysts **5** and **7** (last two columns; in red): molar ratios catalyst/EDA/styrene = 1/400/8000; 50 °C, 4 h. (For interpretation of the references to color in this text, the reader is referred to the web version of the article.)

If we consider just the two reactions where EDA is consumed (cyclopropanation and dimerisation) the yields *vs.* EDA (Table 1, last column, entries 1–10) are, as should be expected, higher than the selectivity in the cyclopropane-containing product. These calculated yields are a better indication of the efficiency of the different catalysts in cyclopropanation since the highest values are attained for runs where the catalyst is disfavouring dimerisation, even though the selectivity is not as high as is the case for **1**, **4** and **5**.

Reactions carried out with the Grubbs I catalyst (**5**) using styrene as the solvent (Table 1, entry 11) gave high selectivity in cyclopropanation (82%), at 50 °C and at a lesser catalyst loading (catalyst/EDA/styrene = 1/400/8000). In further experiments conducted under the latter conditions the influence of temperature on cyclopropanation and its competing processes was also followed. Within the temperature range 30–50 °C we found that selectivity in the desired cyclopropanated product is increasing from 62.5% to 82.0% with dimerisation and styrene metathesis diminishing accordingly (Table 2).

As seen below, analysis of data acquired in this research helps illuminate some of the underpinnings of this complex chemical transformation and provides fresh understanding of the nature of the active catalytic species and the mechanistic pathways. Our tests with a larger array of ruthenium catalysts enable a deeper consideration of the concerted influence of the catalyst and reaction conditions (molar ratios, concentration, solvent, temperature) on yields and selectivity in the targeted cyclopropanated product.

A good accord could be established with available literature information on previously reported cyclopropanation catalysts (**1**–**3**). For example, catalyst **1** employed in cyclopropanation of styrene with EDA (**1**/EDA/styrene = 1/200/5740; addition of EDA over 4 h) was reported [14] to give 93% yield of 1-carbethoxy-2-phenylcyclopropane at 60 °C, *vs.* our result of 87.5%, as expected slightly lower because of working at the same temperature but under high dilution in toluene

Table 2
Influence of temperature on cyclopropanation, dimerisation and metathesis in the reaction of styrene with EDA (in excess styrene).[a]

Entry	Temp. (°C)	Cyclopropanation (%)	*trans/cis*	Dimerisation (%)	Metathesis (%)	Yield (%)
1	30	62.5	2.2	23.5	14.0	72.7
2	35	71.0	1.9	18.0	11.0	79.8
3	40	73.0	1.8	18.0	9.0	80.2
4	45	77.0	1.9	14.5	8.5	84.2
5	50	82.0	2.0	8.5	9.5	90.6

[a] Molar ratios: catalyst/EDA/styrene = 1/400/8000.

(catalyst/EDA/styrene = 1/125/2500); toluene/styrene = 10; Table 1, entry 1). This comparison is supported by EDA dosage during the same time interval (4 h) which is a crucial factor for manipulating competition by dimerisation. It was found, indeed, that the same catalyst can provide 70% dimerisation, at a similar catalyst loading (**1**/EDA = 1/100; room temperature, in THF) but by adding together the catalyst and EDA at the onset of the experiment [15].

It should be mentioned that results from runs with the Ru dimer **2** and the Schiff-base Ru arene complex **3**, affording only moderate yields and selectivities for cyclopropanation (Table 1, entries 2 and 3) parallel those earlier communicated by our group [10]. This resemblance suggests a similar catalyst activation pathway *i.e.* decoordination of the same arene ligand (*p*-cymene). The better selectivity for **3** *vs.* **2** is to be assigned to the stabilizing effect of the Schiff-base ligand on the Ru active species resulting from **3**.

The new catalyst **4** bearing an O,N-bidentate Schiff-base and two PPh_3 ligands (Table 1, entry 4) proved to be a remarkable cyclopropanation promoter (yield 91.1%). Under the applied reaction conditions it disfavoured dimerisation, though an increase in metathesis could not be prevented in this case (as compared to **1**). This is probably due to a longer life-time of the active species arising from **4**, stabilized by the Schiff-base, relative to that from **1**, in spite that both involve the same phosphine (PPh_3) decoordination.

Noteworthy, the Grubbs I and II catalysts (**5** and **6**) appear as particular cases in cyclopropanation. Though these metathesis catalysts have been largely employed in tandem metathesis/cyclopropanation [4c,16], it is well-documented that in the presence of diazoesters catalyst **6** promotes overwhelmingly metathesis with only trace amounts of cyclopropanation products being formed [6b]. On the other hand, the Grubbs catalysts proved also entirely suitable for homocoupling of diazoesters to give maleate and fumarate esters [17a]. Nevertheless, with a1:1 molar ratio EDA/styrene and 0.01% mol **6**, especially under more elevated temperature (50 °C), styrene metathesis to stilbene partially occurred [17]. In case of catalyst **6** all seem to depend, however, on molar ratios and reaction conditions as reported in a recent investigation where by using **6**/EDA/styrene = 1/200/5200 in chlorobenzene (C_6H_5Cl/styrene = 0.4), at 60 °C for 24 h, the cyclopropanated product (1-carbethoxy-2-phenylcyclopropane) formed predominantly (80% yield, based on EDA) and just below 1% metathesis (calculated *vs.* styrene) was observed [2c].

It is intriguing that information regarding applications of Ru complexes **5** and **6** as promoters of styrene cyclopropanation with diazo compounds are quite scarce. Therefore, we undertook a detailed study of this process under these conditions. Noteworthy, when the reaction was carried out with the Grubbs I catalyst (**5**) using styrene as the solvent (Table 1, entry 11), a high selectivity in cyclopropanation (82%) could be achieved, even at 50 °C and at a lesser catalyst loading than in the run at 60 °C (Table 1, entry 5). Furthermore, while keeping the same solvent, concentration and catalyst loading, the effect of reaction temperature on cyclopropanation in the presence of Grubbs I catalyst is totally different *vs.* that on dimerisation and metathesis processes: low temperatures restrain cyclopropanation *vs.* dimerisation and metathesis, while high temperatures act in the opposite direction (Table 2). Under the indicated reaction conditions, within the temperature range 30–50 °C, it was found that selectivity in 1-carbethoxy-2-phenylcyclopropane increases from 62.5% to 82.0% while dimerisation and metathesis diminish; of the latter two reactions, dimerisation is more sensitive to temperature changes. In addition, variation of the reaction temperature in this range has no significant effect on the *trans*/*cis* ratio of the cyclopropanated products that oscillates around the value of 2 (Table 2), in agreement with experiments of Snapper who found that the stereoselectivity of the cyclopropanation with the Grubbs I catalyst is moderate at best (*E*/*Z* = 1/1–3/1) [6b].

A decrease of cyclopropanation at lower temperatures, associated with a practically constant stereoselectivity, as found for the catalyst **5**, has also been previously communicated for the catalyst **1** (43% yield at 30 °C *vs.* 93% at 60 °C) [14].

Aiming at a better understanding of the role played by EDA in the cyclopropanation reaction, we also performed a detailed investigation on the EDA decomposition induced by the catalysts **5** and **7** (Fig. 3).

Thus, we could easily observe that even in the presence of the ruthenium catalyst alone, EDA undergoes rapid decomposition with a rate depending on the catalyst kind. Quite remarkably, catalyst **7** leads to a higher decomposition rate than **5** (Fig. 3). In the absence of the olefin, the decomposition outcome is dimerisation to EtOOC-CH=CH-COOEt, generally accepted as proceeding through the intermediacy of the unstable metalcarbene species [Ru] = CH-COOEt. However, when an olefinic substrate is added, the decomposition rate follows a different course being accelerated when the olefin is styrene and decelerated in the presence of *cis*-stilbene.

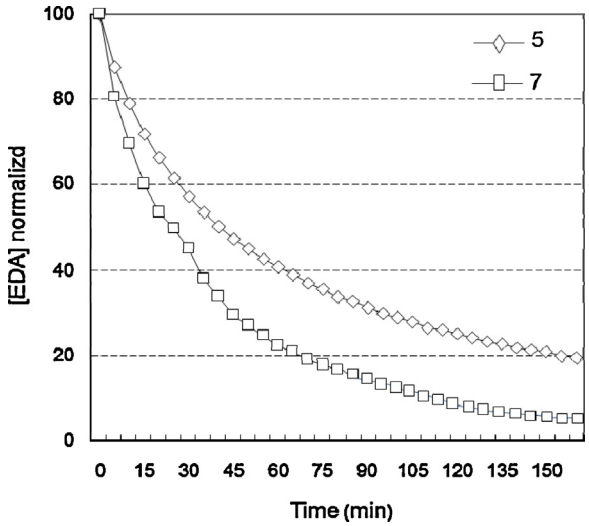
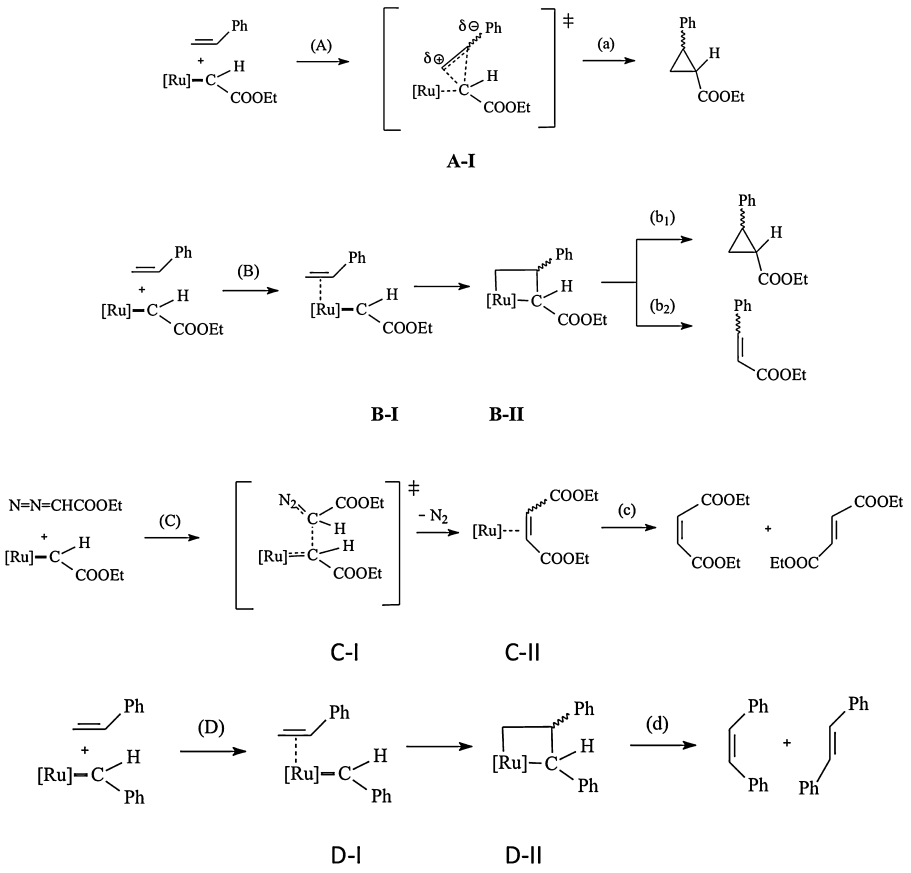


Fig. 3. Decomposition of EDA *vs.* time in the presence of catalyst **5** (◊) and **7** (□), in the absence of an olefin substrate, at 40 °C; **5** or **7**/EDA = 1/400.



Scheme 4. Carbenoid and coordination mechansims for cyclopropanation, dimerisation and metathesis.

Data illustrated in Fig. 3 support results recorded with catalysts **5** and **7** (Table 1, entries 11 and 12): the more rapid decomposition of EDA by the latter catalyst explains the larger proportion of dimerisation, at the detriment of cyclopropanation. Both catalysts lead to a feable metathesis yield, as anticipated lower in the case of **7** reputed as a quite poor metathesis catalyst. The EDA decomposition in the presence of stilbene, found to be slower than in the absence of any olefinic substrate, seems to indicate that stilbene does not compete with styrene for reacting with the [Ru] = CH-COOEt species. The possible rationalization could be the unfavourable steric factors, also accounting for the very reduced percentage (if any) of the putative product of stilbene cyclopropanation, 1,2-diphenylcyclopropane.

At the same time, it should be outlined that 2,6-isopropylphenyl-imidazolinylidene arene-Ru catalyst **9** [2b,c], displayed, under similar reaction conditions, only a moderate cyclopropanation selectivity while also leading to some metathesis and the largest dimerisation production of all catalysts tested in this research (Table 1, entry 9). This behaviour strongly contrasted with chemoselectivity found for the same catalyst but working under a larger excess of styrene and EDA, for a longer duration and in the presence of a more polar solvent (ClC_6H_5) [2c] where cyclopropanation prevailed and metathesis was almost completely suppressed, possibly due to the much higher concentration and to a solvent effect [15].

To our satisfaction, the new catalyst **10**, prepared from $Cl_2Ru(PPh_3)_3$ and the same N-heterocyclic carbene as for **9** (Scheme 2), provided the highest selectivity (85%) in this cyclopropanation reaction, along with a reduced proportion of dimerisation and metathesis products. Accordingly, catalyst **10** falls in the range of promoters which activate through decoordination of a triphenylphosphine (**1**, **4**, **10**), which are all efficient in cyclopropanation. By just replacing a phosphine ligand in **1** by an NHC ligand, C—C forming through cyclopropanation was enhanced, at the expense of metathesis pathway.

Further evaluation of our results in cyclopropanation of EDA/styrene induced by catalysts **1**–**10** led us to suggest a complex mechanistic scheme that involves separate pathways for the three competing C—C coupling reactions, as generally accepted in research on alkene cyclopropanation [4a,c,i,6d,7,8,18]. To account for the particular behaviour we observed for our catalysts, it is reasonable to assume the intervention of distinct Ru active species, of varying stability, for cyclopropanation, dimerisation and metathesis (Scheme 4).

In support of this point of view we decided to look at NMR signals assignable to carbene species that arise at the onset of EDA decomposition in the presence of the catalyst **5** monitoring the evolution of the ^{1}H NMR spectrum of a $CDCl_3$ solution containing the catalyst and one equivalent of EDA. Already at the start, two different carbene signals could be detected: the usual benzylidene carbene deriving from the Grubbs I catalyst and a new signal at 17.128 ppm (Fig. 4). Also, it was observed that the reaction proceeded much slower, as compared to the FT-IR kinetic measurements.

When fresh amounts of EDA were added to the sample, both signals disappeared in time. What is more, when 50 equiv. of EDA

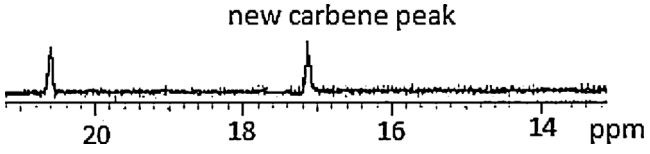


Fig. 4. ^{1}H NMR of EDA decomposition induced by catalyst **5**.

(instead of 1 equiv. as in Fig. 4) were initially introduced no carbene signals were noticed, at any time. Possibly, several carbene species are implied: at low EDA concentration the benzylidene carbene is gradually replaced by a second carbene fragment (δ = 17.128 ppm), whereas at high EDA concentrations a distinct, very reactive carbenoid species is formed. Therefore, deviations observed in FTIR measurements at initial stages of EDA decomposition (Fig. 1) could be explained by a change in the active species when a large excess of EDA is applied.

We assume that the catalytic cycle involves first the decomposition of the diazoester, with extrusion of nitrogen gas, to afford the reactive [Ru] = CHCOOEt intermediate which is playing a role in the various channels for C—C coupling (Scheme 4). Though not detected by NMR in many investigations on cyclopropanation, intervention of this ß-carbonyl-carbene entity is widely accepted. This species is known to be quite unstable, even in solution at low temperature, and to decompose rapidly as compared with the Ru alkylidene complexes of unfunctionalised olefins, yet to be a highly active metathesis promoter [19].

The selectivity in cyclopropanation products found in this study could be accounted for by two main mechanistic pathways [4c,6b]. They imply essentially the carbene transfer from the [Ru] = CHCOOEt carbene to styrene *via* either a carbenoid pathway (A) or/and a coordination pathway (B) (Scheme 4).

As inferred from previous data [4c], in the carbenoid pathway formation of the cyclopropane moiety involves a late, unsymmetrical transition state A-I with build-up of a positive charge at the most distant carbon atom of styrene. Taking into account the 16-electron configuration of our phosphine Ru complexes the carbenoid mechanism, triggered immediately after dissociation of one phosphine, seems to be the favoured pathway. Obviously, for sterical reasons, C—C coupling in the transition state A-I occurs predominantly towards the *trans* diastereoisomer.

On the other hand, in the coordination mechanism (path B), both the olefin and the CHCOOEt carbene coordinate at the metal. Therefore, the catalyst must provide two coordination sites, easily accessible through ligand dissociation within our 18- or 16-electron Ru complexes which contain either two displaceable phosphines (**1**, **4**, **5**, **10**) or a *p*-cymene (**2**, **3**, **9**). Thus, highly reactive, coordinatively unsaturated 14- or 12-electron Ru species may arise. However, the steric configuration imposed by the Schiff-base and NHC ligands in our Ru complexes might sometimes impede simultaneous coordination of both the olefin and the carbene moiety favouring instead the alternative carbenoid pathway (A), hence cyclopropanation. As soon as the complex B-I is formed, it rearranges to the ruthenacyclobutane complex B-II which, by reductive elimination of the Ru fragment provides substituted cyclopropanes (*trans*- and *cis*-1-carbethoxy-2-phenylcyclopropane) or, by [2 + 2] cycloreversion gives the metathesis products (*trans*- and *cis*-ethylcinnamate). Because in our experiments the *cis*- and *trans*-cinnamic esters were detected by GC only in trace amounts, pathway B-b_2 seems disfavoured. Indirect support for formation of distinct carbene species in the routes directing to cyclopropanation (A, B-b1) comes from a study with the Grubbs I catalyzed tandem enyne metathesis-cyclopropanation where the Ru-complex **5** is modified *in situ* by the diazoester to form a cyclopropanation active catalyst that no longer promotes metathesis [6b]. Competing in the overall mechanistic scheme, the carbenoid pathway (C, involving a highly reactive transition state C-I and the intermediate complex C-II) and the coordination pathway (D) can respectively explain the formation of C—C coupling products (maleic and fumaric esters) and metathesis products (*cis*- and *trans*-stilbene). The commonality in this ensemble is the intermediacy of the ß-carbonyl-carbene species [Ru] = CHCOOEt. Although also our ^{1}H NMR experiments (Fig. 4) could not detect the real occurrence of the carbene Ru = CHCOOEt, the high cyclopropanation yields obtained with the new catalysts, **4** and **10**, suggest generation of this unstable metalcarbene in both the carbenoid and the coordination mechanisms.

3. Experimental

3.1. Synthesis of catalysts *4* and *10*

Catalysts **1**, **2**, **5**, **6** are commercially available and were used without further purification. The ruthenium complexes **3** [10], **7** [13], **8** [13] and **9** (*in situ*) [2c] were synthesized according to literature procedures as shown in Scheme 3.

Synthesis of the new ruthenium promoters **4** and **10** was carried out in this work. For the synthesis of complex **4** a THF solution of the thalium salt of the Schiff base ligand [20] was added the equivalent amount of $Cl_2Ru(PPh_3)_3$ and the mixture stirred overnight at room temperature. After work-up [11b,20] the solid residue was dissolved in a minimal amount of toluene, reprecipitated with pentane, filtered off, briefly washed on the funnel with pentane and dried *in vacuo* to afford an orange-brown powder (78% yield) which was stored under inert atmosphere. ^{1}H NMR (300 MHz, $CDCl_3$): δ 2.36 [s, 3H, CH_3]; 7.10–7.80 [m, 34H, aryl-CH]; 9.95 ppm (s, 1H, aldimine ligand).

Catalyst **10** was obtained by adding to1,3-bis(2,6-diisopropylphenyl)imidazolinylidene (*in situ* prepared in THF) [3c] one equivalent of $Cl_2Ru(PPh_3)_3$. The reaction mixture was refluxed in THF with stirring for 1 h, then cooled down and the solid materials filtered off. The filtrate was concentrated *in vacuo*, the residue solved in a minimal amount of toluene, reprecipitated with pentane and then handled as above for complex **4** to give a dark-brown powder. Isolated yield: 81%. ^{1}H NMR (300 MHz, $CDCl_3$): δ 1,25 [d, 24H, $CH(C\underline{H}_3)_2$]; 2,93 [m, 4H, $C\underline{H}(CH_3)_2$], 3.65 ppm (m, 4H, $C\underline{H}_2$).

4. FTIR measurements

Kinetic measurements on the decomposition of diazoacetate in the presence of the Ru catalysts **1**–**10** were performed using a Brucker FT-Raman/FT-IR spectrometer with a Nernst glowing element as the IR source and a DTGS detector. The flow-through IR-cell consists of KBr windows with a 2 mm inner separation. The following operations were carried out in a typical FT-IR experiment. From a preliminary prepared solution, with precise concentration, of the catalyst in freshly distilled toluene, 3 μmol of catalyst were transferred under continuous Ar-flow to an empty 15 ml vessel. The solvent was evaporated under vacuum giving a small amount of solid catalyst. Then 12 ml of extra dry toluene was added to adjust concentration at a predetermined value. For experiments also using an olefin substrate, 4 mmol of olefin were usually added. The vessel was sealed with a septum and stored at −18 °C. Just before the experiment the vessel was introduced into a heating block to reach the desired temperature and 400 μmol EDA were added all at once by a syringe. A needle was inserted through the septum to prevent pressure building. The reaction mixture was circulated through the IR cell in a closed circuit by use of a peristaltic pump. All measurements were performed by following the (N≡N) stretch vibration at 2110 cm^{-1}. Each experiment was repeated at least 5 times. All spectra were normalized to the solvent, integrated and correlated to the concentration by means of a calibration curve.

5. GC measurements

To determine the yield and chemoselectivity in cyclopropanation, capillary GC measurements were performed using a Varian CDS 401 with a Supelco 5DB-24030 capillary column and a FID detection system.

In a typical GC experiment the following operations were undertaken: from a preliminary prepared solution of catalyst in freshly distilled toluene, with known concentration, 2.5 μmol of catalyst were transferred under Ar-flow to an empty 15 ml vessel. The solvent was evaporated *in vacuo* affording a small amount of solid catalyst. Styrene (10 mmol) was next added. EDA (1 mmol) was dissolved in styrene (10 mmol), cooled to 0 °C and the solution added very slowly, at 0 °C (over 4 h, using a peristaltic pump) to the above reaction mixture. After addition of a few drops of the EDA solution, the mixture was heated to the reaction temperature and kept at this temperature overnight. Before GC-analysis, the reaction mixture was passed through a celite filter in order to remove the catalyst. Celite was washed with 20 ml toluene/EtOAc (1/1). The composition of the reaction mixture was determined by GC using authentic samples and diethyl adipate as internal standard.

6. Conclusions

The contrasting outcome observed in intermolecular carbenoid transfer to styrene, catalyzed by different Ru complexes, demonstrated that chemoselectivity in concomitant cyclopropanation, metathesis and dimerisation depends on the Ru catalyst, the kind of its ligands and also on the reaction conditions. The new NHC-Ru complex **10** and the Fischer carbene **7** were proved as most suitable for cyclopropanation (84–85% selectivity), under low catalyst loadings and a large excess of substrate. The Schiff-base ligated complex **4** gave an excellent yield but unimpressive selectivity for cyclopropanation whereas an equal balance between cyclopropanation and dimerisation was found for catalysts **2** and **9**. Therefore, in spite of the competing side-reactions, the right choice of the Ru catalyst can direct mainly to the desired process.

An unexpected behaviour was evidenced for the Grubbs I metathesis catalyst manipulated towards prevailingly cyclopropanation (82%) by using still higher substrate ratios, at a lower temperature. However, for its second generation counterpart (**6**) only metathesis was observed. Data obtained with our Ru promoters could be rationalized assuming a complex mechanistic scheme, implying carbenoid and/or coordinative pathways and distinct catalytically active species in the competing C—C coupling channels considered.

Acknowledgements

F.D. and Y.S. acknowledge the support of the Shenyang Institute of Chemical Technology, Shenyang, PR China. F.V. acknowledges the Chinese Central Government for an “Expert of the State” position in the program of “Thousand talents” and is indebted to FWO-Flanders (project grant Number 3G022912), Ministry of Science and Technology of PR China (Project No 41-24) and the Wuhan University of Technology for financial support during elaboration of this work. I.D. and V.D. thank FWO-Flanders for financial support. Assistance from the Institute of Organic Chemistry, C.D. Nenitzescu” of the Romanian Academy and the Ministry of National Education – UEFISCDI (Contract No 727/2013) are also gratefully appreciated.

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