Nickel-catalyzed cyclization of α,ω-dienes: formation *vs.* cleavage of C–C bonds†

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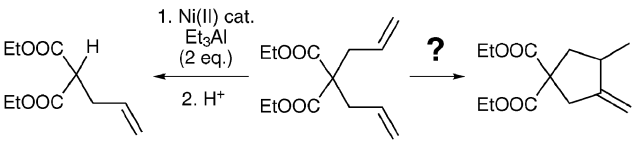
A combination of a catalytic amount of a Ni–phosphine complex and triethylaluminium or chlorodiethylaluminium is able to selectively cyclize a number of 1,7-heptadienes to methylidene (methyl)cyclopentanes and cyclopentenes even in cases where the dienes are prone to deallylation.

C–C bond formation and its reverse process, C–C bond cleavage, are two interrelated reactions often sharing the same intermediates at certain stages of the reaction mechanism. A particular challenge is to design catalysts or catalytic systems that are able to catalyze both processes depending on the reaction conditions. Iridium hydrides may serve as a typical example of the above mentioned catalysts. They catalyze conjugate[1] as well as retro-conjugate addition.[2] In this regard it is of considerable theoretical as well as practical interest to develop or find other catalytic systems whose selectivity for C–C bond cleavage or formation could be controlled by a simple change in the reaction conditions. Herein we would like to report that a nickel–organoaluminium catalytic system depending on its Ni : Al ratio is able to switch the course of the reaction from C–C bond cleavage to C–C bond formation in diallylmalonates and related compounds.

Recently we have reported that allylmalonates of the $(EtOOC)_2CR(allyl)$ type underwent facile deallylation to monosubstituted malonates through cleavage of the C–C bond in the presence of a catalytic amount of a nickel or other transition metal complex and 2 equiv. of Et_3Al.[3,4] We proposed that the catalytically active species was a Ni hydride formed upon the reaction of the Ni(II) complex with triethylaluminium.[4] On the other hand, it is well established that Ni hydrides generated *in situ* by various methods are catalytically active species for the cyclization of α,ω-dienes to cyclopentane derivatives.[5–8] In this regard, our main objective was to look for catalytic conditions that would change the course of the reaction from C–C bond cleavage (deallylation) to C–C bond formation (cyclization) by using the Ni(II)–Et_3Al system in diallylmalonates (Scheme 1). Our second aim was to develop a practical and cheaper protocol for the cyclization of α,ω-dienes.

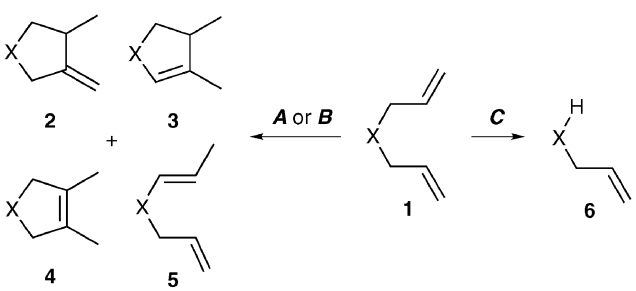


Scheme 1 Deallylation in the presence of Ni complexes.

During our recent study of deallylation reactions under rhodium catalysis it became obvious that the role of Et_3Al was not only to generate a metal hydride species from the corresponding metal halides, but also to activate the carbonyl group[9] *via* Lewis acid–base pairing and thus to enhance the C–C bond cleavage. In this regard it seemed reasonable to reduce the content of Et_3Al to the amount sufficient just to generate the Ni hydride and thus avoid its competitive coordination to the carbonyl group and promoting the deallylation.

Initially, various molar ratios of Ni(II) complexes and Et_3Al or Et_2AlCl were tested to find the best reaction conditions and selectivity for the formation of cyclopentanes. Two candidates emerged as potentially useful catalytic systems *A* ($NiBr_2(PPh_3)_2$, 5 mol%–Et_3Al, 20 mol%) and *B* ($NiBr_2(PBu_3)_2$, 5 mol%–Et_2AlCl, 20 mol%). Both systems had high selectivity for the formation of cyclopentanes **2**, **3** and **4**, but differed in their distribution. In some cases the results of cyclization were compared with deallylation conditions *C* ($NiBr_2(PBu_3)_2$, 5 mol%–Et_3Al, 200 mol%) to give products **6** (Scheme 2).

Dienes were divided into two groups: those that could undergo deallylation (**1a–h**) and those that could not (**1i–l**).



Scheme 2 Cyclization of dienes **1** to cyclopentane derivatives.

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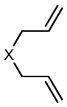
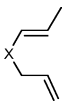
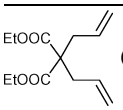
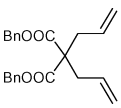
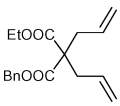
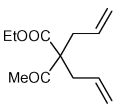
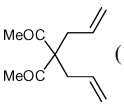
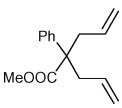
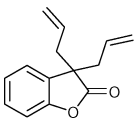
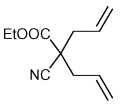
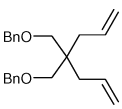
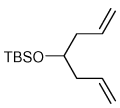
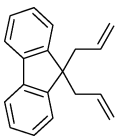
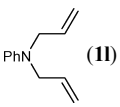
Table 1 Ni-complex catalyzed reaction of dienes **1**

Diene **1**			**2** (%)[a]	**3** (%)[a]	**4** (%)[a]	**5** (%)[a]	**6** (%)[a]
	Conditions	*t*/h					
 (**1a**)	*A*	36	**2a** 37	**3a** 18	**4a** 6		
	B	1	**2a** 92				
	C	1					**6a** 71[b]
 (**1b**)	*A*	48	**2b** 18				
	B	1	**2b** 75				
 (**1c**)	*A*	48	**2c** 9[c]	**3c** 15[d]			
	B	1	**2c** 91				
 (**1d**)	*A*	3	—[e]				
	B	1	**2d** 60				
	C	1					—[e]
 (**1e**)	*A*	3	—[e]				
	B	1	**2e** 28				
 (**1f**)	*A*	27	**2f** 33	**3f** 6[d]	**4f** 6[d]		
	B	1	**2f** 94[d]				
	C	1					—[e]
 (**1g**)	*A*	3	**2g** 47				
	B	1	**2g** 93[f]				
	C	1					**6g** 94
 (**1h**)	*A*	3				**5h** 2	
	B	1	**2h** 30[g]			**5h** 16	
	C	1					**6h** 60
 (**1i**)	*A*	3	**2i** 37	**3i** 15			
	B	1	**2i** 29	**3i** 65			
 (**1j**)	*A*	3	**2j** 71[g]				
	B	1	**2j** 51[f]		**4j** 44		
 (**1k**)	*A*	3	**2k** 85				
	B	1		**3k** 72	**4k** 26		
 (**1l**)	*A*	24	**2l** 47				
	B	36	**2l** 93				

[a] GC and ^{1}H NMR yields. [b] Propylmalonate 29%. [c] Structure confirmed by GC and ^{1}H NMR in the reaction mixture. [e] Complex reaction mixture. [d] Unidentified compound (12%). [f] Dr 5 : 1. [g] Dr 3 : 2.

As for the catalytic systems *A* and *B*, they comparison showed that the latter was more efficient in terms of reaction rate and selectivity (Table 1). Thus the cyclization of allylmalonates **1a–1c** (entries 1–3) proceeded with good selectivity for methylidene(methyl)cyclopentanes **2a–2c** (75–92%) under condition *B*. By using condition *A* a mixture of positional isomers **3** and **4** in rather low yields was usually formed. The cyclization of **1a** was also run with $NiBr_2$(dppm), $NiBr_2$(dppe), $NiBr_2$(dppp), and $NiBr_2$(dppb) in a combination with Et_2AlCl to assess catalytic activity of other complexes. However, the yields of **2a** were rather poor (2%, 18%, 12%, and 1%, respectively). Reactions with the substrates bearing a keto group **1d** and **1e** (entries 4 and 5) furnished medium to low yields of **2d** (60%) and **2e** (28%) (condition *B*). Complex reaction mixtures were obtained under condition *A*.

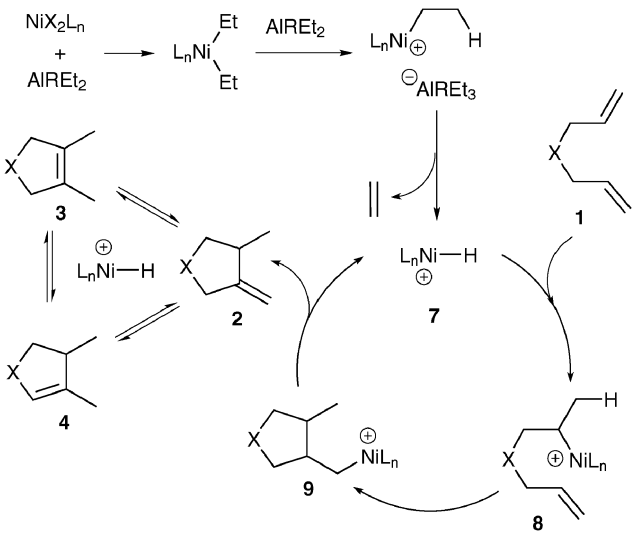
The cyclization of diallylphenylacetate **1f** and diallylcoumaranone **1g** proceeded almost quantitatively under condition *B* to **2f** (94%) and **2g** (93%). By using condition *A* the yields of **2f** and **2g** were 33% and 47%, respectively. The cyclization of diallylcyanoacetate **1h** to **2h** proceeded in rather low yield (30%) only under condition *B* and it was accompanied by double bond migration giving allylpropenylcyanoacetate **5h** in 16% yield.

The cyclization of ethers **1i** and **1j** proceeded in high yields (condition *B*) to give mixtures of **2i** (29%) and **3i** (65%), and of **2j** (51%) and **4j** (44%). Although the overall yields of cyclized products were lower under condition *A*, higher selectivity for methylidenemethylcyclopentanes **2i** (37%) and **2j** (71%) was observed. Similarly the cyclization of diallylfluorene **1k** afforded 85% of **2k**, whereas under condition *B* only the cyclopentene derivatives **3k** (72%) and **4k** (26%) were formed. High selectivity for the formation of the pyrrolidine derivatives **2l** (71%) was observed under condition *B*.

Results obtained with the catalytic system *C* with compounds **1a**, **1d**, **1f**, **1g**, and **1h** are presented for comparison. They clearly demonstrate that when excess of triethylaluminium (200 mol%) was used clean deallylation proceeded to furnish compounds **6a**, **6g** and **6h**. On the other hand, in the case of **1d** and **1f** complex reaction mixtures were formed.

The proposed mechanistic rationale for the Ni-catalyzed cyclization is presented in Scheme 3. It is initiated by alkylation of the Ni(II) complex and results probably in a dialkylnickel compound, reaction of which with the present organoaluminium followed by β-hydrogen elimination gives the cationic Ni hydride **7**. (The cationic Ni species are formed upon the reaction with alkylaluminiums.[10,11]) Then **7** hydrometalates the double bond to give the *sec*-alkylnickel intermediate **8**. This intermediate is the result of anti-Markovnikov addition to the terminal double bonds and is typical for late transition metal hydrides.[12] Then intramolecular addition to the second double bond furnishes the alkylnickel compound **9**. β-Hydrogen elimination releases **7** back into the catalytic cycle and yields the cyclopentane derivative **2**. Repetitive addition and elimination of the Ni hydride **7** accounts for the observed migration of the double bond giving rise to **3** and **4**. Migration of the double bond from **1f** to the propenyl derivative **5f** can be explained by the same reaction mechanism.

Comparison of the two processes, deallylation[4] and cyclization, indicates that they share the common intermediate **8**.



Scheme 3 Proposed reaction mechanism for Ni hydride catalyzed cyclization of dienes.

However, in the case of the reaction of diallylmalonates and similar compounds the crucial moment for the further course of the reaction depends on the amount of organoaluminium present. In excess it also coordinates to the carbonyl group and promotes deallylation.[4,9] When organoaluminium is used in an amount sufficient to generate just the cationic Ni hydride, preferential intramolecular addition of the intermediate **8** to the second double bond takes place to give intermediate **9**.

In conclusion, we have shown that it is possible to re-route the course of the reaction from C–C bond cleavage (deallylation) to C–C bond formation (cyclization) in Ni hydride catalyzed reactions by a change in the amount of organoaluminium. It proceeded in high yields even in cases where deallylation could compete with cyclization (*e.g.* diallylmalonate, *etc.*) in high selectivity. In addition, generation of Ni hydride species *in situ* provides an effective means for fast and selective cyclization of variously substituted 1,6-heptadienes to cyclopentanes. In addition by the appropriate choice of the organoaluminium (Et_3Al or Et_2AlCl) certain levels for the preferential formation of methylidenemethylcyclopentanes or cyclopentenes could be achieved.

Experimental

Typical procedure for the cyclization reaction: to a solution of a diene (**1a–1l**) (0.5 mmol) in dry toluene was added $NiBr_2(PBu_3)_2$ (15.6 mg, 0.025 mmol) (3 mL) and 1.8 M solution of Et_2AlCl in toluene (55 μL, 0.1 mmol) (cond. ***B***) or $NiBr_2(PPh_3)_2$ (18.6 mg, 0.025 mmol) and 1.9 M solution of Et_3Al in toluene (53 μL, 0.1 mmol) (cond. ***A***) under argon. The reaction mixture was stirred at 20 °C for 1 or 3 h, respectively. After that it was quenched with a portion of water (1 mL) followed addition of a 3 M solution of HCl (3 mL). The organic layer was separated and dried ($MgSO_4$). The products were isolated by HPLC (silica gel, hexane–EtOAc).

Acknowledgements

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