

Cycloaddition of electron-deficient olefins to norbornadiene in the presence of nickel bisphosphine systems*

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[2+2+2] Cycloaddition of electron-deficient olefins to norbornadiene in the presence of nickel bisphosphine catalysts was studied. The influence of the bisphosphine structure on the regio- and stereoselectivity of the reaction as well as on the yields of the reaction products was investigated. New evidence for the influence of chiral bisphosphine ligands on the enantioselectivity of the reaction was obtained.

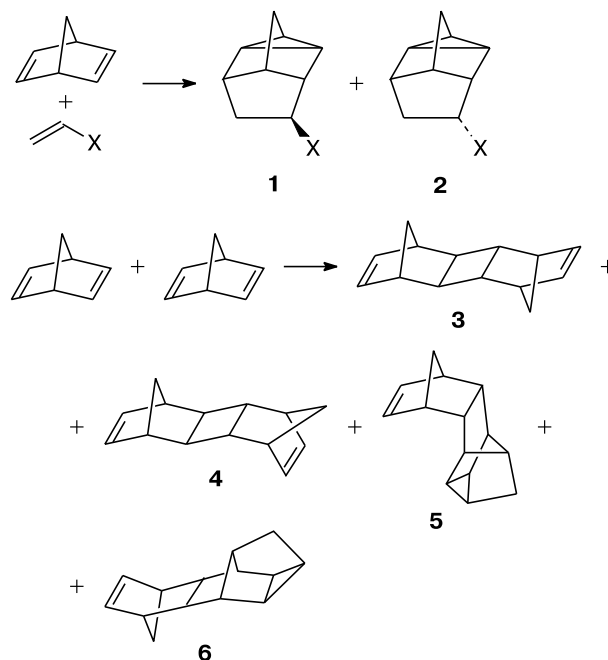
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Catalytic [2+2+2] cycloaddition of norbornadiene (NBD) to electron-deficient olefins provides a single-step route to not easily accessible polycyclic compounds.^{1,2} A great variety of ways in which NBD and an olefin can be coordinated to a transition metal atom allow such processes to follow many pathways.³ Of prime importance are relative positions of substrates in key reaction intermediates and the possibility of regulating these positions. This should be kept in mind when developing a synthetic strategy because the isomerism of the target products and the selectivity of the whole process are both concerned.

In catalytic systems consisting of bis(η^3 -allyl)nickel and NBD, disproportionation of the allyl ligands is known⁴ to give norbornadiene complexes of Ni⁰. Earlier, we have demonstrated that reactions of NBD with acrylic acid esters in the presence of this catalytic system afford *exo*- and *endo*-[2+2+2] cycloadducts **1** and **2** (Scheme 1),^{5,6} with NBD homodimers **3–6** as possible by-products.

Addition of various phosphine ligands has a dramatic effect on the reaction outcome. Phosphine ligands can displace other ligands, thereby filling one or more coordinative vacancies of the Ni atom.^{7,8} For instance, the use of a catalytic system with the molar ratio PPh₃ : Ni = 1 : 1 almost completely suppresses the formation of NBD homodimers and substantially changes the stereochemical course of the codimerization.^{1,9} For P : Ni > 1, the rate of the reaction drops (its nearly complete suppression is achieved at P : Ni = 2 : 1). Interestingly, the action of bisphosphine ligands L at L : Ni = 1 : 1 differs from that of monophosphines in a ratio of 2 : 1. Data on the influence

Scheme 1



of bisphosphine ligands on the stereoselectivity of the reaction are virtually lacking.

Phosphines containing chiral centers can make [2+2+2] cycloaddition enantioselective.¹⁰ We found it interesting and important to study reactions of NBD with acrylic acid esters in the presence of such ligands.

The goal of this work was to investigate reactions of norbornadiene with acrylic acid esters in the presence of various bisphosphine ligands and theoretically estimate

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the relative stability of plausible key intermediates of this process.

Experimental

Bis(η^3 -allyl)nickel employed as a nickel source was prepared according to a standard procedure.¹¹

Reagents and the solvent (toluene, special purity grade) were distilled under reduced pressure immediately before use.

An evacuated static 10-mL reaction vessel was charged with the starting materials and the solvent in calculated amounts. Dissolved oxygen was removed by three sequential freezing (liquid nitrogen)—thawing cycles, whereupon a weighed sample of bis(η^3 -allyl)nickel was transferred *in vacuo*. The reaction vessel was filled with high-purity argon (residual oxygen content < 10⁻⁴%) and kept at a required temperature. The reaction was carried out at 50 °C for 12 h. After completion of the reaction, the catalytic system was decomposed by passing air through the resulting solution. Soluble products and the solvent were separated from the decomposed catalyst by filtration through a short column of silica gel. The filtrate was concentrated on a rotary evaporator *in vacuo* and analyzed by gas chromatography on a Kristall 2000 M chromatograph (flame ionization detector, Zebron ZB-5 capillary columns, a Supelco β -DEX enantioselective column).

Quantum chemical calculations were performed in terms of the density functional theory (DFT) with the Priroda program.¹² The *ab initio* exchange-correlation functional PBE¹³ and the TZ2P basis set were used. The main sets of Gaussian-type functions were as follows (primitive/contracted): (5s1p)/[3s1p] for the H atom, (11s6p2d)/[6s3p2d] for the C atom, and (17s13p8d)/[12s9p4d] for the Ni atom. Earlier, this procedure has been employed for quantum chemical modeling of the catalytic cyclo-dimerization of NBD.¹⁴

Every molecular geometry was optimized without symmetry constraints. The type of stationary points (local minimum or transition state) was determined by calculating the second-order derivatives of the energies and frequencies of normal modes. The Gibbs energies ΔG_{323} of the intermediates were calculated for the experimental temperature (323 K).

Results and Discussion

First, we studied the influence of the structure of bisphosphine ligands on the general trends and stereoselectivity of the [2+2+2] cycloaddition of NBD to methyl acrylate (MA). We employed bis(1,1-diphenylphosphino)methane (dppm), bis(1,2-diphenylphosphino)ethane (dppe), bis(1,3-diphenylphosphino)propane (dppp), and bis(1,4-diphenylphosphino)butane (dppb) as ligands. The data obtained are given in Table 1.

All the above bisphosphine ligands at L : Ni = 1 : 1 proved to completely suppress the formation of NBD homodimers. With dppm and dppe as ligands in the catalytic system, the yields of the cycloadducts were 12 and 15%, respectively; the use of dppp and dppb provides very low yields of the products.

Quantum chemical modeling of plausible intermediates in the cycloaddition reactions of olefins with NBD

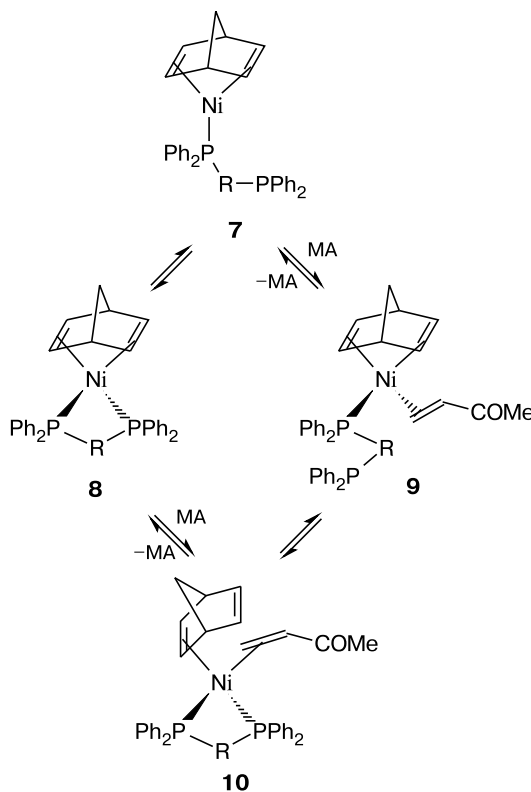
Table 1. Influence of the structure of the bisphosphine ligand L on the ratio of products in the reaction of NBD with MA in the presence of Ni(C₃H₅)₂*

L	Ratio of cycloadducts (%)		Yields of products (%)
	1	2	
dppm	71	29	12
dppe	31	69	15
dppp	43	57	0.8–0.9
dppb	52	48	0.3–0.5

* Conditions: toluene as a solvent, [MA]₀ : [NBD]₀ : [Ni(C₃H₅)₂]₀ = 20 : 20 : 1, L : Ni = 1 : 1, 50 °C, 12 h.

elucidated why the yields of the products depend on the bisphosphine structure. We considered nickel complexes **7–10** (Scheme 2) containing bis(diphenylphosphino)alkanes, NBD, and MA as ligands. The Gibbs energies of all the calculated complexes relative to the sum of the energies of the individual molecules of **7** and MA are given in Table 2. The scatter of the ΔG_{323} values for complexes **9** and **10** is due to the coexistence of several conformers.

Scheme 2



It can be seen in Table 2 that the bidentate coordination of the bisphosphine ligand makes a two-ligand com-

Table 2. Relative Gibbs energies ($\Delta G_{323}/\text{kcal mol}^{-1}$) of plausible intermediates in the cycloaddition reaction of MA with NBD for different bisphosphine ligands L (see Scheme 2)

L	7	8	9	10
dppm	0.0	-20.2	-9.6 ÷ -11.5	-2.3 ÷ -2.7
dppe	0.0	-24.1	-8.2 ÷ -8.6	-2.4 ÷ -2.8
dppp	0.0	-18.1	-7.5 ÷ -10.1	3.6-4.0
dppb	0.0	-16.5	-7.8 ÷ -9.8	9.0-9.2

plex (**7** and **8**) more stable. By comparing the Gibbs energies of the two-ligand complexes with monodentate (**7**) and bidentate coordination (**8**) of the bisphosphine ligand, one can estimate the strength of the nickel—bisphosphine bond. According to our calculations, the dissociation energy of this bond changes in the decreasing order $\text{dppe} > \text{dppm} > \text{dppp} > \text{dppb}$.

Comparison of the Gibbs energies of three-ligand complexes **9** and **10** shows that the monodentate coordination of the bisphosphine ligand is thermodynamically more favorable here. The noticeable increase in the Gibbs energy for complex **10** with the ligand size can be associated with the increasing steric effect on the neighboring ligands. Thus, the sequence $\text{dppe} > \text{dppm} > \text{dppp} > \text{dppb}$ results from a combination of two factors: (1) the ligand—nickel bond becomes weaker, which increases the Gibbs energy of the system, and (2) the steric effect on the neighboring ligands (NBD and MA) increases. These factors are responsible for the low yields of the cycloadducts when dppp and dppb are used as ligands.

The bisphosphines dppm and dppb favor the formation of the *exo*-cycloadduct (**1**), the ratio of **1** : **2** being 71 : 29 for dppm. This ratio is much higher than those achieved through the use of PPh_3 (**1** : **2** = 51 : 49 for PPh_3 : Ni = 1 : 1 and **1** : **2** = 53 : 47 for PPh_3 : Ni = 2 : 1).⁶ This is probably due to a larger cone angle at the P atom in dppm. In contrast, the cycloaddition catalyzed by the Ni complexes with dppe and dppp mainly produces stereoisomer **2**. Interestingly, the use of dppb affords a mixture of *exo*- and *endo*-products in the same ratio as in the presence of an equimolar amount of PPh_3 .

To estimate the influence of the bisphosphine ligands L on the selectivity of the cycloaddition reaction, we employed dppm and dppe because they provide the maximum yields of the products. Data on the influence of the molar L : Ni ratio are summarized in Table 3.

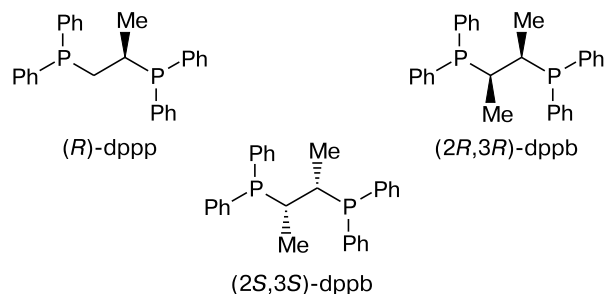
When the dppe : Ni ratio was varied from 0.5 to 1, the yields of the products were 15–20%. These values are much lower than those achieved in the presence of catalytic systems modified with triphenylphosphine ligands; in addition, the reaction proceeds nonselectively. The formation of NBD homodimers is completely suppressed only at dppe : Ni = 1 : 1. The yields of cycloadducts obtained with dppm as a ligand were 12–14%.

Table 3. Influence of the molar ratio of the bisphosphine ligand L to nickel on the yields of the products (*Y*) and on the selectivity of the reaction of NBD with MA*

L	L : Ni	Ratio (%) of				<i>Y</i> (%)
		products		cycloadducts		
		1+2	3+4+5+6	1	2	
dppm	0.5	100	0	63	37	14
	0.75	100	0	68	32	12
	1	100	0	71	29	12
dppe	0.5	89	11	21	79	20
	0.75	92	8	27	73	15
	1	100	0	31	69	15

* Conditions: toluene as a solvent, $[\text{MA}]_0 : [\text{NBD}]_0 : [\text{Ni}(\text{C}_3\text{H}_5)_2]_0 = 20 : 20 : 1$, 50 °C, 12 h.

To study the enantioselectivity of the cycloaddition reaction of methyl acrylate with NBD, we used the chiral bisphosphine ligands (*R*)-dppp, (*2R,3R*)-dppb, and (*2S,3S*)-dppb.



The reaction was carried out for the bisphosphine ligand : Ni = 1 : 1. The normalized (to 100%) ratios of different groups of isomers are given in Table 4.

According to the data obtained, the chiral bisphosphines facilitate the formation of *endo*-isomer **2** rather than *exo*-isomer **1**. The low yields of the products agree with those achieved when achiral dppp and dppb were

Table 4. Ratio of the stereoisomers and enantiomers in the reaction of NBD with MA in the presence of $\text{Ni}(\text{C}_3\text{H}_5)_2$ and various chiral bisphosphines L (*R* : *S*)^a

L	Ratio (%) of				<i>Y</i> ^b (%)
	cycloadducts		enantiomers		
	1	2	(<i>R</i>)-1 : (<i>S</i>)-1	(<i>R</i>)-2 : (<i>S</i>)-2	
(<i>R</i>)-dppp	25	75	53 : 47	42 : 58	8
(<i>2R,3R</i>)-dppb	28	72	57 : 43	45 : 55	2
(<i>2S,3S</i>)-dppb	32	68	47 : 53	54 : 46	1

^a Conditions: toluene as a solvent, $[\text{olefin}]_0 : [\text{NBD}]_0 : [\text{Ni}(\text{C}_3\text{H}_5)_2]_0 = 20 : 20 : 1$, L : Ni = 1 : 1, 50 °C, 12 h.

^b *Y* is the yield of the reaction products.

Table 5. Ratio of the stereoisomers and enantiomers obtained in the reaction of NBD with MA^a for different (2*R*)-dppp : Ni ratios

L : Ni	Ratio (%) of			Y ^b (%)
	cycloadducts	enantiomers (<i>R</i>) : (<i>S</i>)		
		1 : 2	1	
0.25 : 1 ^c	45 : 55	49 : 51	49 : 51	16
0.5 : 1	26 : 74	49 : 51	35 : 65	10
1 : 1	25 : 75	53 : 47	42 : 58	8
1.5 : 1	—	—	—	—

^a Conditions: toluene as a solvent, [olefin]₀ : [NBD]₀ : [Ni(C₃H₅)₂]₀ = 20 : 20 : 1, 50 °C, 12 h.

^b Y is the yield of the reaction products.

^c NBD homodimers 3–6 are detected (up to 9% yield).

employed. This cycloaddition reaction was always slightly enantioselective (see Table 4), giving (*R*)-**1** and (*S*)-**2** (for the phosphines with the (*R*)-configuration) and (*S*)-**1** and (*R*)-**2** as predominant products (for the phosphines with the (*S*)-configuration). This outcome does not depend on the alkyl chain length in the phosphine.

The influence of the amount of chiral phosphine on the selectivity of the cycloaddition was studied with (*R*)-dppp as an example. The data obtained are given in Table 5.

One can see that with an increase in the amount of the chiral bisphosphine, the total yield of the products decreases, as with the achiral bisphosphines. The formation of NBD homodimers occurs at L : Ni ≤ 1 : 4 and is suppressed at higher L : Ni ratios. For L : Ni = 1.5 : 1, no cycloaddition occurs at all.

To sum up, our studies and quantum chemical calculations of the most plausible intermediates of the cycloaddition reaction revealed that the low yields of the cycloadducts obtained in the presence of the Ni complexes with dppp and dppb can be due to appreciable weakening of the nickel–bisphosphine bond as well as to the growing steric

effects of these ligands. The use of chiral bisphosphines affords nonracemic products with a moderate enantiomer excess.

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