Kinetic and Modeling Studies on the Nickel-Catalyzed Homo-Diels−Alder Addition of 7-Substituted Norbornadienes

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Pseudo-first-order rate constants have been determined for several 7-substituted norbornadienes in their nickel-catalyzed homo-Diels−Alder cycloaddition with methyl vinyl ketone. The rate of reaction was slightly influenced by the nature of the substituent. Relative reactivities followed the order 7-Ph > H > 7-OTIPS. The observed activation parameters ($\Delta H^{\ddagger} = 15-18$ kcal/mol; $\Delta S^{\ddagger} = -19$ to -24 cal/mol K) were also affected by the 7-substituent and are in good agreement with those established for reductive elimination from related nickel phosphine complexes. With regard to regioselectivity, the more reactive norbornadiene was also the less selective. Force field modeling studies of possible organonickel intermediates suggest that the preferred exo selectivity arises from steric interactions between the dienophile substituent and the phosphine ligands. Good qualitative and quantitative agreement with observed exo stereoselectivity was found with three of the five model systems studied. Of these three models, reasonably good agreement with regioselectivity was found with only one of them.

Introduction

The nickel-catalyzed homo-Diels−Alder reaction of norbornadienes (NBD) with electron-deficient olefins has been reported to proceed with high degrees of stereo- and even some enantioselectivity.[1,2] In contrast to the uncatalyzed process,[1c,3] the catalytic reaction affords the exo isomer predominantly, and exo/endo isomerization of the products is negligible under the reaction conditions. This stereoselectivity is influenced by the steric nature of an added phosphorus ligand[1b] and the steric bulk of the olefin substituent.[1c,4c]

More recently, the effect of 7-norbornadienyl substituents on regioselectivity in the deltacyclane product has been examined with encouraging results.[4a,b] The extent of regioselectivity is dependent upon the nature of the norbornadiene substituent and ranges from negligible (in the case of alkyl and phenyl) to extremely high (in the case of alkyl and silyl ethers). Experimental studies suggest a dominant electronic influence on the regiochemical outcome with a lesser contribution from steric factors.[4] Determination of these substituent effects is necessary to provide further insight into the control of regiochemistry and expand the scope of synthetic applications for this chemistry.

Due to the complexity of this reaction mechanism[5−7] and the current scarcity of detailed information concerning the actual nickel-bonded intermediates, we started a theoretical investigation to provide some clues for a greater understanding of this transformation. Our results of a density functional (DFT) study into the relative stabilities of proposed intermediates in the nickel-catalyzed pathway have been reported in an earlier paper.[8] In preparation for an investigation of the relevant DFT-calculated transition state energies, we carried out a kinetic study of selected 7-substituted norbornadienes to obtain relative rates and activation energies which could be used to test the reliability of the DFT predictions.

This paper reports the details of our examination of substituent-induced perturbation on the rate and activation parameters, along with related molecular mechanics calculations which attempt to assess the importance of proposed intermediate complexes to the observed regio- and stereochemical behavior of the molecule in nickel-catalyzed homo-Diels−Alder reactions. As the following results will show, steric interactions in several organonickel intermediates successfully reproduce quantitatively the observed exo/endo diastereoselectivities, but reasonable correlation with the observed anti/syn regioselectivities was found with only one of the complexes.

Results and Discussion

Homo-Diels−Alder Reaction with Methyl Vinyl Ketone. Three norbornadienes (NBD) were chosen as representative examples for neutral (Z = H), weakly regioselective (Z = Ph), and strongly regioselective (Z = OTIPS) substituents. The kinetic runs were studied in benzene-d_6 at 30−70 °C and followed to 70−94% comple-

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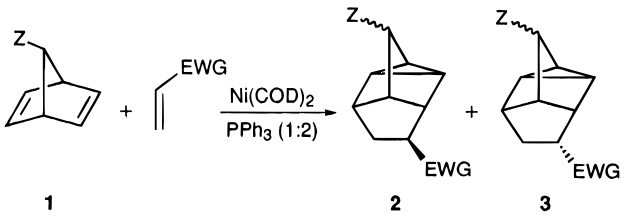
Scheme 1



1 2 3

Table 1. Reactivity and Regioselectivity Data[a,b]

Z	T (°C)	$10^3 k_{obs}$ (min^{-1})	$t_{1/2}$ (min)	A/S[c]
OTIPS				
	30	2.59 ± 0.04	268	93:7 ± 0.6
	40	7.77 ± 0.09	89	91:9 ± 0.7
	50	14.1 ± 0.4	49	87:13 ± 1
	60	40.3 ± 1.9	17	90:10 ± 1
	70	71.0 ± 3.0	10	88:12 ± 4
H				
	30	3.48 ± 0.01	199	
	40	9.29 ± 0.03	75	
	50	20.2 ± 1.0	35	
	55	41.3 ± 1.1	17	
	60	53.8 ± 1.3	13	
Ph				
	30	6.79 ± 0.2	102	
	40	18.4 ± 1.1	38	
	50	47.7 ± 3.2	15	
	60	76.6 ± 1.0	9	
	70	131 ± 5.0	5	

[a] Pseudo-first-order rate constants and anti/syn ratios were obtained from the averages of multiple kinetic runs over 2−4 half-lives in C_6D_6. $[MVK]_o = 3.5[NBD]_o$. [b] Standard deviations are of the averages. [c] Kinetic anti:syn ratios (A/S).

tion by ^{1}H NMR analysis of the disappearing norbornadiene **1** and the appearing cycloadducts (see Experimental Section for details). When heated with methyl vinyl ketone (MVK), 20 mol % $Ni(COD)_2$, and 40 mol % PPh_3 in benzene, the norbornadienes **1** proceeded to give **2**, the isomer arising from exo addition (Scheme 1).

Signals due to endo isomers (**3**) were not readily apparent in the ^{1}H NMR spectra. If endo isomers are present, their concentrations are less than 3% and could not be distinguished from noise in the base line. Anti:syn ratios could be determined only for the 7-OTIPS adduct. In the 7-phenyl adducts, all useful diagnostic signals overlapped, but it appears that the syn-exo and anti-exo 7-phenyl adducts were formed in similar amounts with slightly more of the anti-exo isomer. These results compare favorably with those earlier reported by Lautens and co-workers.[4a]

A large excess (3.5 equiv) of methyl vinyl ketone was used, and the reactions all showed clean pseudo-first-order kinetics over *ca.* 2−4 half-lives. Each run was carried out in duplicate or triplicate trials. The pseudo-first-order rate constants given in Table 1 were determined by linear least-squares regression of a plot of ln ($[NBD]_o/[NBD]_t$) versus time. Close scrutiny of the NMR data indicated that possible side reactions were not competitive under the conditions except at 70 °C with the unsubstituted norbornadiene. In this case, a new signal at δ 4.1 began to appear along with the expected ones; thus, the reaction rates were monitored at 60 °C or lower where this side reaction did not occur. At higher temperatures, there may be competition from the [2 + 2] cycloaddition manifold which is also known to be catalyzed by nickel.[1,5]

On the basis of this study, replacement of hydrogen by a 7-phenyl substituent on norbornadiene results in a slight increase in the rate of reaction whereas replacement by a 7-OTIPS group slightly decreased the rate. The relative reactivity is 7-Ph (1.93) > H (1.0) >7-OTIPS (0.75). With regard to regioselectivity, the limited data indicate that the more reactive norbornadiene is also the less selective. Nickel-catalyzed homo-Diels−Alder cycloadditions of norbornadienes are known to be irreversible; consequently, the observed regio- and stereoselection is a result of kinetically-controlled dienophile capture.

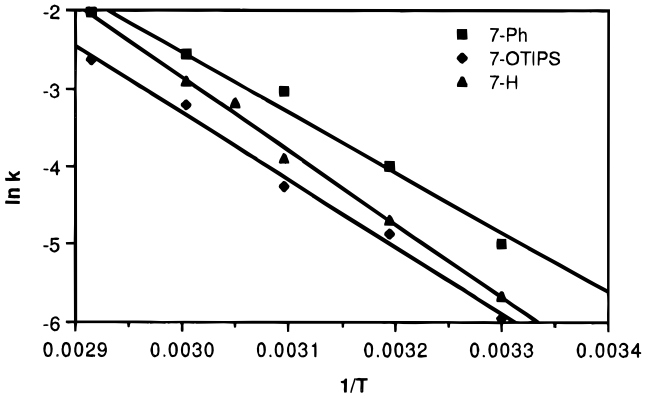


Figure 1. Plot of ln k versus $1/T$. Straight lines are from the least-squares regression.

Table 2. Arrhenius and Eyring Activation Parameters.[a]

Z	E_a	A	$\Delta H^‡$	$\Delta S^‡$	$\Delta\Delta H^‡$	$\Delta\Delta S^‡$
H	18.6	844×10^8	17.9	−18.8		
Ph	15.2	7.87×10^8	14.6	−20.0		
OTIPS	17.1	60.3×10^8	16.5	−24.1	2.6[b]	−3.6[b]

[a] Energies are given in kcal/mol. Entropies are given in cal/mol K. Arrhenius A factors are given in min^{-1}. The estimated uncertainty is ±1 kcal/mol in energy terms and ±2 eu in entropy terms. [b] The values given were determined from the intercepts and slopes of plots of ln (k_A/k_S) vs $1/T$ using the following equations: $\Delta\Delta H^‡ = \Delta H^‡_S - \Delta H^‡_A = E_a(S) - E_a(A)$ and $\Delta\Delta S^‡ = \Delta S^‡_A - \Delta S^‡_S = R \ln (A_A/A_S)$.

We investigated the influence of temperature on the reactivity to examine the substituent effect on the corresponding activation parameters. Analysis of the Arrhenius and Eyring plots (Figure 1) provided the activation parameters that appear in Table 2. By assuming the kinetic anti:syn product ratio (A/S) is equal to the ratio of the rate constants (k_A/k_S), the differences in activation parameters for syn and anti addition in the 7-OTIPS case were obtained by plots of ln (k_A/k_S) vs $1/T$.

In proposed mechanisms for this reaction, a final, irreversible reductive elimination to yield the deltacyclane product is thought to be the rate-limiting step. The relatively small enthalpies of activation and the large negative entropies of activation are of similar magnitude to those reported for reductive elimination from related nickel phosphine complexes ($\Delta H^‡ = 14-23$ kcal/mol; $\Delta S^‡ = -8$ to -21 eu).[9] Compared to norbornadiene, a substituent in the 7-position leads to a stronger interaction between reactants (decreasing $\Delta H^‡$) accompanied by tighter binding in the transition state (more negative $\Delta S^‡$). Concerning the differences in the anti/syn activation parameters for the formation of OTIPS-substituted adducts, enthalpy changes favor the anti TS while entropy changes favor the syn TS.

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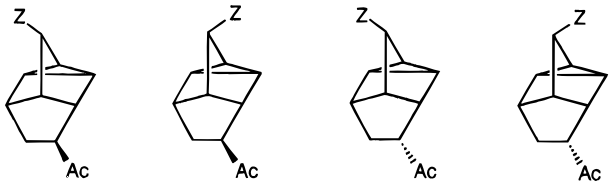
Table 3. Relative MM2 Energies and Calculated Regio-/Stereoselectivities of Deltacyclane Model[a]



anti-exo (AX) | syn-exo (SX) | anti-endo (AN) | syn-endo (SN)

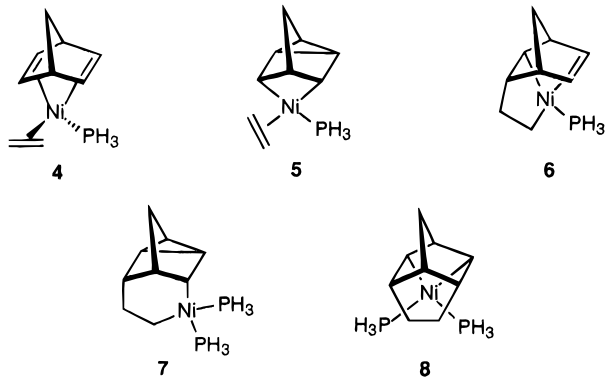
G	calcd rel energies AX	SX	AN	SN	calcd ratio (anti:syn)	calcd ratio (exo:endo)	obsd ratio (anti:syn)	obsd ratio (exo:endo)
n-hexyl	0.06	0.00	0.49	0.36	46:54	68:32	42:58	98:2
	(32)	(36)	(14)	(18)				
Ph	0.03	0.00	0.44	0.27	46:54	65:35	55:45	99:1
	(31)	(34)	(15)	(20)				
Cl	0.00	0.28	0.57	0.49	56:44	65:35	72:28	99:1
	(40)	(25)	(16)	(19)				
O_2CPh	0.30	0.00	0.69	0.55	45:55	70:30	80:20	100:0
	(27)	(43)	(18)	(12)				
OTIPS	0.00	3.38	0.61	3.49	100:0	74:26	91:9	99:1
	(74)	(0)	(26)	(0)				
OBu-t	0.02	0.00	0.55	0.55	49:51	72:28	95:5	100:0
	(35)	(37)	(14)	(14)				

[a] Relative energies given in kcal/mol. The numbers in parentheses are the predicted Boltzmann distributions of the various isomers calculated at 25 °C.

Modeling Studies. In an attempt to better understand the origins of the regio- and stereoselectivity, we first conducted MM2 calculations on the isomeric deltacyclane products. We determined the global minimum energy conformations for all reasonable isomers which included exploring all possible rotors of the particular substituent. The more thermodynamically stable exo diastereomers (according to MM2) were the major products of reaction, but there was no correlation between the steric energy differences and the observed product ratios (Table 3). Experimental results suggest a predominant electronic factor may be involved in the anti/syn regioselectivity of this reaction. The molecular mechanics models which lack explicit electronic considerations yield nearly identical energies for syn and anti isomers (except for Z = OTIPS) and as expected fail to provide any satisfactory explanation for the anti/syn regioselectivity exhibited by the 7-norbornadienyl group.

On the premise that steric interactions among one (or more) of the various proposed ground state nickel complexes might influence the exo/endo diastereoinduction of these nickel-catalyzed cycloadditions, and having no *a priori* reason to draw conclusions about the product-determining species, we chose to investigate the geometrical and conformational characteristics of all feasible nickel species (Chart 1). However any analysis is subject to the usual caveat that the catalytically active species may not be the most stable form of these complexes, but may be a less stable, more reactive form. With regard to exo/endo stereoselectivity, it is obvious that for steric reasons orientation of an olefin substituent away from the phosphine ligand would be more favorable in any of the complexes. The choice to test the possible models first for predictions of exo/endo stereoselectivity was based on the expectation that the exo/endo preference would be largely governed by steric interactions for which such molecular mechanics models are well suited. Thus, it was hoped that evaluating the complexes in this manner would clearly eliminate some of the possible structures and reduce the number of working models to be examined in the further investigations into effects of the 7-substituent.

Chart 1



Using a modified MM2 force field,[10] molecular mechanics calculations were performed on model complexes **4**−**8** with three different phosphine ligands (PH_3, PMe_3, and PPh_3) to examine how the steric bulk of the phosphorus ligand effects the predicted exo/endo stereoselectivity. To evaluate these models, the relative energies of stereoisomeric intermediates were compared to the observed stereochemical ratios. Only the global conformational minima were used to determine relative energies. The calculated differences in steric energy were taken to be an approximation of the free energy differences for these complexes and used to predict the expected ratios. In complex **7**, there was some conformational flexibility found in the ethano-linkage (arising from the original dienophile carbons). The alternate staggered conformation was predicted to be 2 kcal/mol higher in energy than the global minimum.

In models containing a triphenylphosphine ligand, the energetically preferred rotor conformations of the three phenyl rings for each type of complex were determined. The method used was to drive the dihedral angles of the individual phenyl−phosphorus bonds and the nickel−phosphorus bond through 180° (in 15° increments) to

(10) Gugelchuk, M. M.; Houk, K. N. *J. Am. Chem. Soc.* **1994**, *116*, 330.

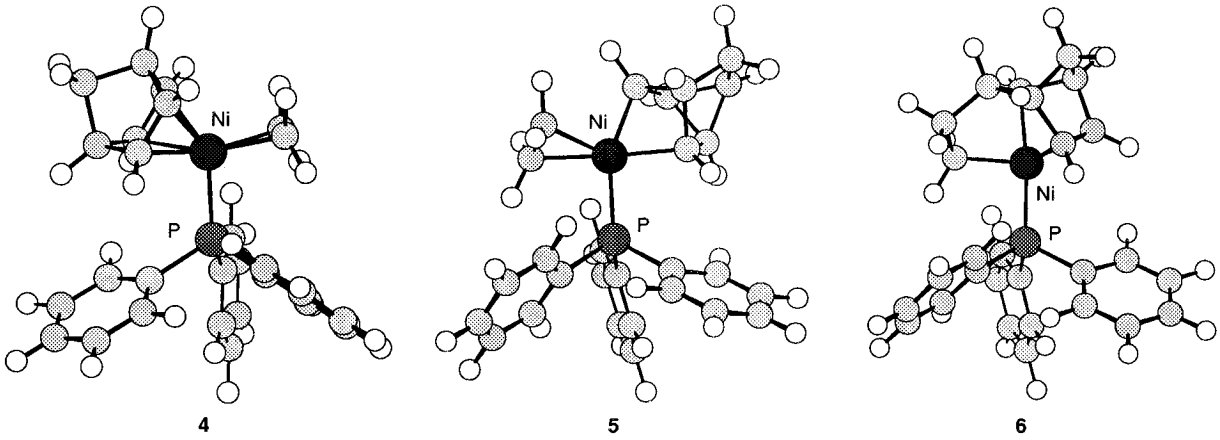


Figure 2. MM2-optimized structures of the lowest energy conformations for complexes **4**–**6**.

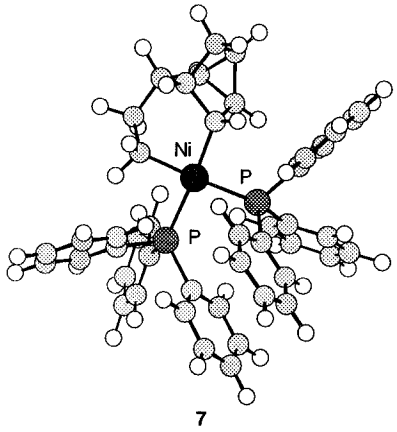


Figure 3. MM2-optimized structure of the lowest energy conformation for complex **7**.

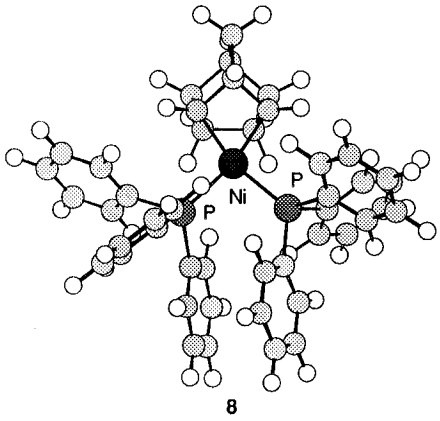


Figure 4. MM2-optimized structure of the lowest energy conformation for complex **8**.

Table 4. Relative MM2 Energies of Triphenylphosphine Conformations.

model	rotor	rel energy (kcal/mol)
4	CCW	0.0
	CW	0.7
5	CW	0.0
	CCW	0.7
6	CW	0.0
	CCW	0.5
7	CW–CW	0.0
	CCW–CW	0.5
	CW–CCW	1.4
	CCW–CCW	1.7
8	CW–CW	0.0
	CW–CCW	0.4
	CCW–CCW	1.7

Table 5. Relative MM2 Energies and Calculated Exo/Endo Selectivities of Model Complexes 4–8[a]

complex	PR_3	ΔE_s (endo–exo)	calc ratio (exo:endo)
4	PH_3	0.46	67:33
5	PH_3	−2.6	1:99
6	PH_3	−1.6	6:94
7	PH_3	3.3	99.6:0.4
8	PH_3	0.06	52:48
4	PMe_3	1.0	83:17
5	PMe_3	−8.1	0:100
6	PMe_3	−6.0	0:100
7	PMe_3	3.1	99.5:0.5
8	PMe_3	1.0	83:17
4	PPh_3	1.5	93:7
5	PPh_3	−5.4	0:100
6	PPh_3	−3.9	0.1:99.9
7	PPh_3	5.2	100:0
8	PPh_3	7.2	100:0

[a] Steric energy differences given in kcal/mol. Calculated ratios are at 25 °C. Experimental exo:endo ratio is 93:7 (25 °C, PPh_3).

ensure we located the lowest possible conformation of the ligand for the various complexes.

Generally, the MM2-calculated barrier to rotation about the phenyl–phosphorus bond was around 2–3 kcal/mol and that about the nickel–phosphorus bond approximately 3–5 kcal/mol. For the monophosphine complexes **5** and **6**, the clockwise (CW) rotor was slightly favored over the counterclockwise (CCW) rotor, but for complex **4** the counterclockwise rotor was favored (see Figures 2–4). In the case of the bisphosphine complexes **7** and **8**, the conformation having both triphenylphosphine ligands in clockwise orientations was the most stable. Mixed CW–CCW conformations were slightly higher in energy, and the CCW–CCW conformations were 1.7 kcal/mol higher than the global minimum (Table 4). The calculated energy differences between the right-hand and left-hand rotors were all less than 1–2 kcal/mol which is consistent with experimental values. The right-hand and left-hand screw configurations in organometallic complexes typically differ by less than 1 kcal/mol, and the helicity reversal process has a low energy barrier.[11]

With acrylonitrile as dienophile, steric properties of the phosphorous ligand have been shown to strongly influence the exo/endo selectivity, whereas the electronic

Table 6. Relative MM2 Energies and Calculated Regio-/Stereoselectivities of Model Complexes 4, 7, and 8[a]

G	calcd rel energies AX	SX	AN	SN	calcd ratio (anti:syn)	calcd ratio (exo:endo)	obsd ratio (anti:syn)	obsd ratio (exo:endo)
					complex **4**			
n-hexyl	0.05	0.00	1.67	1.96	49:51	95:5	42:58	98:2
	(46)	(49)	(3)	(2)				
Cl	0.16	0.00	1.95	1.63	43:57	95:5	72:28	99:1
	(41)	(54)	(2)	(3)				
OBu-*t*	0.20	0.00	1.78	1.67	42:58	94:6	95:5	100:0
	(39)	(55)	(3)	(3)				
					complex **7**			
n-hexyl	1.74	0.00	9.62	7.57	5:95	100:0	42:58	98:2
	(32)	(36)	(14)	(18)				
Cl	0.12	0.00	8.15	7.23	45:55	100:0	72:28	99:1
	(40)	(25)	(16)	(19)				
OBu-*t*	1.07	0.00	9.33	7.79	14:86	100:0	95:5	100:0
	(35)	(37)	(14)	(14)				
					complex **8**			
n-hexyl	0.003	0.000	3.26	3.05	49.8:50.2	99.5:0.5	42:58	98:2
	(49.6)	(49.9)	(0.2)	(0.3)				
Cl	0.00	0.31	3.01	3.31	62.8:37.2	99.4:0.6	72:28	99:1
	(62.4)	(37)	(0.4)	(0.2)				
OBu-*t*	0.00	0.32	2.89	3.36	63:37	99.3:0.7	95:5	100:0
	(62.5)	(36.8)	(0.5)	(0.2)				

[a] Relative energies given in kcal/mol. The numbers in parentheses are the predicted Boltzmann distributions of the various isomers calculated at 25 °C.

character had no appreciable effect.[1a] Assuming that bond formation occurs with retention of configuration, the modeling results indicate that complexes **4, 7**, and **8** consistently give good quantitative agreement with the observed exo stereoselectivity (Table 5). Complexes **4** and **8** best reproduced the trend of increasing exo selectivity with increasing cone angle of the phosphorous ligand ($PH_3 = 87$, $PMe_3 = 118$, $PPh_3 = 145$).[12] The endo isomer was predicted to be the energetically more stable isomer with model complexes **5** and **6**.

We also carried out a preliminary study of the anti/syn energy differences in the 7-substituted complexes with various substituents for the more promising models **4**, **7**, and **8** (see Table 6). Three substituents were chosen as representative examples for weakly syn regioselective (Z = *n*-hexyl), modestly anti regioselective (Z = Cl), and strongly anti regioselective (Z = OBu-*t*) substituents. The lowest energy conformers of the various triphenylphosphine complexes were used to derive the corresponding 7-substituted complexes. We determined the global minimum energy conformations for all reasonable isomers which included exploring all possible rotors of the particular substituent. Only the global conformational minima were used to determine relative energies.

Using complex **4**, nearly identical energies were found for the syn and anti isomers of a given endo or exo complex with the syn isomers being favored. In the case of complex **7**, there was more sensitivity to the orientation of the substituent (except for Cl) but again with the syn isomer being the lower energy form. The most viable predictive model was complex **8**. We found this model to correlate well with both the extent and direction of the observed regioselectivity. The quantitative agreement with regioselectivity, while good, was still less than perfect. This was not entirely unexpected due to the likelihood that significant electronic factors, which are absent in the force field models, play a role in the regiochemical outcome. Yet a closer inspection of the various interaction energies did reveal that for the Cl and *t*-BuO cases the main energy difference between the syn and anti orientations was a result of dipole interactions between the C−Cl bond with the C═O bond of the acetyl group, whereas for the *n*-hexyl substituent the energy differences were largely due to van der Waals interactions between the substituent and the rest of the complex. Although we have not proven the origins of regiocontrol lie within complex **8**, our study does suggest that similar interactions may be involved in the stereodiscriminating step and provides a direction for further study of this complex reaction.

There is still a need to more carefully address the electronic influences of the 7-substituent and how they may translate into a regiochemical preference in these systems, but at this early stage we prefer not to speculate on this matter. Extensive work on the transmission of stereoelectronic substituent effects through norbornene and similar systems has been carried out by many groups and many different viewpoints abound, such as transition-state hyperconjugation, through-bond and through-space electrostatic effects, $\sigma-\pi$ orbital mixing, torsional strain, and steric interactions.[13] Our ongoing investigation involves a systematic study using molecular orbital methods which may shed further insight into the anti/syn selectivity issue and provide evidence for or against the previously suggested hypotheses.

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Table 7. Diagnostic ^{1}H NMR Signals Used and Initial Concentrations of Reactants

Z	reactant	product	$[NBD]_o$	$[MVK]_o$	$[Ni(COD)_2]_o$	$[PPh_3]_o$
H	3.38 (2H)	2.55 (1H)	0.401	1.397	0.0800	0.1597
OTIPS	3.31 (2H)	2.79 (1H, SX) 2.36 (1H, AX)	0.260	0.917	0.0520	0.1040
Ph	3.7−3.5 (3H)	3.10 (1H, AX + SX)	0.305	1.068	0.0609	0.1220

[a] Chemical shifts are given in ppm and concentrations in mol/L.

Conclusions

The rate of nickel-catalyzed homo-Diels−Alder cycloaddition of 7-substituted norbornadienes with MVK was found to be slightly influenced by the nature of the substituent. Relative reactivities followed the order: 7-Ph > H > 7-OTIPS. The observed activation parameters ($\Delta H^{\ddagger}$ = 15−18 kcal/mol; $\Delta S^{\ddagger}$ = −19 to −24 cal/mol K) are also affected by the 7-substituent and are in good agreement with those established for reductive elimination from related nickel phosphine complexes. Force field modeling studies of possible organonickel intermediates suggest that the preferred exo selectivity arises from steric interactions between the dienophile substituent and the phosphine ligands. The anti/syn preferences are most likely a blend of steric and electronic factors and were not as well predicted by force field models. However, good qualitative and quantitative agreement with both the observed exo/endo stereoselectivity and anti/syn regioselectivity was found with only one complex. More detailed studies are needed to test its viability as a predictive model for this chemistry.

We are currently examining the influence of substituents on the stabilities of these organonickel intermediates, using a combined electronic structure/molecular mechanics approach. We are also undertaking an investigation into possible transition structures for the formation and collapse of these intermediate complexes using density functional methods. As more experimental and theoretical data is gathered, more stringent tests and further refinement of these models will be possible and presented in due course.

Experimental Section

General. Triphenylphosphine was purified by recrystallization from hexane and dried in a vacuum oven. Methyl vinyl ketone was distilled under nitrogen prior to use. Benzene-d_6 was dried and degassed by standard procedures. Norbornadiene, 7-phenylnorbornadiene, and 7-(*tert*-butyldimethylsiloxy)norbornadiene were used as received.[14] Bis(cycloocta-1,5-diene)nickel(0) was purchased from Alfa AESAR and used without further purification. Standard solutions (0.095 M) of $Ni(COD)_2$ in benzene-d_6 were carefully prepared in a glovebox under a nitrogen atmosphere prior to the kinetic runs to aid in the measurement and transfer of such small quantities. Syringe techniques were employed in the transfer all liquid reactants. ^{1}H NMR spectra for kinetic runs were recorded on a 200 MHz FT-NMR with a variable-temperature probe rated at ±1 °C and calibrated prior to the kinetic study. Preliminary ^{1}H NMR spectra of the individual reactants and products were recorded on a 250 MHz FT-NMR in both benzene-d_6 and chloroform-d_3.

Kinetics. Rate constants for the nickel-catalyzed reaction of **1** with methyl vinyl ketone in C_6D_6 were determined at various temperatures in the NMR. NMR tubes (5 mm) equipped with rubber septa and containing a solution of **1**, $Ni(COD)_2$ (20 mol %), and PPh_3 (40 mol %) in C_6D_6 under nitrogen were heated in the probe of the machine. The tube was removed, and methyl vinyl ketone (3.5 equiv) was added. After the tube was returned to the probe, the machine was shimmed to constant values (ca. 2.5 min total). Data (eight scans) were collected at 5 min to 1 h time intervals depending on the 7-substituent and reaction temperature. Relative concentrations of **1** and the isomeric exo adducts (**2**) were determined by comparison of the integrations of characteristic proton resonances for **1** and **2**, normalized to 100% (summarized in Table 7).

Pseudo-first-order rate constants were obtained by linear regression from slopes of plots of ln ($[NBD]_o/[NBD]_t$) vs time. These plots were linear (r > 0.99) over ca. 2−4 half-lives at which time the reactions were ≥70% complete. Variable-temperature results (30−70 °C) were used to obtain the linear Arrhenius and Eyring plots (r > 0.99) for these reactions. Activation parameters were determined from least-squares analyses of ln k and ln (k/T) vs $1/T$ plots.

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