
Quantum Chemical Study on Enantioselective Reduction of Aromatic Ketones Catalyzed by Chiral Cyclic Sulfur-Containing Oxazaborolidines. Part 2. Structures of Catalyst–Borane–Ketone Adducts

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ABSTRACT: In the present paper, the ab initio molecular orbital method is employed to study the structures of the adducts of borane and aromatic ketone to chiral cyclic sulfur-containing oxazaborolidine used as a catalyst in the enantioselective reduction of aromatic ketone. The catalyst–borane–ketone adducts have four different structures. All the structures are optimized completely by means of the Hartree–Fock method at 6-31g* basis sets. The structure which is of the greatest advantage to a hydride transfer from the borane moiety to the carbonyl carbon of aromatic ketone is the one with the next lowest formation energy, and the plausible transition state for the hydride transfer is predicted to be of a twisted boat structure. © 2000 John Wiley & Sons, Inc. *Int J Quant Chem* 78: 252–260, 2000

Key words: ab initio; cyclic sulfur-containing oxazaborolidine; enantioselective reduction; catalyst–borane–ketone adduct

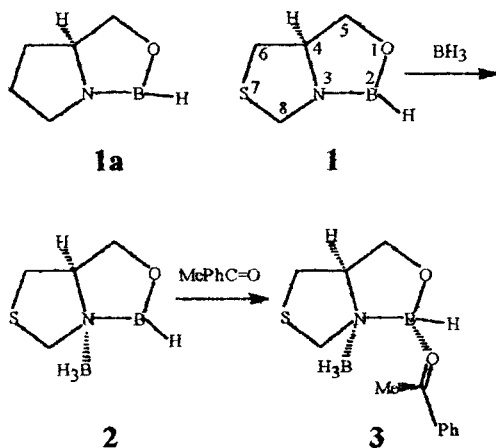
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Introduction

In 1996, Li and Xie [1] replaced pyrrolidine with thiazolidine in chiral oxazaborolidine **1a** and first obtained a new oxazaborolidine type of chiral catalyst—chiral (R)-cyclic sulfur-containing oxazaborolidine **1**. When the catalyst **1** is used in the enantioselective catalytic reduction of aromatic ketone with borane, (S) alcohols, not (R) alcohols, are obtained. The chirality of the reduced products is just the opposite to that of the (R) alcohols generated in the enantioselective reduction of aromatic ketone catalyzed by the (4S)-CBS catalyst **1a** with borane used as a source of hydrogen. Later, Huang et al. [2], Reiners et al. [3], and Trentmann et al. [4] also reported the same results as those obtained by Li and Xie. The chiral cyclic sulfur-containing oxazaborolidine is of importance in enantioselective reduction. For the purpose of convenient discussion, in the present paper, the chiral cyclic sulfur-containing oxazaborolidine **1** is termed the Chengdu–Taipei–Oldenburg (CTO) catalyst.



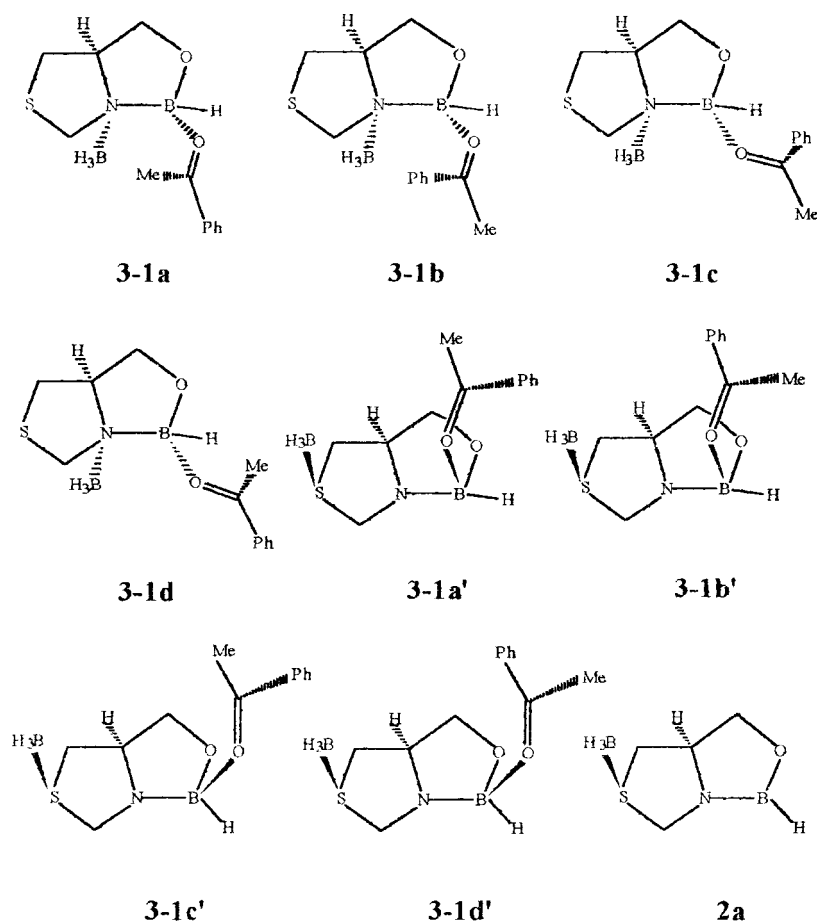
Corey et al. [5] suggested the mechanism of the CBS catalytic reduction. According to this mechanism of catalysis, the enantioselective reduction of aromatic ketone catalyzed by the CTO catalyst mainly involves the following steps: formation of the CTO–borane adduct **2**; coordination of ketone to be reduced to the adduct **2**, leading to the CTO–borane–ketone adducts **3**; hydride transfer from the BH_3 moiety to the carbonyl carbon in **3** followed by a number of regenerative steps. The final products of the reduction are the chiral alcohols $\text{R}_L\text{R}_S\text{C}(\text{OH})\text{H}$. Nevalainen [6–10] carried out quantum chemical modeling studies on the enantioselective reduction of ketone catalyzed by the

oxazaborolidine **1a** by employing the ab initio molecular orbital method at the 6-31g level. In his investigations, the molecule $\text{H}_2\text{C=O}$ was substituted for ketone $\text{R}_L\text{R}_S\text{C=O}$ and a small modeling system for the oxazaborolidine **1a** was used. Many theoretical results given by Nevalainen are reasonable and reveal some observed experimental phenomena successfully, but the observed enantioselectivity of the catalytic reduction is not explained and the conformations of catalyst–borane–ketone adducts cannot be described entirely because of the small theoretical molecular models used in the investigations and because of the substitution of $\text{H}_2\text{C=O}$ for $\text{R}_L\text{R}_S\text{C=O}$. Ab initio studies on the enantioselective reduction of aromatic ketone catalyzed by the chiral cyclic sulfur-containing oxazaborolidine (CTO) has not been reported yet. Therefore, the aim of this work is to investigate this enantioselective reaction.

In this article, the structures of the CTO–borane–ketone adducts **3** in the enantioselective reduction of aromatic ketone and their properties are studied by employing the ab initio molecular orbital method.

Computations and Results

For all the investigated systems, standard ab initio molecular orbital calculations were carried out. Since there is a sulfur atom S(7) in the CTO catalyst **1**, borane may coordinate at the S(7) site. When aromatic ketone MePhC=O reacts with the CTO catalyst **1** in the presence of borane, the formed CTO–borane–ketone adducts involve eight plausible structures, as shown in Scheme 1, where the structures in which borane coordinates at the S(7) site have four plausible structures—**3-1a'**, **3-1b'**, **3-1c'**, and **3-1d'**—and the structures in which borane coordinates at the N(3) site also have four plausible structures—**3-1a**, **3-1b**, **3-1c**, and **3-1d**. These eight structures of the CTO–borane–ketone adducts are optimized completely by means of the Hartree–Fock method at 6-31g* basis sets with program Gaussian 92. The optimized structures are shown in Figure 1. Table I gives the energies of all the structures and their formation energies. The selected bond lengths and the Mulliken overlap populations are summarized in Tables II and III, respectively. The selected stabilization interaction energies $E(2)$ obtained from the second-order perturbative theory [11, 12] are summarized in Table IV. The selected atomic charges are summarized in Table V. For the purpose of convenient comparison, the results of the



SCHEME 1.

CTO–borane adduct **2a** for the coordination of BH_3 at the S(7) site are also listed in these tables.

Discussion

COORDINATION OF BORANE TO THE SULFUR SITE

For the coordination of borane at the S(7) site of the CTO catalyst, each of the four structures of the CTO–borane–ketone adducts (**3-1a'**, **3-1b'**, **3-1c'**, and **3-1d'**) is decomposed into aromatic ketone and the CTO–borane adduct when it is optimized completely. In other words, the adducts **3-1a'**, **3-1b'**, **3-1c'**, and **3-1d'** are considerably unstable. As shown in Tables II and III (**3-1a'** is listed only), the distance between the carbonyl oxygen of aromatic ketone and the B(2) atom of the CTO catalyst is 4.796 Å, the carbonyl bond length $R_{\text{C=O}} = 1.200$ Å, the distance between the carbonyl carbon and the phenyl

is 1.499 Å, the B(2)—N(3) bond length in the CTO catalyst is 1.423 Å, and the B—H bond length in the BH_3 moiety is 1.205 Å. In correspondence, the Mulliken overlap populations of these bonds, respectively, are $\text{O}_{\text{C=O}}-\text{B}(2)$, -0.0 ; $\text{C}=\text{O}$, 0.571; $\text{C}_{\text{C=O}}-\text{Ph}$, 0.339; $\text{B}(2)-\text{N}(3)$, 0.428; $\text{B}_{\text{BH}_3}-\text{H}_{\text{BH}_3}$, 0.417. Compared with those of **2a** and aromatic ketone, these results remain almost unchanged, which implies that the carbonyl oxygen of the aromatic ketone does not coordinate at the B(2) site of the CTO catalyst, if borane coordinates at the S(7) site, to form the CTO–borane–ketone adducts. The reason for this is that aromatic ketone is repulsed by the atoms arising from the chair rear of the CTO catalyst with a twisted chair structure. It is seen, of course, from Table I that in this case, the total energies of the systems are about -1116.5920 au and their formation energies about -18.75 kJ/mol. The total energies are lower than those of the CTO–borane–ketone adducts for the coordination of borane at the N(3) site of the CTO catalyst and also lower than the sum

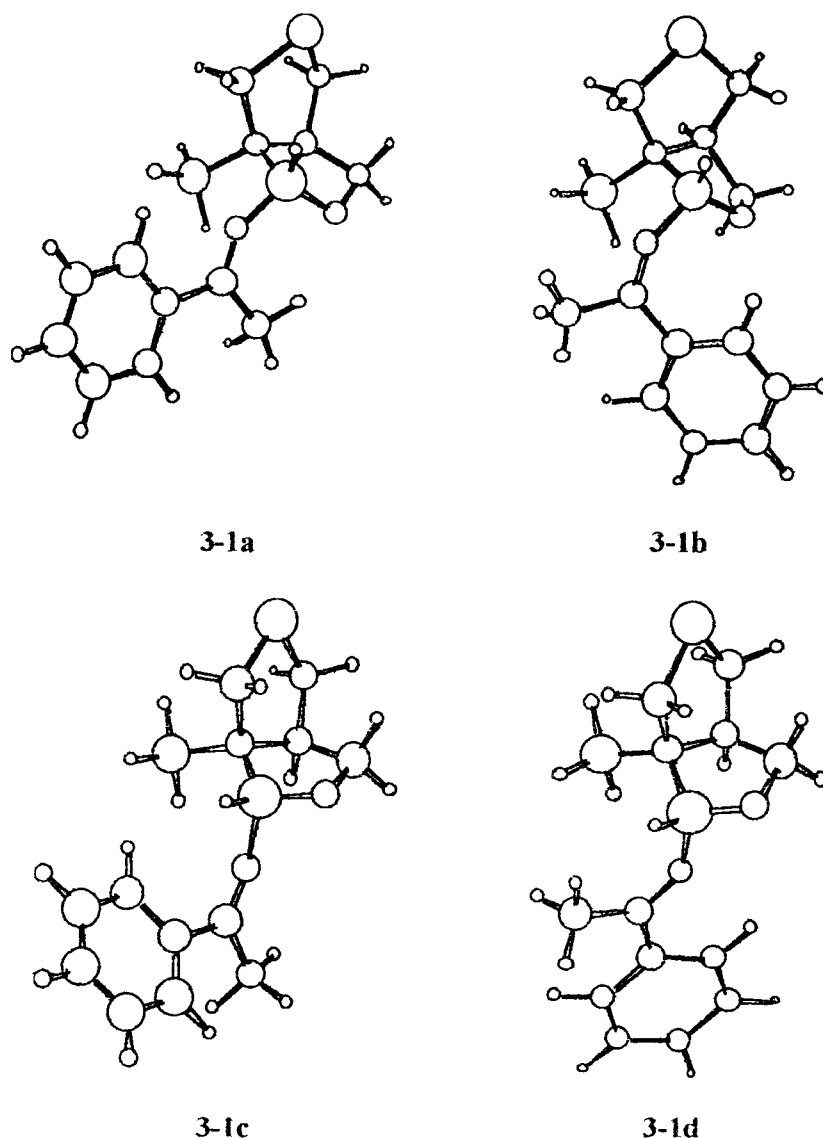


FIGURE 1. The optimized structures of CTO–borane–ketone adducts.

(-1116.5884 au) of the energies of the CTO–borane adduct **2** and aromatic ketone. Maybe this result implies the existence of a possible intermediary state before the formation of the CTO–borane–ketone adducts. The intermediary state may be caused by the weak interaction between the aromatic ketone and the oxazaborolidine–borane adduct.

COORDINATION OF BORANE TO THE NITROGEN SITE

Borane can coordinate well at the N(3) site of the catalyst **1** to form the CTO–borane adduct **2**. When aromatic ketone reacts with the adduct **2**,

the carbonyl oxygen of aromatic ketone coordinates at the B(2) site to form four plausible structures (see **3-1a**, **3-1b**, **3-1c**, and **3-1d** illustrated in Scheme 1). The completely optimized structures are shown in Figure 1. The total energies of the four optimized structures are **3-1a**, -1116.5810 au; **3-1b**, -1116.5768 au; **3-1c**, -1116.5767 au; **3-1d**, -1116.5846 au, and their formation energies are 19.29, 30.38, 30.65, and 10.00 kJ/mol, respectively. The reaction is endothermic. In these structures, **3-1a** and **3-1d** have lower formation energies, compared with **3-1b** and **3-1c** (the formation energy of **3-1a** is higher than that of **3-1d**, but their energy difference is only 9.29 kJ/mol); thus their stabilities

TABLE I
 Dipole moments D (D), total energies E (au), formation energies ΔE (kJ/mol), and levels of highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) (au) for CTO–borane–ketones.

	D	E	ΔE	HOMO	LUMO
3-1a'		-1116.5920	-18.75		
3-1a	6.05	-1116.5810	19.29	-0.3354	0.0451
3-1b	6.78	-1116.5768	30.38	-0.3279	0.0528
3-1c	7.61	-1116.5767	30.65	-0.3291	0.0582
3-1d	8.03	-1116.5846	10.00	-0.3269	0.0440
2	3.91	-734.1133			
2a	5.24	-734.1097			
O=CMePh	3.25	-382.4751			
BH ₃		-26.3893			

are higher. According to the mechanism of catalysis suggested by Corey et al. [5], the formation of the CTO–borane–ketone adducts and the hydride transfer from the BH₃ moiety to the carbonyl carbon are key to the enantioselective catalytic reduction, and the chirality of reduced products depends on the structures of the oxazaborolidine–borane–ketone adducts. As a result, the chirality of the products of the reduction catalyzed by the CTO catalyst depends mainly on the structures **3-1d** and **3-1a**. Notice further that four structures of the CTO–borane–ketone adducts determine two types of chirality (R and S). One is determined by **3-1a** or **3-1c** and the other by **3-1d** or **3-1b**. The chirality of the reduced products determined by **3-1d** is in correspondence with that of the CTO catalyst; i.e., the chirality determined by **3-1d** is the R type if (4R)-CTO is used. The chirality determined by **3-1a** is opposite to that of CTO; i.e., the chirality determined by **3-1a** is the S type if (4R)-CTO is used. The experimental products obtained by Li and Xie [1] are of an S type when (4R)-CTO is used. If the ef-

fect of energies on the chirality is taken into account only, obviously, the chirality of the reduced products is mainly determined by **3-1d**, because it has the lowest formation energy, which is opposite to the experiments.

In the present work, to study chemical bonds in detail, a natural bond orbital (NBO) analysis for the CTO–borane–ketone adducts is carried out. The stabilization interaction energies $E(2)$ obtained from the second-order perturbative theory [11, 12] are calculated. [In the natural bond orbital analysis, $E(2)$ is used to describe the interaction between the donor bond and the acceptor bond of an intramolecule or to describe the delocalization trend of electrons from a donor bond to an acceptor bond]. The selected stabilization interaction energies $E(2)$ for the CTO–borane–ketone adducts are summarized in Table IV, where BD and BD* represent bonding and antibonding natural bond orbitals, respectively, LP and CR are lone pairs and core electrons. For the four structures of the CTO–borane–ketone adducts, the stabilization interaction energies $E(2)$ between

TABLE II
 Selected bond lengths (Å) for CTO–borane–ketone adducts.

	3-1a'	3-1a	3-1b	3-1c	3-1d	2	2a	O=CMePh	BH ₃
B _{BH3} —H _{BH3}	1.205	1.217	1.215	1.215	1.215	1.210	1.202		1.188
C=O	1.200	1.227	1.223	1.216	1.223			1.196	
C _{C=O} —Ph	1.499	1.477	1.476	1.480	1.479			1.500	
N(3)—B _{BH3}		1.664	1.676	1.660	1.654	1.717			
H _{BH3} —C _{C=O}		2.782	2.785	3.291	2.829				
B(2)—N(3)	1.423	1.596	1.586	1.558	1.572	1.496	1.359		
O _{C=O} —B(2)	4.796	1.581	1.633	1.734	1.644				
O _{C=O} —B _{BH3}		2.843	2.830	3.016	3.007				

TABLE III
Selected Mulliken overlaps for CTO–borane–ketone adducts.

	3-1a'	3-1a	3-1b	3-1c	3-1d	2	2a	O=CMePh	BH ₃
B _{BH₃} —H _{BH₃}	0.417	0.403	0.405	0.405	0.407	0.414	0.415		0.413
C=O	0.571	0.418	0.442	0.470	0.449			0.599	
C _{C=O} —Ph	0.339	0.410	0.385	0.370	0.409			0.333	
N(3)—B _{BH₃}		0.173	0.166	0.173	0.176	0.118			
H _{BH₃} —C _{C=O}		0.003	0.005	0.002	0.005				
B(2)—N(3)	0.428	0.225	0.253	0.260	0.255	0.309	0.409		
O _{C=O} —B(2)	-0.000	0.129	0.092	0.058	0.081				
O _{C=O} —B _{BH₃}		-0.003	-0.003	-0.000	0.004				

the B_{BH₃}—H_{BH₃} antibonding orbital of the BH₃ moiety and other bonding orbitals (or lone pairs) are all very small, which shows the weak trend of the electron transfer from other bonding orbitals to the B_{BH₃}—H_{BH₃} antibonding orbitals. [The larger $E(2)$ is, the greater the trend of the electron transfer from the donor to the acceptor is.] This result implies that in the subsequent hydride transfer, the B_{BH₃}—H_{BH₃} bonds are barely affected by other electrons or lone pairs. For the carbonyl of aromatic ketone, $E(2)$ between other bonding orbitals and the π antibonding orbital of the carbonyl are much larger than those between other bonding orbitals and the σ antibonding orbital of the carbonyl, which implies that the trend of the electron transfer from other bonding orbitals to the π antibonding orbital of the carbonyl is much stronger than to its σ antibonding orbital. Therefore, the π carbonyl bond is weakened considerably, which causes the carbonyl bond length to increase (see Table II). As shown in Table IV, among the structures of the CTO–borane–ketone adducts, $E(2)$ for **3-1a** are the largest, and electrons transferring to the π carbonyl antibonding orbital $BD^*(\pi)_{O21-C22}$ are largely due to the π bonding orbital $BD(\pi)_{C24-C25}$ or the π lone pair orbitals $LP(\pi)_{C24}$ arising from the phenyl. $E(2)$ between $BD(\pi)_{C24-C25}$ [or $LP(\pi)_{C24}$] and $BD^*(\pi)_{O21-C22}$ are **3-1a**, 76.53 kcal/mol; **3-1d**, 34.06 kcal/mol; **3-1b**, 29.64 kcal/mol; **3-1c**, 27.89 kcal/mol. [$E(2)$ for free aromatic ketone is 22.31 kcal/mol.] The sums of the stabilization interaction energies $E(2)$ between all other bonding orbitals (or lone pairs) and the π carbonyl antibonding orbital $BD^*(\pi)_{O21-C22}$ are **3-1a**, 92.24 kcal/mol; **3-1d**, 49.24 kcal/mol; **3-1b**, 46.75 kcal/mol; **3-1c**, 42.28 kcal/mol. Among the four structures, obviously the trend of the electron transfer to the π carbonyl antibonding orbital $BD^*(\pi)_{O21-C22}$ for **3-1a** is the strongest; in other

words, the π carbonyl bond for **3-1a** is broken up much more easily than those for other structures. In addition, as illustrated in Table II, the B_{BH₃}—H_{BH₃} bond (1.217 Å) and the carbonyl bond (1.227 Å) for **3-1a** are the longest among all the structures and the distance B_{BH₃}—C_{C=O} (2.782 Å) between H_{BH₃} and C_{C=O} is the shortest. Therefore, it can be considered that **3-1a** is the structure for which the hydride of the BH₃ moiety transfers most easily to the carbonyl carbon among all the conformations. As discussed above, the chirality of the reduced products determined by **3-1a** is opposite to the chirality of CTO; i.e., the chirality determined by **3-1a** is the S type if (4R)-CTO is used in the enantioselective catalytic reduction, which is in correspondence with the experiments [1]. It must be emphasized that since the formation energy for **3-1d** is the smallest, the chirality of the reduced products determined by **3-1d** may be obtained; i.e., some R products are also obtained when (4R)-CTO is used in the enantioselective reduction of aromatic ketone.

As shown in Tables II and III, after the formation of the CTO–borane–ketone adducts, the lengths of the B_{BH₃}—H_{BH₃} bonds nearest to the carbonyl carbon of aromatic ketone are **3-1a**, 1.217 Å; **3-1b**, 1.215 Å; **3-1c**, 1.215 Å; **3-1d**, 1.215 Å, which are increased considerably by 0.029, 0.027, 0.027, and 0.027 Å, compared with that of the free BH₃ (1.188 Å). Apparently, the B_{BH₃}—H_{BH₃} bonds for all the structures of the CTO–borane–ketone adducts are greatly weakened. For the carbonyl bonds, the lengths are increased from 1.196 Å of free aromatic ketone to **3-1a**, 1.227 Å; **3-1b**, 1.223 Å; **3-1c**, 1.216 Å; **3-1d**, 1.223 Å. The overlap populations are also changed correspondingly. The reason for these variations is that the interaction between other bonding orbitals (or lone pairs) and the π carbonyl antibonding orbital $BD^*(\pi)_{O21-C22}$ is strengthened

TABLE IV
Selected donor–acceptor interaction energies $E(2)$ for CTO–borane–ketone adducts.

	Donor NBO	Acceptor NBO	$E(2)$ (kcal/mol)
3-1a	BD(σ) C23—H36	BD*(π) O21—C22	8.22
	BD(σ) C23—H37	BD*(π) O21—C22	7.49
	LP(π) C24	BD*(π) O21—C22	76.53
Total			92.24
Total	BD(σ) C6—H13	BD*(σ) B16—H20	0.83
			0.83
3-1b	BD(π) C24—C25	BD*(π) O21—C22	29.64
	BD(σ) C23—H36	BD*(π) O21—C22	5.73
	BD(σ) C23—H37	BD*(π) O21—C22	7.01
	LP(σ) O21	BD*(π) O21—C22	4.37
Total			46.75
Total	BD(σ) N3—C4	BD*(σ) B16—H20	0.08
	BD(σ) N3—C6	BD*(σ) B16—H20	0.13
	BD(σ) C6—H13	BD*(σ) B16—H20	0.76
	BD(σ) B2—N3	BD*(σ) B16—H20	0.81
	LP(σ) S7	BD*(σ) B16—H20	0.05
Total			1.83
3-1c	BD(σ) C23—H36	BD*(π) O21—C22	7.04
	BD(σ) C23—H37	BD*(π) O21—C22	5.61
	BD(σ) C24—C25	BD*(π) O21—C22	0.70
	BD(π) C24—C25	BD*(π) O21—C22	27.89
	LP(σ) O21	BD*(π) O21—C22	1.56
Total			42.28
Total	BD(σ) C4—H10	BD*(σ) B16—H20	0.16
	BD(σ) N3—C6	BD*(σ) B16—H20	0.19
	BD(σ) B2—N3	BD*(σ) B16—H20	1.07
	CR(σ) N3	BD*(σ) B16—H20	0.07
	LP(σ) N3	BD*(σ) B16—H20	0.05
Total			1.54
3-1d	BD(π) C24—C25	BD*(π) O21—C22	34.06
	BD(σ) C23—H36	BD*(π) O21—C22	6.09
	BD(σ) C23—H37	BD*(π) O21—C22	9.09
Total			49.24
Total	BD(σ) B2—N3	BD*(σ) B16—H20	0.72
	BD(σ) N3—C4	BD*(σ) B16—H20	0.21
	BD(σ) N3—C6	BD*(σ) B16—H20	0.14
	BD(σ) C6—H13	BD*(σ) B16—H20	0.57
	LP(σ) N3	BD*(σ) B16—H20	0.08
Total			1.72
O=CMePh	BD(σ) C3—H16	BD*(π) O1—C2	5.73
	BD(σ) C3—H17	BD*(π) O1—C2	5.73
	BD(π) C4—C5	BD*(π) O1—C2	22.31
Total			33.77

TABLE V
Selected atomic charges for CTO–borane–ketone adducts.

	3-1a	3-1b	3-1c	3-1d	2	O=CMePh	BH ₃
O(1)	-0.720	-0.716	-0.698	-0.704	-0.591		
B(2)	0.934	0.925	0.913	0.923	0.682		
N(3)	-0.772	-0.761	-0.732	-0.728	-0.730		
S(7)	0.115	0.116	0.131	0.128	0.145		
O _{C=O}	-0.628	-0.630	-0.625	-0.646		-0.545	
C _{C=O}	0.643	0.618	0.598	0.631		0.564	
B _{BH3}	0.167	0.158	0.152	0.142	0.098		0.115
BH ₃	-0.308	-0.292	-0.281	-0.299	-0.225		
O=CMePh	0.221	0.185	0.134	0.179			

greatly, which results in a great increase in the trend of the electron transfer to the π carbonyl antibonding orbital and causes the π carbonyl bond to be weakened greatly. These consequences are of great advantage to hydride transfer from the BH₃ moiety to the carbonyl carbon. In addition, the N(3)—B_{BH3} and B(2)—N(3) bonds are also changed greatly. In the CTO–borane adduct **2**, the N(3)—B_{BH3} and B(2)—N(3) lengths are 1.717 and 1.496 Å and their Mulliken overlap populations 0.118 and 0.309. Compared with those of the CTO–borane adduct **2**, the N(3)—B_{BH3} lengths of the CTO–borane–ketone adducts are decreased considerably by **3-1a**, 0.053 Å; **3-1b**, 0.041 Å; **3-1c**, 0.057 Å; **3-1d**, 0.063 Å, and the B(2)—N(3) lengths increase by **3-1a**, 0.100 Å; **3-1b**, 0.090 Å; **3-1c**, 0.062 Å; **3-1d**, 0.076 Å. The decreasing values of the Mulliken overlap populations of the N(3)—B_{BH3} bonds are 0.055, 0.048, 0.055, and 0.058, whereas the increasing values of the overlap populations of the B(2)—N(3) bonds are 0.084, 0.056, 0.049, and 0.054. The distances O_{C=O}—B(2) between the carbonyl oxygen and B(2) are **3-1a**, 1.581 Å; **3-1b**, 1.633 Å; **3-1c**, 1.734 Å; **3-1d**, 1.644 Å, and the corresponding Mulliken overlap populations are 0.129, 0.092, 0.058, and 0.081. The changes in these bonds are presented in Figure 2, where s and w, respectively, represent the bonds strengthened and weakened.

The hydride transfer from the BH₃ moiety to the carbonyl carbon of aromatic ketone is closely related to the changes in bonds. In other words, when the bonds in the CTO–borane–ketone adducts are changed, the hydride of the BH₃ moiety transfers gradually toward the carbonyl carbon of aromatic ketone and thus a plausible transition state as illustrated in Figure 2 is formed. For the CBS catalytic system, the results of studies on plausible

transition states of the hydride transfer were reported by Jones et al. [13], who employed the modified neglect of differential overlap method. Jones et al. proposed that the hydride transfer occurs via a chair transition state, whereas Nevalainen, who investigated the CBS–borane–ketone adducts using the ab initio method at the HF/6-31g level (small models were used in computations), conjectured the plausible transition state to stay in a conformation which could be described as a twisted boat [6, 7]. In this work, the CTO–borane–ketone adducts have four different structures, of which **3-1a** and **3-1b** have twisted boat structures and **3-1c** and **3-1d** have twisted chair structures. As a consequence, the transition state of the hydride transfer depends on the conformations of the CTO–borane–ketone adducts.

From the point of view of energy, **3-1d** is the prior structure among all the structures because its formation energy is the smallest. When a hydride transfers from the BH₃ moiety toward the carbonyl carbon

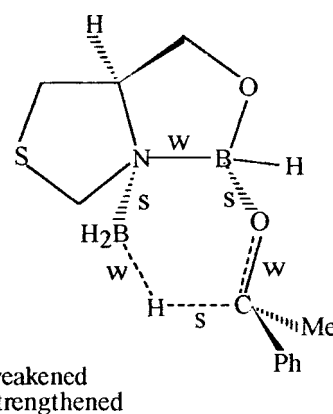


FIGURE 2. Plausible transition state for hydride transfer.

of aromatic ketone, the transition state determined by **3-1d** must have a twisted chair structure, which is just the result given by Jones et al. [13]. However, it is seen from Tables II and III that among the four structures of the CTO–borane–ketone adducts, the C=O and B_{BH₃}—H_{BH₃} bonds for **3-1a** are the longest and their overlap populations are the smallest, whereas the C_{C=O}—H_{BH₃} distance between the carbonyl carbon and the hydride of the BH₃ moiety (2.782 Å) is the shortest. As a result, the carbonyl carbon for **3-1a** is attacked most easily by the hydride of the BH₃ moiety in the hydride transfer. In other words, among all the structures, **3-1a** is the structure in which the hydride of the BH₃ moiety transfers most easily to the carbonyl carbon of aromatic ketone. Therefore, the structure of the transition state could be determined by **3-1a**. Since **3-1a** is of a twisted boat structure, the transition state ought to stay in a structure which could be described as a twisted boat. This result is in correspondence with results given by Nevalainen [6, 7].

Moreover, it is clear from Table V that aromatic ketone has a positive charge after the formation of the CTO–borane–ketone adducts, which implies that electrons of aromatic ketone transfer partially to the CTO–borane adduct. The electron transfer leads to two changes. On the one hand, electrons are redistributed in aromatic ketone and the CTO catalyst; on the other hand, electrons transfer partially to the BH₃ moiety. The net charges of the carbonyl oxygen and the carbonyl carbon in free aromatic ketone are –0.545 and 0.564, respectively. After the formation of the CTO–borane–ketone adducts, the negative charge of the carbonyl oxygen and the positive charge of the carbonyl carbon increase by about –0.085 and 0.065, respectively. The charges of all the atoms of the CTO catalyst are also changed and the variations in the charges of B(2) and O(1) are considerable. The formation of the CTO–borane–ketone adducts results in the partial electron transfer from the CTO catalyst to the BH₃ moiety. Its negative charge increases from –0.225 for the free BH₃ to –0.3. It must be emphasized, however, that electrons transferring to the BH₃ moiety are mainly distributed in the hydrogen atoms, whereas the positive charge for B_{BH₃} increases from 0.098 to 0.155. The increases in the positive charge for the carbonyl carbon and the negative charge for H_{BH₃} strengthen the interaction between the two atoms, which is advantageous to the hydride transfer from the BH₃ moiety to the carbonyl carbon of aromatic ketone. Similarly, the increases in the negative charge for the carbonyl oxygen and the positive charge for

B_{BH₃} strengthen the interaction between the carbonyl oxygen and B_{BH₃}. Finally, this interaction will result in the formation of the CTO–alkoxyborane adducts with a B–O–B–N four-membered ring.

Conclusions

All the results of this work imply that borane coordinates at the N site of chiral cyclic sulfur-containing oxazaborolidine (CTO) and that the adduct of borane and aromatic ketone to the CTO catalyst has four different structures. The structure with the lowest formation energy is **3-1d** and the structure which is of the greatest advantage to a hydride transfer from the BH₃ moiety to the carbonyl carbon of aromatic ketone is **3-1a** which is of a twisted boat structure. The chirality of the products of the enantioselective reduction of aromatic ketone catalyzed by CTO is determined by **3-1a**; i.e., the chirality of the reduced products determined by **3-1a** is the S type if CTO is of a R type, which corresponds with the experiments.

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