

Theoretical investigation on the mechanisms of transfer hydrogenation of ketones catalyzed by iridium complexes

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Abstract

The detailed catalytic mechanisms on transfer hydrogenation of ketones are explored by employing the representative reaction of 3-pentanone and 2-propanol catalyzed by the model complex $\text{IrH}_3[(\text{Me}_2\text{PC}_2\text{H}_4)_2\text{NH}]$, derived from the catalyst $\text{IrH}_3[(^i\text{Pr}_2\text{PC}_2\text{H}_4)_2\text{NH}]$, with the aid of the density functional theory calculations. The geometrical transformation from an octahedron to a Y-type involved in the catalytic cycle is also elucidated in terms of molecular theory of transition metal complexes. The trend for the variation of Ir–N bond distance is also analyzed.

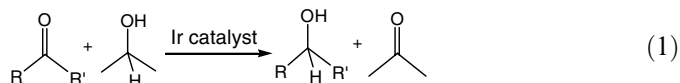
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Keywords: Transfer hydrogenation; Ketone; Iridium catalyst; Catalytic cycle; DFT

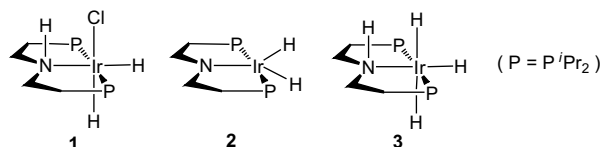
1. Introduction

Hydrogenation of ketones catalyzed by transition metal complexes is a fundamental and indispensable process for the production of a wide range of alcohols including chiral compounds [1–3]. Noyori and co-workers have developed $\text{RuCl}_2(\text{PR}_3)_2(\text{diamine})$ and $\text{RuCl}_2(\text{diphosphine})(\text{diamine})$ systems, which serve as very active and selective catalysts for hydrogenation of ketones [1–11]. They also theoretically investigated the mechanism for asymmetric transfer hydrogenation in 2001 [8]. Other transition metal catalysts containing tetradentate diaminodiphosphine or aminodiphosphine ligands have also been shown to be very effective for transfer hydrogenation of ketones [12–15]. Abdur-Rashid and Morris have developed many ruthenium complexes used as hydrogen catalysts [16,17] and clarified the reaction mechanisms [18]. It has been demonstrated that the bifunctional M–H/N–H motif, a hydride and amine *cis*-coordinated on the metal center, plays an important

role for the hydrogenation of ketones [7–9,16a,18]. Recently, Abdur-Rashid and co-workers have developed very active and effective iridium catalysts for transfer hydrogenation of a variety of ketones in 2-propanol [19]. The reactions are shown in the following equation:



The iridium chlorodihydride complex $\text{IrH}_2\text{Cl}[(^i\text{Pr}_2\text{PC}_2\text{H}_4)_2\text{NH}]$ (**1**), prepared by warming the mixture of the ligand $(^i\text{Pr}_2\text{PC}_2\text{H}_4)_2\text{NH}$ and $[\text{Ir}(\text{coe})_2\text{Cl}]_2$ (coe = cyclooctene), can serve as a precursor to the compounds $\text{IrH}_2[(^i\text{Pr}_2\text{PC}_2\text{H}_4)_2\text{N}]$ (**2**) and $\text{IrH}_3[(^i\text{Pr}_2\text{PC}_2\text{H}_4)_2\text{NH}]$ (**3**) as shown below, which are effective for transfer hydrogenation of ketones under base-free conditions [19].



Abdur-Rashid proposed the mechanistic pathway for the catalytic reaction in which $\text{IrH}_3[(^i\text{Pr}_2\text{PC}_2\text{H}_4)_2\text{NH}]$ (**3**)

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acts as a catalyst [19]. The proposed mechanism is similar in some degree to those accepted mechanisms for the hydrogenation of ketones catalyzed by *trans*-dihydro(diamine) ruthenium complexes [8,18]. Abdur-Rashid and Morris have done the theoretical study on the mechanism for the catalytic hydrogenation of ketones catalyzed by the *trans*-dihydride complexes of ruthenium in the presence of dihydrogen in 2002 [18]. To date, theoretical study on the transfer hydrogenation of ketones is limited and there have no theoretical study on this kind of reaction catalyzed by iridium complexes. In this paper, with the aid of density functional theory (DFT) calculations, we attempt to theoretically investigate the detailed reaction mechanisms for the transfer hydrogenation of ketones catalyzed by iridium complexes with the help of the experimental observations and the proposed reaction mechanism. The aim is to examine what kinds of intermediates are involved, how their structures are, and how about the related energetics in terms of thermodynamics and kinetics. We hope this work would present detailed and deep understanding for transfer hydrogenation of ketones catalyzed by transition metal complexes containing N–H/M–H motif, and provide further information for experimentalists.

2. Computational details

In our calculations, we optimized all molecular geometries at the Becke3LYP(B3LYP) level of density functional theory (DFT) [20–22]. In order to identify all stationary points as minima (zero imaginary frequencies) or transition states (one imaginary frequency), we calculated frequencies at the same level of theory. All the transition states were checked by IRC (Intrinsic Reaction Coordinate) analysis [23,24]. To describe Ir and P atoms we use the effective core potentials (ECPs) of Hay and Wadt with double- ζ valence basis sets (LanL2DZ) [25], and to describe C, H, N and O atoms we use standard 6-31G basis sets. Polarizations functions were added for H($\zeta(p)=0.11$) and those atoms directly involved in bond-forming and bond-breaking processes, C($\zeta(d)=0.8$), O($\zeta(d)=0.8$), N($\zeta(d)=0.8$) and P($\zeta(d)=0.34$) [26]. All the calculations were performed with the GAUSSIAN 98 software package [27].

The computational method and the basis sets used in this work have been widely used and recognized in theoretically studying the bonding, structures and reaction mechanisms of organometallic systems [28]. In this work, we

choose 3-pentanone as a substrate to undergo transfer hydrogenation in the presence of 2-propanol. $\text{IrH}_3[(^i\text{Pr}_2\text{PC}_2\text{H}_4)_2\text{NH}]$ (**3**) is employed as a catalyst. For saving computational time, the catalyst is modeled by replacing the ^iPr group with methyl to give the model catalyst, $\text{IrH}_3[(\text{Me}_2\text{PC}_2\text{H}_4)_2\text{NH}]$ (**Cat**). Table 1 shows both the original catalyst **3** and the model catalyst **Cat** have close structural data, indicating the modeling of the catalyst is reasonable.

3. Results and discussion

3.1. Reaction mechanisms

Abdur-Rashid and co-workers have proposed the reaction mechanism for transfer hydrogenation of ketones catalyzed by the catalyst, $\text{IrH}_3[(^i\text{Pr}_2\text{PC}_2\text{H}_4)_2\text{NH}]$ (**3**), on the basis of their experimental observations [19]. Based on Abdur-Rashid's proposal and our calculated results, the more detailed catalytic cycle for the transfer hydrogenation of 3-pentanone in the presence of 2-propanol is shown in Fig. 1. Step I is formation of the N–H \cdots O=C hydrogen

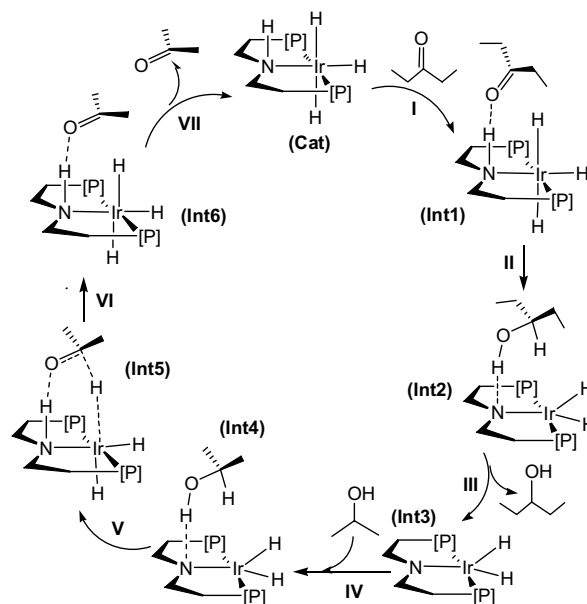


Fig. 1. Theoretically proposed catalytic cycle for transfer hydrogenation of 3-pentanone catalyzed by iridium trihydride complex in the presence of 2-propanol.

Table 1
Selected calculated bond angles ($^\circ$) and bond lengths (\AA) of the initial catalyst $\text{IrH}_3[(^i\text{Pr}_2\text{PC}_2\text{H}_4)_2\text{NH}]$ (**3**) and the model catalyst $\text{IrH}_3[(\text{Me}_2\text{PC}_2\text{H}_4)_2\text{NH}]$ (**Cat**)

	P–Ir–P	N–Ir–H2	Ir–N	Ir–P	Ir–H2	Ir–H3	Ir–H4	N–H1
3	168.0	92.7	2.26	2.30	1.68	1.60	1.68	1.02
Cat	167.7	92.3	2.27	2.29	1.69	1.60	1.69	1.02

bonding. In step II (**Int1** to **Int2**), the hydrogen atoms on nitrogen and iridium are respectively transferred to the oxygen and the O=C carbon of 3-pentanone, to form the O–H and C–H bonds. Step III is disassociation of the product 3-pentanol from **Int2** to give a five-coordinate iridium complex **Int3**, and step IV is the occurrence of hydrogen bonding between 2-propanol and **Int3**. Step V is formation of the N–H bond accompanying the occurrence of the C···H···Ir interaction. Step VI is formation of Ir–H bond, and finally, step VII is the dissociation of another product, 2-propanone, to regenerate the catalyst. On the whole, the catalytic cycle consists of two parts. One is the hydrogenation of 3-propanone (steps I–III) by the catalyst, and the other is dehydrogenation of 2-propanol to regenerate the catalyst (steps IV–VII).

3.2. Calculated energy profile

The transformations including related transition states are illustrated in Scheme 1. The potential energy profile for the transfer hydrogenation of 3-pentanone catalyzed by the model catalyst $\text{IrH}_3[(\text{Me}_2\text{PC}_2\text{H}_4)_2\text{NH}]$ (**Cat**) in the presence of 2-propanol is shown in Fig. 2. The geometrical structures together with selected structural parameters are shown in Fig. 3.

The geometrical structure of the catalyst (**Cat**) was optimized at the B3LYP level of density functional theory as shown in Fig. 3, which is consistent with the experimental prediction. The Ir center is coordinated by three hydrides and the tridentate ligand, $(\text{Me}_2\text{PC}_2\text{H}_4)_2\text{NH}$, to give a

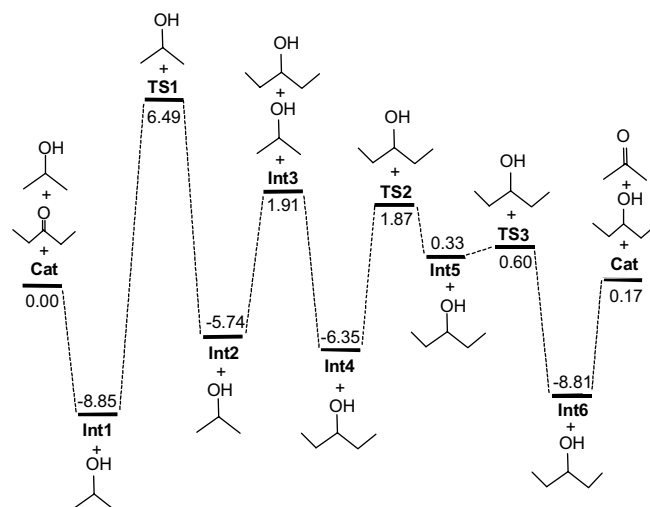
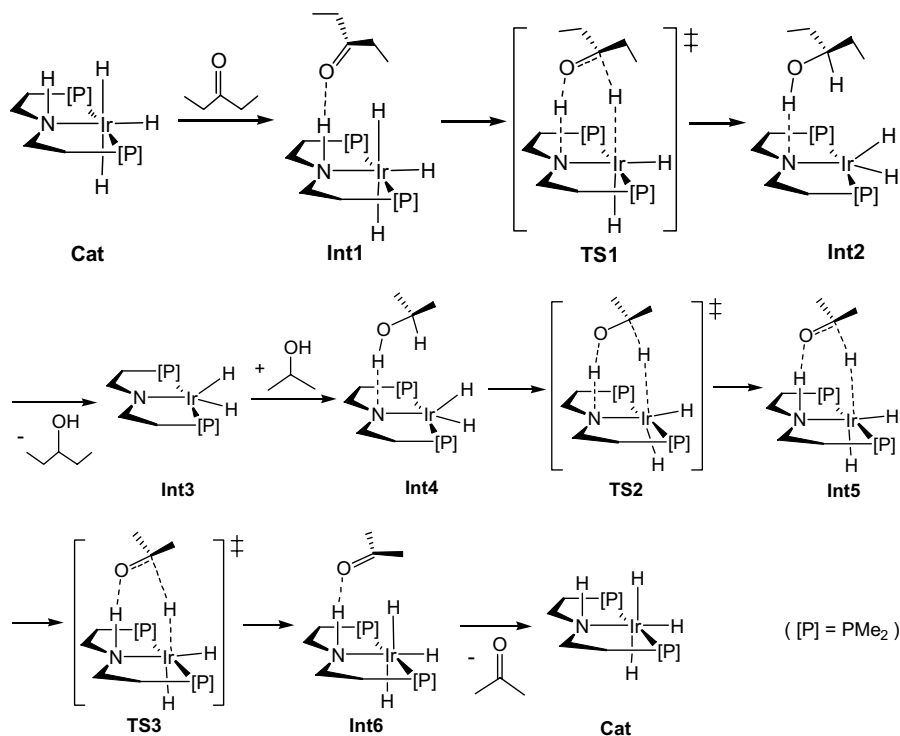


Fig. 2. Potential energy profile for transfer hydrogenation of 3-pentanone catalyzed by iridium trihydride complex in the presence of 2-propanol. The energies are given in kcal/mol.

six-coordinate octahedral complex. As is known, the hydride has high *trans*-influence while the amine has low *trans*-influence. Therefore, H2 and H4 can be labilized by each other to a higher degree than H3 by the amine ligand. As a result of our calculations, Ir–H₂ and Ir–H₄ are longer than Ir–H₃. In other words, H2 and H4 are more reactive than H3. As 3-propanone approaches to the catalyst, an intermediate (**Int1**) is located in which the N–H1···O=C hydrogen bonding occurs. The N–H1 becomes longer by only 0.0031 Å, indicating this interaction is weak. Other



Scheme 1. Proposed reaction mechanism for transfer hydrogenation of 3-pentanone catalyzed by iridium trihydride complex in the presence of 2-propanol.

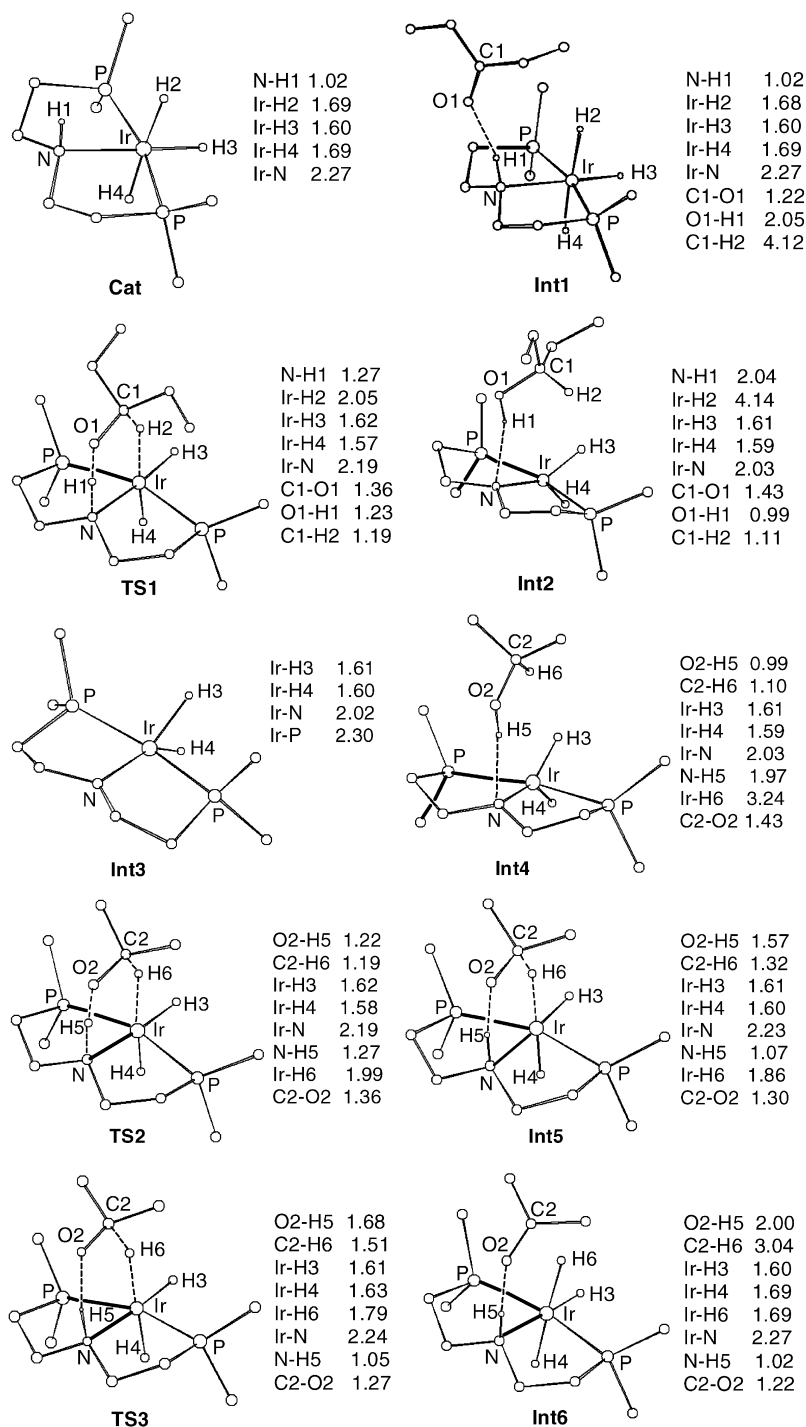


Fig. 3. B3LYP optimized structures for those species shown in Fig. 1 together with selected bond distances. The bond distances are given in Å. For clarity, the H atoms on all the carbon atoms, except for the C2 atom of 2-propanol, are omitted.

bond distances remain almost unchanged. **Int1** is more stable than (**Cat** + 3-propanone) by -8.85 kcal/mol, mainly arising from the occurrence of the hydrogen bonding. In the step **Int1** to **Int2**, H1 and H2 migrate from nitrogen and Ir to O1 and C1, respectively, to form a O1–H1 and a C1–H2 bond. As calculated, the C1–O1 bond is elongated from **Int1** via **TS1** to **Int2**. **TS1** is confirmed by MP2 calculations directly connecting **Int1** and **Int2**. The amine

changes from a L-type to a X-type ligand. The Ir–N bonding changes from a dative to a normal covalent bond, resulting in the Ir–N bond shorter. **Int2** becomes five-coordinate due to the loss of H2, making the complex changing from an 18e to a 16e species. It is noted that as the Ir center becomes five-coordinate, the structure of **Int2** turns to a Y-type geometry, while not remain a square planar one. And, the subsequent **Int3** and **Int4** have also the Y-type

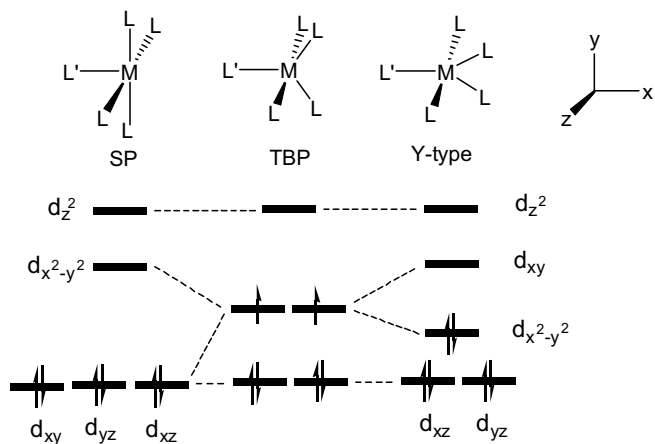


Fig. 4. Orbital correlation diagram for the metal d orbitals which connect square planar, trigonal bipyramidal and Y-type geometries.

geometry. The H3–Ir–H4 bond angles are calculated to be 67.6°, 67.6° and 67.8° in the three intermediates, respectively. This can be rationalized in terms of molecular theory of transition metal complexes [29,30]. As shown in Fig. 4, for a 16e d^6 ML₅ transition metal complex, TBP is the least stable, Y-type is intermediate, and SP is the most stable. In fact, d^6 ML₅ species never show pure TBP, but show SP or Y-type geometry, dependent on the character of L'. Normally, a Y-type geometry is favored when L' is a π -donor like N and Cl, and SP geometry is preferred when L' is a high-*trans*-effect ligand. In **Int2**, **Int3** and **Int4**, N serves clearly as a π -donor, so the Y-type geometry is preferred. The step from **Int2** to **Int3** is the removal of 3-pentanol. **Int3** is less stable than **Int2** as a result of breaking the N···H1–O1 hydrogen bonding. The course from **Cat** to **Int3** completes the hydrogenation of 3-pentanol.

As 2-propanol approaches **Int3**, the N···H5–O2 hydrogen bonding is formed in **Int4**. The Ir–N becomes longer only slightly. From **Int4** to **Int5**, H5 migrates from O2 to nitrogen to afford a N–H5 bond and also the C2···H6···Ir interaction occurs. As shown in Fig. 3, the O2–H5 and C2–H6 increase, and N–H5 and Ir–H6 decrease in distance from **Int4** via **TS2** to **Int5**. **Int5** is less stable than **Int4** due to the fact that the C2···H6···Ir interaction is not very stable. The Ir–N bonding changes in nature from a normal covalent bond in **Int4** to a dative bond in **Int5**. The activation barrier for the step is calculated to be only 0.27 kcal/mol. To verify **Int5** to be a stationary point, we optimized it by using HF and MP2 methods. The basis set employed for the two methods is the same as in the B3LYP calculations. Our results of calculations show that the HF and MP2 calculated structures are similar to the B3LYP calculated structure. The Mulliken charge on the migrating H5 is calculated to be 0.60, indicating that the H5 on N migrates as a proton. The negative charge (–0.29) on the migrating H6 indicates that H6 serves mainly as a hydride in **Int5**. From **Int5** to **Int6**, H6 again migrates to the metal center from C2 to form an Ir–H6 bond. In this transforma-

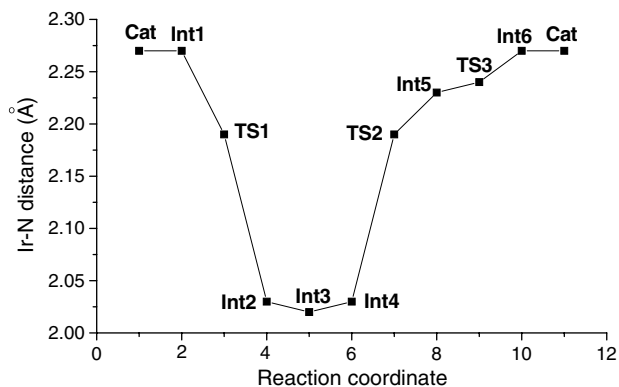


Fig. 5. Variation for Ir–N distance of all the species with the reaction coordinate in the catalytic cycle.

tion, **Int6** becomes an 18e d^6 species having an octahedral geometry. Finally, disassociation of 2-propanone from **Int6** regenerates **Cat** to complete the catalytic cycle. All the reaction energy difference is calculated to be 0.17 kcal/mol, indicating this reaction is thermodynamically in equilibrium.

It is interesting to find that the Ir–N distance involved in all the species has a trend as shown in Fig. 5. In **Cat** and **Int1**, the Ir–N distance is long due to the bond being a dative bond. From **Int1** via **TS1** to **Int2**, the Ir–N distance decreases sequentially because the Ir–N bond is changed from a dative bond toward a covalent σ -bond with the migration of H1 and H2 from N and Ir to O1 and C1, respectively. There is sharp decrease for Ir–N distance from **TS1** to **Int2**. Two factors contribute to the bond strength. One is that the bond has almost completely become a normal covalent bond. The other is that the geometry around Ir center changes from an octahedron to a Y-type which reduces the *trans*-influence between N and H3. The Ir–N distance is just slightly decreased from **Int2** to **Int3** due to the disappearance of the O1–H1···N weak hydrogen bonding.

Conversely, the Ir–N distance is a slight increase from **Int3** to **Int4** as a result of the occurrence of the O2–H5···N weak hydrogen bonding, a sharp increase from **Int4** to **TS2** as a result of the bond changing from a normal covalent σ -bond to a dative bond and the increased N–Ir–H3 *trans*-influence, and a mild increase from **TS2**, through **Int5**, **TS3** and **Int6**, to **Cat** as a result of the bond changing to a complete normal covalent bond.

4. Conclusions

On the basis of the experimental observations, the transfer hydrogenation of ketones catalyzed by the catalyst IrH₃[(ⁱPr₂PC₂H₄)₂NH] is theoretically investigated with the aid of the density functional theory calculations. Detailed mechanistic study on the catalytic cycle for the reaction of 3-pentanone with 2-propanol catalyzed by the model catalyst IrH₃[(Me₂PC₂H₄)₂NH] is revealed. The catalytic reaction mainly consists of two parts. The first part is the hydrogenation of 3-pentanone by the catalyst in

which the two hydrogen atoms attached on the N and Ir of the catalyst are transferred to the oxygen and the carbonyl carbon of 3-pentanone. The other is the dehydrogenation of 2-propanol by the catalyst in which the two hydrogen atoms from the oxygen and the carbonyl carbon of 2-propanol are transferred to the nitrogen and the Ir center of the catalyst one after the other. In addition, the related geometric changes involved in the catalytic cycle was elucidated in terms of the molecular theory of transition metal complexes. The variation for Ir–N distance of all the species along the reaction coordinate in the catalytic cycle was also analyzed. It is found that the Ir–N distance decreases from **Cat** to **Int3**, and increases from **Int3** to **Cat** sequentially along the reaction coordinate.

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