Synopsis

Significant developments have been made in the field of C–H activation. However, various disadvantages, mainly low reactivity and selectivity, limit their usage in large-scale synthesis. It is crucial to understand the mechanisms and the nature of the transient species involved in the C–H activation paths to develop effective catalytic routes for homogeneous C–H functionalization reactions. Computational techniques are employed in this study to throw light on these processes.

Chapter 1 briefly introduces C–H activation and functionalization reactions. After classifying the reactions on the basis of mechanisms, computational studies on the mechanisms of C–H activation reactions are described. The challenges involved in the discovery of efficient homogeneous C–H functionalization catalysts and progress made in the field are discussed. The insights provided to overcome the problems associated with the catalytic C–H functionalization reactions in a few examples are highlighted.

In Chapter 2, DFT model studies are carried out to estimate the affinity and selectivity of 16-electron half-sandwich d^6-metal fragments (η^5–C_5H_5)Re(CO)_2 and (η^6–C_6H_6)W(CO)_2 for binding with alkane C–H bonds. Different C–H binding sites of pentane, at the M06 level of theory have been evaluated. The effects of ancillary ligand variations on the metal–pentane binding strength are studied by substituting different ligands such as N-heterocyclic carbene (NHC), PF_3 and NO^+ for one of the carbonyl ligands. Isomers of the metal-pentane C–H σ-complexes studied in this chapter are shown in Scheme 1.

Binding energies of the terminal methyl C–H bonds (C1 and C5) are significantly lower than those of the methylene C–H bonds (C2, C3 and C4) in all the cases. The metal–pentane binding interactions of the rhenium complexes are significantly stronger than those of the corresponding tungsten analogs. The PF_3 complexes have slightly greater binding energies compared to the CO complexes, in both Re(I) and W(0) analogs. These results are in conformity with the experimental results. The electron-deficient nitrosyl complexes have the highest binding energies. These results illustrate that by proper tuning of the electronic factors of the transition-metal fragments with different ancillary ligands, the alkane C–H binding affinity can be controlled. Energy decomposition analyses (EDA) are carried out to determine the nature of the interaction between the metal fragments and pentane C–H bonds.
Chapter 3 addresses the energetics of various intramolecular site-exchange (chain walking) processes and C–H oxidative addition reactions (Scheme 2) of the pentane C–H σ-complexes studied in Chapter 2. Four possible site-exchange processes such as 1,2-, 1,3-, 1,4- and 1,5-migration processes are studied using DFT/M06 level of theory. η²-(H,H)···M type transition states are located for these migrations (Scheme 2). The 1,3-migration is the most favorable process. Two different pentyl hydride isomers, as shown in Scheme 2, are obtained for oxidative addition of methyl and methylene C–H bonds of pentane for all systems, at same level of theory. Oxidative insertion of metal into the methyl C–H bonds is more favorable than insertion into the methylene C–H bonds for all complexes.

The activation energies of all site-exchange and C–H oxidative addition processes of the Re(I) complexes are significantly greater than those of the corresponding W(0) complexes. For all these processes, the activation barriers of the electron-deficient NO⁺ complexes are the greatest among all ligand systems studied, in both Re(I) and W(0) systems. These results are consistent with the experimental results and suggest that the experimentally observed pentyl hydride isomer $[(\eta^5-C_5H_5)\text{Re(CO)}(\text{PF}_3)\text{H}(\text{C}_5\text{H}_{11})]$ might be Isomer B and not Isomer A (Scheme 2). The C–H oxidative addition reactions are less favorable than dynamic site-exchange processes in all complexes. These results imply that the metal fragments migrate along the pentane chain more easily than insert into the pentane C–H bonds.
Chapter 4 deals with the mechanisms and energetics of a unique metal migration process of an olefin complex that proceeds via olefinic (C–H)···Metal interaction. Migration of the Re(I) fragment from one \( \pi \) face of the olefin to the opposite \( \pi \) face in \([\eta^5\text{-C}_5\text{H}_5]\text{Re(NO)(PPh}_3\text{(PhCH=CH}_2\text{)]^+}\) has been documented experimentally by Gladysz and coworkers. The experimental results provide evidences for an intramolecular mechanism for this process (i.e., without styrene dissociation from Re(I)) and based on kinetic isotope effects (KIE), the involvement of a \textit{trans} C–H bond is indicated. Either oxidative addition or a vinylic (C–H)···Re interaction could account for the experimentally observed kinetic isotope effect.

In this study, the free energy of activation for the migration of Re from one enantioface of the olefin to the other through various pathways is computed using DFT calculations at the B3LYP and M06 levels. Two pathways, one that involves migration of Re
through a *trans* (C–H)⋯Re interaction and another that involves oxidative addition of Re into the *trans* C–H bond, are identified as possible paths (Scheme 3) at the B3LYP level. Surprisingly, at the M06 level, DFT computes a lower energy path for the conducted tour mechanism that is not consistent with the experimental KIE. But the computed energy profiles for the reaction are consistent with the experiment when computations are carried out at the B3LYP level.

**Scheme 3.** Mechanisms of olefin π face exchange reaction

In Chapter 5, the mechanistic studies of C–H metathesis of d⁶ half-sandwich complex [(η⁵–C₅Me₅)Ru(CH₃)(CO)(C₆H₆)] are discussed. A 1-step mechanism that proceeds via a four-center transition state and a 2-step Oxidative Addition and Reductive Coupling mechanism (OA/RC) are identified as possible mechanisms (Scheme 4) using DFT/M06 level of theory. The 1-step mechanism is more favorable than the 2-step mechanism. As in the oxidative addition intermediate, metal–hydrogen bond is observed in the four-center transition state of the 1-step mechanism. This mechanism is referred to as Oxidative Hydrogen Migration (OHM) rather than σ-Bond Metathesis (σ-BM) which proceeds via a transition state without M–H bonding. The effects of metal (M = Fe(II), Ru(II) or Os(II)) and ancillary ligand (L = H–, NHC, CO or NO⁺) variations on the mechanisms and energetics of the model Cp complex [(η⁵–C₅H₅)M(CH₃)(L)(C₆H₆)] are also studied (Scheme 4).
Increase in the electron-density on the metal center, using electron-donating ligands such as $\text{H}^-$, favors the formation of the oxidative species (intermediate or transition state) and reduces the activation barriers of the C–H metathesis reaction. Similarly, the electron-withdrawing NO$^+$ ligand, which reduces the electron density on the metal center, increases the activation energies of the C–H metathesis reaction or disfavors the formation of the oxidative species. Factor affecting the choice of the mechanism of the C–H metathesis reaction is found to be the net charge transfer between the two fragments $[\eta^5\text{C}_5\text{H}_5]\text{M}(\text{CH}_3)(\text{L})$ and benzene in $[\eta^5\text{C}_3\text{H}_5]\text{M}(\text{CH}_3)(\text{L})(\text{C}_6\text{H}_6)]$.

The computational studies reported in this thesis provide valuable insight into the mechanisms and energetics of C–H binding, activation and fluxional processes of the (C–H)···Metal $\sigma$ alkane and alkene complexes. These studies will be helpful in solving problems associated with the C–H activation reactions.

Reference
Thenraj, M.; Samuelson, A. G. Organometallics 2013, 32, 7141.