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Computational catalysis using density functional theory (DFT) and artificial force-induced reaction (AFIR) method

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Transition metal catalysis is an efficient way to perform catalytic reactions in a controlled and a selective fashion. Quantitative details of the mechanism and selectivity of a catalytic reaction are very important to develop more efficient catalysis. In this direction, computational chemistry is very useful.[1,2] We have used density functional theory (DFT) and artificial force-induced reaction (AFIR) method to rationalize the mechanism and selectivity of two catalytic reactions,[3,4] specifically iron-catalyzed carbon-carbon bond formation reaction in aqueous media,[5] and a palladium-catalyzed regioselective borylative ring-opening reaction of 2-arylaziridines.[6] The multi-component (MC)-AFIR method was used to probe conformational complexity in the selectivity-determining step. The energy decomposition analysis (EDA) was used to establish the origin of the selectivity.

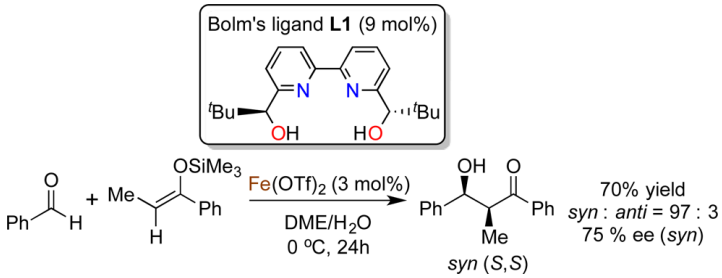

Figure 1. Carbon-carbon bond formation between silyl enol ethers and aldehyde catalyzed by iron(II) with the Bolm's ligand (L1)

Development of transition metal catalysts for efficient and highly selective carbon-carbon bond formation reactions is very important in synthetic organic chemistry. Figure 1 shows the iron-catalyzed enantioselective carbon-carbon reaction that works in aqueous media under mild conditions. Thermodynamically stable six- or seven-coordinate complexes in the solution were rationalized by DFT. The active intermediates for the selectivity-determining outer-sphere carbon-carbon bond formation were proposed, and transition states (TSs) for this step was systematically determined by MC-AFIR. The calculated diastereomeric ratio and enantiomeric excess are in good agreement with the experimental data. The overall mechanism consists of (a) coordination of the aldehyde, (b) selectivity determining carbon-carbon bond formation, (c) rate-determining proton transfer from water to aldehyde, and (e) dissociation of trimethylsilyl group. According to EDA, deformation (DEF) of the substrates (i.e. aldehyde and silyl enol ether) is responsible for the origin of the selectivity. The selectivity of the reaction can be improved by modifying the bulky substituents in L1 and the substrates or by modifying the tetradentate ligand. Our study provides important mechanistic insights for the development of Fe-based catalysts for carbon–carbon bond formation reactions.

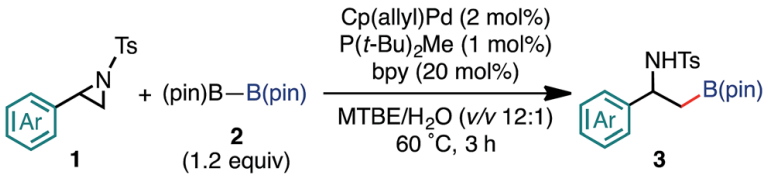

Figure 2. Palladium-catalyzed regioselective ring-opening reaction of 2-arylaziridines.

Aziridine rings can be opened in a stereo- and regioselective fashion to synthesize chemically or biologically important organic compounds. Low-valent late-transition-metal complexes can be used as the catalysts for this purpose. We have developed a palladium-catalyzed regioselective ring-opening reaction of 2-arylaziridines (Figure 2). Our NMR and DFT studies suggested that the active form of the catalyst is a PdL_2 complex, where L = P(*t*-Bu)$_2$Me. The regioselectivity-determining aziridine ring-opening step was systematically determined by MC-AFIR. The calculated regioselectivity is in agreement with the experimental results, where the ring-opening is favorable at the less-hindered carbon in the S_N2 fashion. According to EDA, origin of the selectivity comes from the interactions (INT) between the catalyst and the substrate. The subsequent steps of the full catalytic cycle consist of (a) proton transfer, (b) phosphine ligand dissociation from the catalyst, (c) rate-determining boron-boron bond cleavage, and reductive elimination. Our study guides the design of catalytically novel and chemically significant regioselective ring-opening reactions of aziridines.

References

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