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Title	Quantum Chemical Calculation-Aided Design of Carboxylation Reactions and Their Experimental Demonstration
Author(s)	神名, 航
Degree Grantor	北海道大学
Degree Name	博士(理学)
Dissertation Number	甲第16363号
Issue Date	2025-03-25
DOI	https://doi.org/10.14943/doctoral.k16363
Doc URL	https://hdl.handle.net/2115/94943
Type	doctoral thesis
File Information	KANNA_Wataru.pdf



Quantum Chemical Calculation-Aided Design of Carboxylation Reactions and Their Experimental Demonstration

(量子化学計算を活用した
カルボキシル化反応の設計と実験的実証)

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March 2025

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Chapter 1. General Introduction

1.1. Theoretical analysis of chemical reactions

Chemical reactions are fundamental to numerous processes, from combustion to biological systems, driving the transformations essential to life and technology. They involve the reorganization of atoms and bonds, converting one or more chemical substances into others. Understanding and controlling these reactions is critical for advancing fields such as drug discovery and the creation of innovative materials. While experimental studies have traditionally played a central role in uncovering reaction mechanisms, theoretical calculations have emerged as a powerful complement. These methods offer unparalleled insights into the atomic-scale dynamics of reactions, enabling predictions and designs that were once beyond reach.

1.1.1. Transition state theory

Reaction kinetics provides a framework for understanding chemical reactions as the time-dependent evolution of the concentrations of chemical species. Within this framework, the reaction rate is a fundamental concept, defined as the change in concentration per unit time. When the reaction rate is proportional to the concentration raised to the power of d , the reaction is referred to as a d -th order reaction, and the proportionality constant is termed the rate constant.

Rate constants are often determined experimentally. However, simulating chemical reactions kinetically requires a theoretical approach to estimate rate constants based on quantum chemical calculations. Transition state theory (TST)¹ enables the computation of rate constants without relying on experimental parameters. Instead, TST employs a statistical treatment of reaction dynamics, using information from the potential energy surface (PES) alone to estimate rate constants.

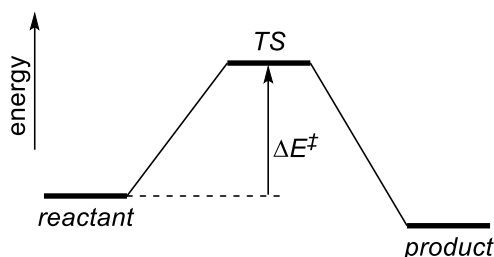


Figure 1.1. Transition state in chemical reactions

In Transition State Theory (TST), two key assumptions are introduced. The first is the non-recrossing assumption. In this assumption, a concept called the transition state (TS) is defined as a hyperplane in phase space that separates the reactant region from the product region. The non-recrossing assumption states that once a trajectory crosses the TS from the reactant region to the product region, it will not return to the reactant region. The second assumption is the quasi-equilibrium assumption, which assumes that thermal equilibrium is maintained within the reactant region. Based on these two assumptions, the rate constant can be estimated using the following equation.

$$k = \frac{k_B T}{h} \frac{Q_{TS}}{Q_R} \exp\left(-\frac{\Delta E^\ddagger}{k_B T}\right) \quad (1.1)$$

In eq. (1.1), k is the rate constant, k_B is Boltzmann's constant, T is temperature, h is Planck constant, and Q_{TS} and Q_R are the distribution functions for TS and reactants, respectively. $\Delta E^\ddagger$ is the potential energy difference between the reactant region and TS. Reactant region and TS are usually characterized by minimum (MIN) on the PES and first-order saddle point on the PES. Q_{TS} and Q_R are also estimated based on the harmonic approximation for those points. Once the rate constants are obtained, chemical reactions can be simulated by solving the resulting rate equations.

1.1.2. Marcus theory

Marcus theory is a framework that explains how electrons are transferred between molecules during a chemical reaction². It focuses on energy changes and the interactions between the reactants and the environment (like solvents) during this process.¹ In the framework of Marcus theory, TS of electron transfer is the crossing point of two curves: a potential curve of reactants and that of products.

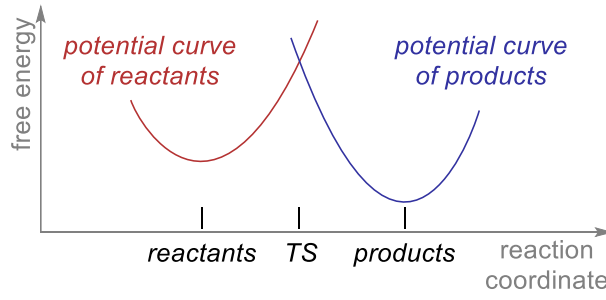


Figure 1.2. TS of electron transfer in the framework of Marcus theory.

The expression for the rate constant k of the reaction is given by

$$k = A \exp\left(-\frac{\Delta G^*}{k_B T}\right) \quad (1.2a)$$

where ΔG^* , in turn, is given by

$$\Delta G^* = \frac{\lambda}{4} \left(1 + \frac{\Delta G^0}{\lambda}\right)^2 \quad (1.2b)$$

The A in eq. (1.2b) is a term depending on the nature of the electron transfer reaction (e.g., bimolecular or intramolecular), ΔG^0 is the standard free energy of reaction and equals zero for a self-exchange reaction, λ is a “reorganization term”, composed of solvational (λ_0) and vibrational (λ_i) components.

$$\lambda = \lambda_0 + \lambda_i \quad (1.3)$$

1.1.3. Crossing point optimization

In quantum chemical calculations, ΔG^* in eq. (1.2a) is a relative energy of minimum energy crossing point to that of minimum in the state before ET. For states before/after ET, ignoring the coupling between these and other states, consider the following two-level potential matrix:

$$\hat{V} = \begin{vmatrix} V_{BET} & U \\ U & V_{AET} \end{vmatrix} \quad (1.4)$$

where V_{BET} and V_{AET} are the diabatic potentials of states before/after ET, and U is the diabatic coupling. Following equations of the adiabatic potentials E_1 and E_2 are given by diagonalization of this matrix.

$$E_1 = \frac{1}{2} (V_{BET} + V_{AET}) - \frac{1}{2} \sqrt{(V_{BET} - V_{AET})^2 + 4U^2} \quad (1.5a)$$

$$E_2 = \frac{1}{2} (V_{BET} + V_{AET}) + \frac{1}{2} \sqrt{(V_{BET} - V_{AET})^2 + 4U^2} \quad (1.5b)$$

Because eq. (1.5a) and (1.5b) have the same form as the equation of a cone, the potential crossing

between the states with non-zero diabatic couplings U is called a conical intersection (CI). On the other hand, between the states with different symmetry or spin, the intersection is not conical because of zero diabatic couplings U , and such a potential crossing is called seam of crossing (SX).

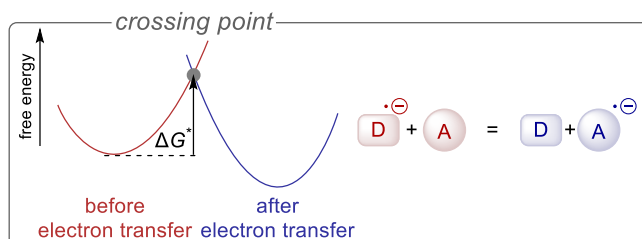


Figure 1.3. Crossing point between two states: before/after electron transfer.

In case of single electron transfer (SET) reaction, crossing point is the state where the total energy of an electron donor $D^{\bullet+}$ and an electron acceptor A (denoted as $E(D^{\bullet+}+A)$) is the same as that of an oxidized electron donor D and a reduced electron acceptor $A^{\bullet+}$ (denoted as $E(D+A^{\bullet+})$). Therefore, following equation is a requirement to be crossing of the states.

$$E(D^{\bullet+} + A) = E(D + A^{\bullet+}) \quad (1.6)$$

1.1.4. Energy shift method for crossing point estimation

Electron transfer reactions are categorized into two types of mechanisms: inner sphere electron transfer where electron donor and electron acceptor are covalently connected and outer sphere electron transfer where electron donor and electron acceptor are not covalently connected. In the outer sphere mechanism, it can be assumed that there is little interaction between donor and acceptor. With this assumption, eq. (1.6) can be deformed as follows:

$$E(D^{\bullet+}) + E(A) = E(D) + E(A^{\bullet+}) \quad (1.7a)$$

Eq. (1.7a) can also be described as follows:

$$E(D^{\bullet+}) + (E(A) - E(A^{\bullet+})) = E(D) \quad (1.7b)$$

The second term in eq. (1.7b), $(E(A) - E(A^{\bullet+}))$, is an energy difference of electron acceptor in two different states, before/after ET, and replacing the term with redox potential of $A/A^{\bullet+}$ gives following equation:

$$E(D^{\bullet+}) + V(A/A^{\bullet+}) = E(D) \quad (1.7c)$$

where, $V(A/A^{\bullet+})$ is redox potential of $A/A^{\bullet+}$. In eq. (1.7c), crossing point is denoted as where $E(D^{\bullet+})$

shifted by the redox potential equals $E(D)$. Therefore, crossing points for ET can be estimated by optimizing the crossing points between $E(D)$ and shifted $E(D^{\cdot-})^3$. Note that crossing points also can be estimated by optimizing the crossing points between $E(A)$ and $E(A^{\cdot-})$ shifted with redox potential of electron donor $V(D/D^{\cdot-})$.

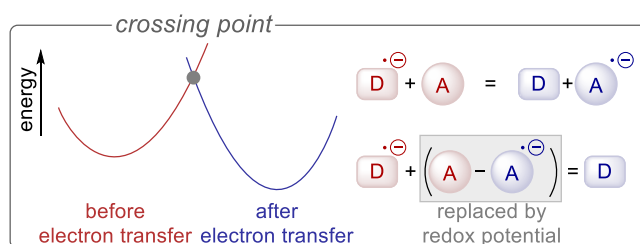


Figure 1.4. Energy shift approach for crossing point estimation.

1.2. Quantum chemical calculation as a prediction tool

1.2.1. Advantages

Quantum chemical calculations are commonly used to investigate molecular properties and reaction mechanisms, offering detailed insights into known reactions. Now, not only the charge transfer reactions explained above, but also other phenomena in chemical reactions, can now be described through quantum chemistry calculations due to advancements in computational methods. In other words, with the progress of quantum chemical computational techniques, the scope of what can be reproduced by calculations in chemical reactions has significantly expanded. If the quantum chemical calculations can provide results almost same as experimental outcomes, calculations have significant potential as a tool to predict “what happens in a flask”.

Because in quantum chemical calculations, synthesis of substrates and catalysts is not required, calculations have great potential to accelerate reaction development processes. Computational predictions are particularly powerful when identifying candidates for substrates and/or catalysts is challenging. Moreover, advancements in computational hardware have dramatically reduced calculation times over the past few decades, a trend that is expected to continue. This acceleration in computational capabilities will drastically reduce experimental costs, and that is one of the major advantages of theory-driven reaction design.

1.2.2. Challenges

Unlike methods in biochemistry that simulate single processes (e.g., molecular docking), quantum chemical predictions require analyzing multiple potential reaction pathways. However, some complex phenomena, like dynamical bifurcations, are still challenging to model accurately. While primarily used for mechanistic understanding, these calculations are increasingly seen as critical for developing new synthetic methodologies, such as novel selectivities, catalyst designs, and synthetic routes.

Although these predictive strategies are not yet fully mature for practical applications, they hold promise as a transformative tool in the future.

1.3. Purpose of the thesis

The purpose of this thesis is to showcase how quantum chemical calculations can be used as a tool for reaction design, predicting the outcomes of experiments conducted in a flask. Furthermore, the use of quantum chemical calculations as prediction tools was extended to electron transfer reactions, where transition states are crossing points of two different potentials.

1.4. Overview of the thesis

Chapter 1 gives the general introduction for theoretical analysis of chemical reaction. In addition, prediction of chemical reactions using quantum chemical calculation is discussed.

In Chapter 2, development of a new reaction, carboxylation of a palladacycle(II) formed via $C(sp^3)-H$ activation, utilizing quantum chemical calculation as a prediction tool is described. On this research, palladacycle formed via $C(sp^3)-H$ activation was selected as a substrate of carboxylation with CO_2 . I focused on a key intermediate, Pd(I) complex, generated via one-electron reduction of a palladacycle(II). At first, computational search with automated search method for unstable species, Pd(I) intermediates which are hard to investigate their character and reactivity experimentally is shown. Next, computational prediction of the reactivity calculating pathways of carboxylation with CO_2 from possible intermediates is shown. And then, reactions were conducted experimentally, and the predicted reaction was verified.

In Chapter 3, development of catalytic olefin aminocarboxylation is shown. In this research, a new computational method was introduced to search for representative crossing points. With the method, crossing points of concerted one-electron reduction and carboxylation were found, and the diastereoselectivity of product β -amino acids was predicted based on kinetics in the crossing region. Finally, the reaction was verified experimentally in the same diastereoselective manner as predicted.

Chapter 4 summarizes this thesis and describes a future perspective.

1.5. References

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- (2) For Marcus theory, see: (a) Marcus, R. A. On the Theory of Oxidation-Reduction Reactions Involving Electron Transfer. I. The Journal of Chemical Physics **1956**, *24*, 966–978. (b) Marcus, R. A. Electrostatic Free Energy and Other Properties of States Having Nonequilibrium Polarization. I. *J. Chem. Phys.* **1956**, *24*, 979–989. (c) Marcus, R. A. On the Theory of Oxidation-Reduction Reactions Involving Electron Transfer. II. Applications to Data on the Rates of Isotopic Exchange Reactions. *J. Chem. Phys.* **1957**, *2*, 867–871. (d) Marcus, R. A. On the Theory of Oxidation-Reduction Reactions Involving Electron Transfer. III. Applications to Data on the Rates of Organic Redox Reactions. *J. Chem. Phys.* **1957**, *26*, 872–877.
- (3) Harabuchi, Y.; Hayashi, H.; Takano, H.; Mita, T.; Maeda, S. Oxidation and Reduction Pathways in the Knowles Hydroamination via a Photoredox-Catalyzed Radical Reaction. *Angew. Chem., Int. Ed.* **2023**, *62*, e202211936.

Chapter 2. Carboxylation of a Palladacycle Formed via C(sp³)–H Activation: Theory-Driven Reaction Design

2.1. Introduction

2.1.1. C(sp³)–H carboxylation

C–H activation is a powerful tool owing to its ability to cleave relatively unreactive C–H bonds, the pK_a values of which are usually greater than 30, under almost neutral conditions without the need for highly basic or acidic reagents.¹ Over the last three decades, many C–H functionalization reactions catalyzed by transition metals have been discovered. C(sp³)–H bonds are ubiquitous, yet stable compared to hybridized C–H bonds and therefore catalytic transformations of these bonds are a significant challenge.² For example, transforming C(sp³)–H + CO₂ to C(sp³)–CO₂H, ideally in the absence of any additional stoichiometric reagents, is a very attractive reaction due to the potential for realizing an atom-economic transformation from CO₂. CO₂ is an ideal C1 synthon as it is abundant, inexpensive, non-toxic, and potentially renewable.³ However, since CO₂ is chemically stable due to its linear structure resulting from the delocalization of its lone pair electrons over each adjacent C=O π bond, harsh reaction conditions are generally required to break this linear orientation and successfully synthesize carboxylic acid derivatives. Therefore, the development of reactions between C(sp³)–H bonds and CO₂ under mild conditions using transition-metal catalysts remains extremely difficult.

Murakami previously reported that UV light can promote benzylic, allylic, and aliphatic C(sp³)–H carboxylations by merging a photoredox catalyst and a transition-metal catalyst (Figure 2.1).⁴ Meanwhile, Jamison developed a UV-light-promoted catalytic C(sp³)–H carboxylation at the position adjacent to a nitrogen atom, a reaction suitable for preparing α -amino acids.⁵ Although these methods represent milestones in the development of catalytic C(sp³)–H carboxylations, they require irradiation with high-energy UV light.

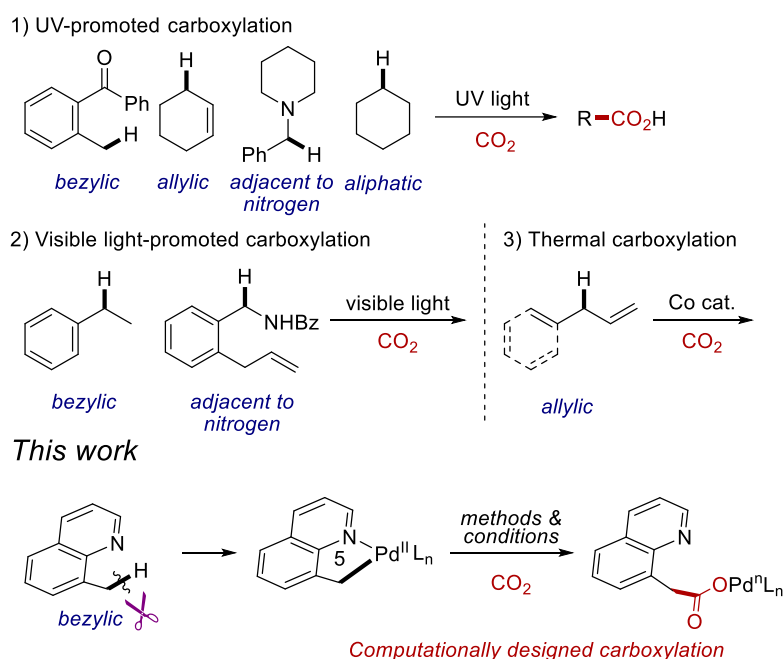


Figure 2.1. Previous examples of C(sp³)-H carboxylation reactions.

Very recently, König reported the carboxylation of benzylic C(sp³)-H bonds using a combination of a photoredox catalyst and a hydrogen atom transfer (HAT) catalyst with irradiation of the reaction with a blue LED.⁶ Moreover, Yu reported the carboxylation of C(sp³)-H bonds using a 1,5-HAT strategy.⁷ However, the development of thermal and catalytic variants of these reactions is still in its infancy, and only our method, which uses an *in-situ*-generated low-valent Co(I)-Xantphos complex, has been successful so far.⁸ Therefore, it is still a significant challenge to undertake C(sp³)-H carboxylations using air- and moisture-stable transition-metal catalysts. In this context, I envisioned using a high-valent Pd(II) complex⁹ to cleave the C(sp³)-H bonds via a novel concerted metalation-deprotonation (CMD) mechanism¹⁰ without changing the valency of the metal center.

There have been many examples of directing-group-assisted Pd(II)-catalyzed reactions of the benzylic C(sp³)-H bonds of 8-methylquinoline derivatives. Here, a five-membered palladacycle(II) is the key intermediate,¹¹ which is generated via the cleavage of the benzylic C(sp³)-H bond of 8-methylquinoline via a CMD mechanism. Although components such as acetoxy groups, carbon monoxide, alkynes, and ethoxycarbonyl groups can be incorporated into a palladacycle(II),¹² there have not been any reports, to the best my knowledge, that CO₂ can be incorporated into the

metallacycle.¹³ In this chapter, I computationally designed and elucidated the incorporation of CO₂ into a palladacycle(II) prior to realizing the carboxylation with CO₂ experimentally.

2.1.1. Computational reaction design

Computational design followed by experimental realization represents both an advanced methodology and a long-standing challenge in organic synthesis. This future-oriented strategy significantly helps to accelerate the development of new transformations based on logical considerations and thus eliminates inefficient and resource-consuming trial-and-error approaches. There have been several elegant demonstrations of this strategy to generate effective catalysts by predicting the reactivity and selectivity of the catalytic transformation using density functional theory (DFT) calculations.¹⁴ I have already developed a three-component reaction (3CR) for the synthesis of difluoroglycine derivatives from *tert*-amines, difluorocarbene, and CO₂¹⁵ on the basis of reaction paths proposed by an automated reaction path search using the artificial force induced reaction (AFIR) method implemented in the Global Reaction Route Mapping (GRRM) program.¹⁶ The AFIR method is a powerful automated reaction path-search tool that explores reaction paths systematically and automatically. Moreover, the AFIR method not only conducts automated searches, but also has several search options to specify a reaction center. This can greatly accelerate the discovery of specific reaction paths based on a chemist's knowledge and one can efficiently obtain desired reaction paths and examine the barrier heights and actual deformations of molecular geometries along these paths. In this study, computational prediction using a sequential AFIR search-validation protocol was applied for the discovery of suitable conditions for the carboxylation of a palladacycle(II).

2.2. Results and discussion

2.2.1. Reaction design

Accordingly, a phosphine-coordinated monomeric palladacycle(II) (**3**) generated via benzylic C(sp³)–H activation was set as the starting molecule for the evaluation with the AFIR method (Figure 2.2). The target palladacycle(II) **3** (R = Ph)^{11c} is readily prepared from PPh₃ and dimeric complex **2**, which in turn is synthesized according to a reported experimental procedure from

$\text{Pd}(\text{OAc})_2$ and 8-methylquinoline in AcOH , via the cleavage of a $\text{C}(\text{sp}^3)\text{--H}$ bond, followed by treatment with LiCl .¹¹

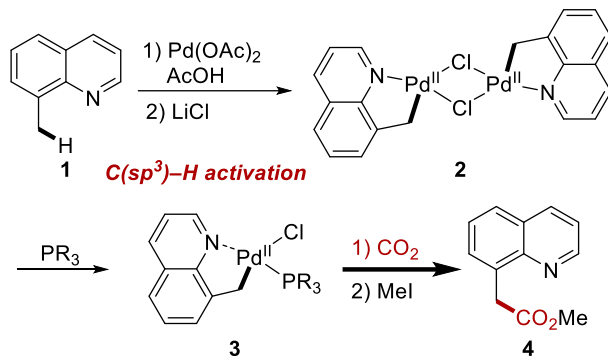


Figure 2.2. Synthesis of **3** following literature procedures and synthesis of **4**, designed using the AFIR method.

I considered two potential reaction pathways (Figure 2.3). Firstly, the direct insertion of CO_2 into palladacycle(II) **3**^{11c} using PPh_3 as a ligand, and secondly, the carboxylation of $\text{Pd}(\text{I})$ species **5**, generated via a one-electron reduction. The latter possibility has been intensively studied by Iwasawa,¹⁷ Martin,^{17a} Jana,¹⁸ and Feng,¹⁹ who all proposed a $\text{Pd}(\text{I})$ intermediate formed via the one-electron reduction of an $\text{Ar–Pd}(\text{II})\text{--X}$ ($\text{X} = \text{Cl}, \text{Br}, \text{and OTf}$) species arising from the oxidative addition of Ar–X or Ar–OTf to $\text{Pd}(0)$. Recently, Iwasawa and Yu independently reported theoretical DFT studies on the palladium-catalyzed carboxylation of Ar–X , in which transient $\text{Pd}(\text{I})$ or $\text{Pd}(0)$ species are active in carboxylations.²⁰ To uncover a positive pathway from palladacycle(II) **3**, generated by $\text{C}(\text{sp}^3)\text{--H}$ activation, I initially conducted calculations to understand whether palladacycles **3** or **5** would be active in carboxylation reactions before conducting the experiments.

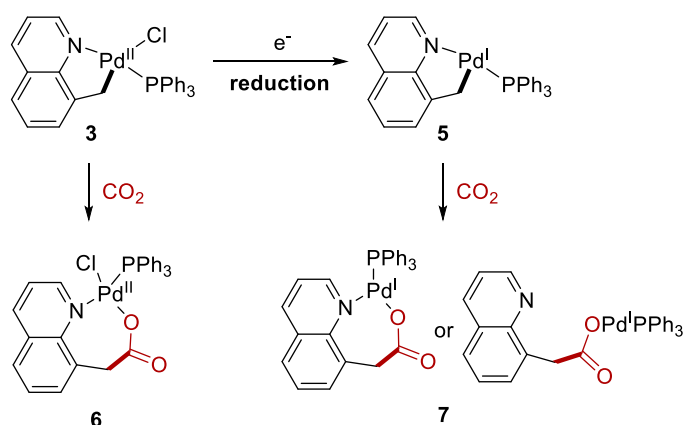


Figure 2.3. Possible reaction pathways considered for the synthesis of **4**.

2.2.2. Preliminary calculation

To theoretically investigate the possibility of the direct carboxylation of palladacycle(II) **3** without its reduction, the reaction diagram for its carboxylation, including the transition state (TS) and the intrinsic reaction coordinate (IRC) paths, was calculated. The ω B97X-D functional and Def2-SV(P) basis set were used with the Grid = FineGrid option for these calculations. The solvent effect of DMF was considered using the conductor-like polarizable continuum model (CPCM)²¹ Single-point calculations were performed at the ω B97X-D/Def2-TZVP with the Grid = FineGrid option in DMF, as modelled by the CPCM method (denoted by the ω B97X-D/Def2-TZVP/DMF// ω B97X-D/Def2-SV(P)/DMF). The calculated energy profile is shown in Figure 2.4. Due to the high stability of the five-membered palladacycle(II) **3**, the insertion of CO_2 into the C–Pd bond seemed unlikely, showing a transition state with a very high $\Delta G^\ddagger$ (48.1 kcal/mol), which cannot be overcome at ambient temperature. Furthermore, the resulting seven-membered palladacycle(II) **II** is higher in energy than reactant **3**, and this endothermic process can be expected to be disfavored compared to the reverse decarboxylation.

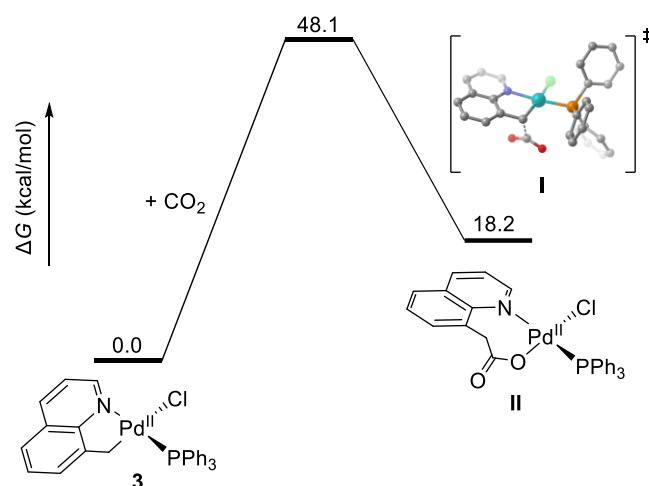


Figure 2.4. The calculated carboxylation reaction pathway starting from palladacycle(II) **3**. The Gibbs free energies of palladium complex **3** and CO₂ (not shown), the transition state, and palladacycle(II) **II** were obtained from DFT calculations at the same level of theory, where **3** and CO₂ were calculated individually.

2.2.3. Conformation search of possible Pd(I) intermediates

Next, a plausible anionic Pd(I) species, formed by the addition of one electron to **3**, was employed in a calculation using the single component (SC)-AFIR method^{16b} because the structure of the Pd(I) species had not yet been defined. Since these Pd complexes consist of four fragments, i.e., 8-methylquinoline (8-MQ), Cl[−], PPh₃, and Pd, I searched for possible structures that would reasonably describe the corresponding Pd(I) complex. Random combinations of each of the four fragments with a charge of −1 and a doublet spin multiplicity were sought. The bond recombination pathway within each fragment was excluded from the search, and the coordination patterns of the Pd complexes were solely explored. The calculations were conducted at the GFN1-xTB level of theory and the initial structure of the SC-AFIR search, **IV**, was derived from **3** via a one-electron reduction. The SC-AFIR search, with a collision energy parameter $\gamma = 100$ kJ/mol, was terminated when the last 80 AFIR paths did not update the 80 local minima with the lowest electronic energies. This automated search eventually proposed 1048 structures, which were classified into 19 groups according to their binding patterns. The obtained structures of representative complexes were then relaxed at the ω B97X-D/Def2-SV(P)/DMF level of theory to obtain reasonable conformations for the complexes. Single-point calculations were performed at the ω B97X-D/Def2-TZVP/DMF level of theory. The GFN1-xTB²² energies and gradients were calculated using the ORCA 4.2.0 program,²³ and the DFT

calculations were performed using the Gaussian16 package. A developmental version of the GRRM program was used for the structure searches using the SC-AFIR method and for optimization of the transition states and stable structures.

Considering the coordination patterns of the potential Pd complexes, eight structures can be predicted (Figure 2.5): with or without N coordination (palladacycle or non-palladacycle), with or without Cl^- coordination, and with one or two molecules of PPh_3 . Of these eight structures, no optimized structure could be obtained for the five-coordinated Pd structure, **III**, and the two-coordinated Pd structure, **X**. These structures are likely to be unstable because they are 19- and 13-electron Pd complexes, respectively. In other words, the initial exploratory calculations using the SC-AFIR method proposed six important structures based on the coordination patterns of the Pd complexes. It is important to emphasize that these structures could be obtained automatically without the need for any prior assumptions by me on the structures of these coordination complexes. These results clearly indicate that Pd complexes coordinated by two molecules of PPh_3 are more stable than those coordinated by a single molecule. Even though one equivalent of PPh_3 with respect to Pd is employed in the following chemical experiments (Table 2.1), it is expected that the coordination product will be more stable when an additional equivalent of PPh_3 is present in the reaction.

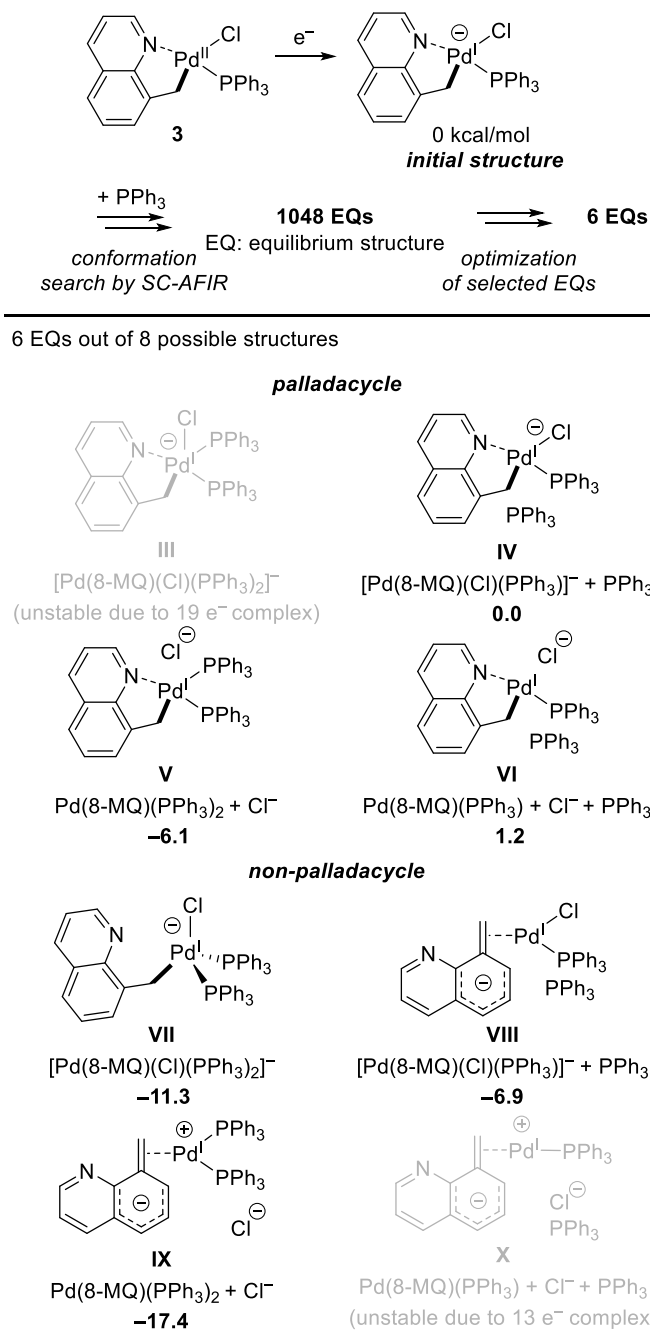


Figure 2.5. Six representative structures out of 1048 EQs. The Gibbs free energies of each EQ calculated at the ω B97X-D/Def2-TZVP/DMF// ω B97X-D/Def2-SV(P)/DMF level of theory are shown relative to **IV** in kcal/mol, where EQs of the palladium complex bearing one PPh₃ and non-coordinated PPh₃ (**IV**, **VI**, and **VIII**) were calculated individually.

With stable structures of the Pd complexes in hand, I calculated energy diagrams for the carboxylation of palladacycle(II) **3**. Two distinct energy diagrams starting from **IV** are described here (Figure 2.6). Firstly, the carboxylation of a Pd complex coordinated by two molecules of PPh₃ with CO₂ (right-hand pathway, Figure 2.6) and secondly, the carboxylation of a mono-coordination product (left-hand pathway, Figure 2.6). The Gibbs free energies ($T = 298.15$ K) are shown in kcal/mol relative to **IV**. The solid lines in the figure indicate reaction pathways that have been confirmed by intrinsic reaction coordinate (IRC) calculations and the dotted lines represent the conformational changes between each palladium complex, which are expected to have a sufficiently low energy barrier. In the right-hand pathway, not only the structure of the square planar orientation of **IV**, formed from the reduction of **3**, changes dramatically, but also the delocalization of its anion to the aromatic ring, resulting in the formation of **VIII**. This species is then coordinated by an additional molecule of PPh₃ to generate bis(triphenylphosphine) adduct **VII**. Following chloride dissociation, the most stable complex (**IX**) is generated, from which there are two potential carboxylation pathways. One is the direct carboxylation of **IX** via transition state **XI** in which the carbonyl carbon of CO₂ coordinates the palladium center to form the palladium carboxylate **XII**. The activation energy of this pathway is relatively high (30.6 kcal/mol). On the other hand, Cl⁻ can coordinate the palladium center to regenerate **VII**, from which carboxylation occurs at the benzylic position without CO₂ coordination to Pd via transition state **XIII**, producing carboxylate **XIV** with an activation energy of 32.5 kcal/mol. I also calculated a pathway for the carboxylation of Pd(I) **VIII** with only one coordinated phosphine where the activation energy is much smaller (26.7 kcal/mol).

Analysis of the three possible carboxylation pathways shown in Figure 2.6 shows that the activation energies along two carboxylation paths from **IX**, which would be a resting state, are very large ($\Delta G^\ddagger = 30.3$ and 32.5 kcal/mol), indicating that these pathways with two molecules of PPh₃ are energetically unfavored. On the other hand, if there is insufficient PPh₃ present in the reaction system, the carboxylation proceeds from mono-coordinated **VIII** through transition state **XV** ($\Delta G^\ddagger = 26.7$ kcal/mol). According to these calculations, one-electron reduction in the presence of an equivalent of PPh₃ to Pd is

necessary to distort the structure of the stable square planar five-membered palladacycle(II), and is thus a key factor for promoting carboxylation.

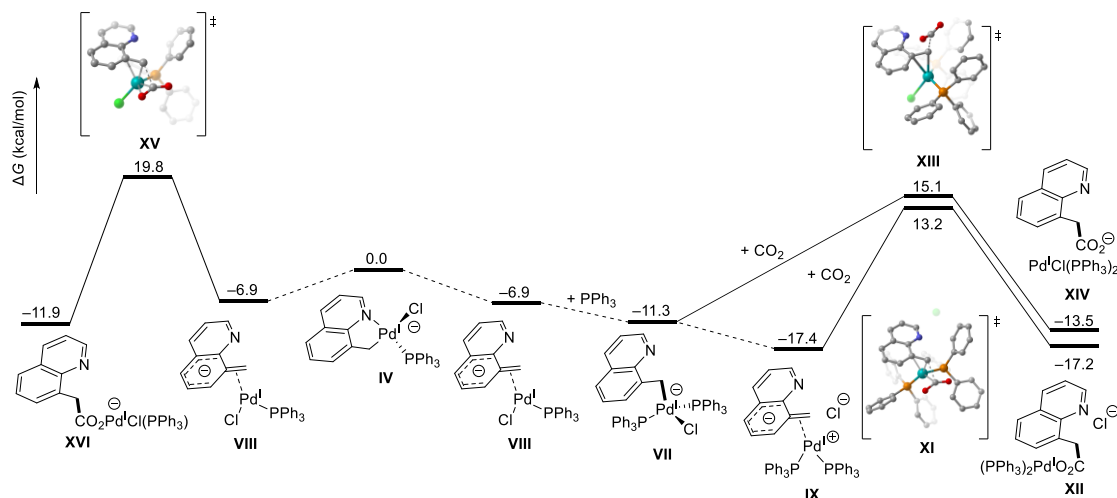


Figure 2.6. The calculated reaction diagram following one-electron reduction of **3**. The Gibbs free energies relative to **IV** are indicated in kcal/mol. The Gibbs free energies of the palladium intermediates for carboxylation and CO₂ (not shown) were calculated individually. Cartesian coordinates (x, y, z) of all structures are listed in the experimental section.

2.2.4. Experimental investigations

Given that the computational analysis found a structural change from Pd(II) to Pd(I) to be a critical factor, I started the screening of reductants (Table 2.1) in the presence of dimeric palladacycle(II) **2** and PPh₃ (1 equiv relative to Pd) as the ligand (conditions for the in-situ generation of palladacycle(II) **3**). When the carboxylation was conducted without a reductant, the insertion of CO₂ did not occur and monomer **3** was obtained in 96% yield (entry 1). This is consistent with the calculation results that **3** cannot be expected to react with CO₂ unless it is already in its reduced form. Next, an excess of Mn and Zn was used as the reductant, but only **3** was obtained in either case (entries 2 and 3). Since the cyclic voltammogram of **3** indicated that the reductive potential of **3** from Pd(II) to Pd(I) was -1.68 V (vs SCE in CH₃CN, Figure 2.7), it is clear that Mn and Zn do not have a sufficiently negative reduction potential ($E_{1/2} = -1.00$ V and -1.43 V vs SCE in CH₃CN, respectively). However, the highly reactive one-electron reductant Cp*₂Co ($E_{1/2} = -1.51$ V vs SCE in CH₃CN) was found to efficiently promote CO₂ insertion

(entry 4). After methyl esterification with MeI, **4** was obtained in 87% yield. I also examined the Ir-based photoredox catalyst [Ir(ppy)₂(dtbpy)]PF₆ ($E_{1/2} = -1.51$ V vs SCE (IrII/IrIII)) for the reduction of **2** in the presence of a stoichiometric amount of the sacrificial reductant *i*-Pr₂NEt under irradiation from a blue (440 nm) LED (entry 5). In this case, **4** was obtained in 32% yield together with **3** in 40% yield. Other photoredox catalysts such as fac-Ir(ppy)₃ and fac-Ir(dFppy)₃ were found to be unsuitable (entries 6 and 7). Although an unsatisfactory yield was obtained in entry 5, it demonstrates that reductants with a reductive potential around -1.5 V promote the desired carboxylation with CO₂. I also conducted carboxylation under electrochemical conditions. Anode and cathode electrodes were selected to be Mg and Pt, respectively with *n*-Bu₄N⁺PF₆⁻ as the supporting electrolyte. When the electrolysis was conducted at constant voltage (-1.60 V), the carboxylation proceeded at 2 F/mol (entry 8). Although more electrons were consumed at 4 F/mol, the yield was not improved (entry 9). A higher voltage (-1.80 V) with 8 F/mol did not change the outcome (entry 10) and overreduction of the quinoline structure decomposed the product leading to a decrease in the yield.

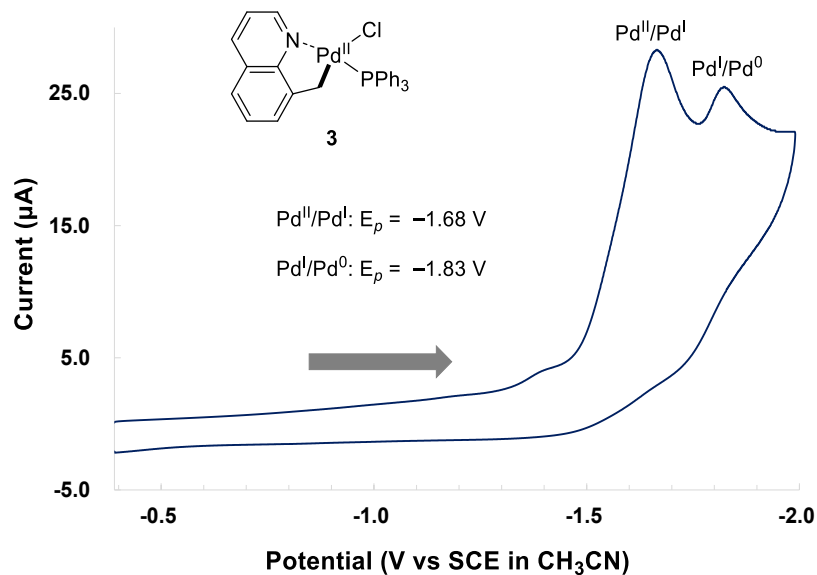


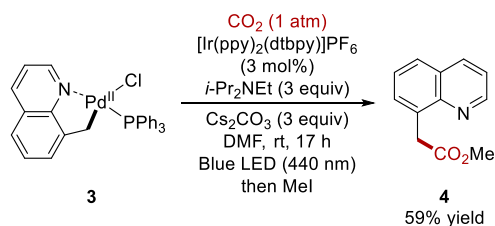
Figure 2.7. Cyclic voltammogram of **3**.

Table 2.1. Screening of the reaction conditions.

Entry	Reductant	Redox potential ^a (V)	Other Reagents	Temp (°C)	Time (h)	yield ^b (%)	
						4	3
1	None			100	2	-	96
2	Mn (3 equiv)	-1.00		100	2	-	99
3	Zn (3 equiv)	-1.43		100	2	-	98
4	Cp*2Co ^{II} (19e) (3 equiv)	-1.51		rt	2	87	2
5	[Ir(ppy) ₂ (dtbpy)]PF ₆ (6 mol%)	-1.51 (Ir ^{II} /Ir ^{III})	<i>i</i> -Pr ₂ NEt (6 equiv) Cs ₂ CO ₃ (6 equiv) Blue LED (440 nm)	rt	14	32	40
6	<i>fac</i> -Ir(ppy) ₃ (6 mol%)	-2.19 (Ir ^{II} /Ir ^{III})	<i>i</i> -Pr ₂ NEt (6 equiv) Cs ₂ CO ₃ (6 equiv) Blue LED (440 nm)	rt	16	12	-
7	<i>fac</i> -Ir(dFppy) ₃ (6 mol%)	-2.01 (Ir ^{II} /Ir ^{III})	<i>i</i> -Pr ₂ NEt (6 equiv) Cs ₂ CO ₃ (6 equiv) Blue LED (440 nm)	rt	16	8	3
8	(+)/Mg/(-)/Pt (electrochemical)	-1.60 ^c (constant V)	<i>n</i> -Bu ₄ N·PF ₆ (0.7 M)	rt	2 F/mol	10	58
9	(+)/Mg/(-)/Pt (electrochemical)	-1.60 ^c (constant V)	<i>n</i> -Bu ₄ N·PF ₆ (0.7 M)	rt	2 F/mol	5	26
10	(+)/Mg/(-)/Pt (electrochemical)	-1.80 ^c (constant V)	<i>n</i> -Bu ₄ N·PF ₆ (0.7 M)	rt	2 F/mol	5	20

^a Relative value vs SCE. ^b Yields were determined using ¹H NMR analysis with 1,1,2,2-tetrachloroethane as the internal standard. ^c Sacrificial reductant *i*-Pr₂NEt (6 equiv), Cs₂CO₃ (6 equiv) under irradiation from a blue LED (440 nm). ^d *n*-Bu₄N·PF₆ (0.07 M) electrolyte. ^e Relative to Ag/AgCl. SCE = Ag/AgCl-0.05 = -1.65 (entries 8 and 9). SCE = Ag/AgCl-0.05 = -1.85 (entry 10). Rather than starting from complex **2**, I also tested the reactivity of **3** experimentally (Scheme 2.1). The desired carboxylation proceeded in the presence of [Ir(ppy)₂(dtbpy)]PF₆ and **4** was obtained in 59% yield. Combined with the fact that intermediate **3** was observed in Table 2.1 when the yield of carboxylate **4** was low, carboxylation of dimer **2** must proceed via **3**.

Scheme 2.1. Direct carboxylation of **3**.



Even though Cp^*Co gave the highest yield among the conditions screened, the use of a stoichiometric amount of this strong reducing agent is not preferred when considering the development of this catalytic variant. Therefore, I focused on a photoredox system to improve the yield of **4**. I then examined the scope of phosphine ligands and CO_2 pressures in the photoredox reaction (Table 2.2). First, I attempted the reaction in the absence of a phosphine ligand and found that **4** was still obtained in 6% yield (entry 2). Under 10 atm of CO_2 pressure, the yield increased dramatically to 65% (entry 3). The reaction time was shortened to 3 h, resulting in a similar outcome to entry 3 (entry 4). Use of twice the amount of ligand decreased the yield slightly, probably because the additional PPh_3 accelerated the formation of resting state **IX** (*vide supra*) (entry 5). Various bidentate phosphine ligands were then investigated under 10 atm of CO_2 pressure and a reaction time of 3 h (entries 6-13). Although dppm was found not to be a suitable ligand (entry 6), the use of dppe increased the yield to 90% (entry 7). Even under 1 atm of CO_2 , the product was obtained in 71% yield (entry 8). Other bidentate phosphines with larger bite angles such as dppp, dppb, dppbz, dppf, BINAP, and Xantphos (entries 9-14) generated outcomes inferior to that of dppe. Monodentate alkylphosphines such as *Pt*- Bu_3 and PCy_3 did not promote the carboxylation well (entries 15 and 16). According to these experimental results, the use of the bidentate phosphine dppe resulted in the best performance.

Table 2.2. Screening of the reaction conditions.

Entry	Ligand	CO ₂ Pressure (atm)	Time (h)	Yield ^a (%)
1	PPh ₃ (2 equiv)	1	14	32 (31 ^b)
2	None	1	17	6
3	PPh ₃ (2 equiv)	10	14	65
4	PPh ₃ (2 equiv)	10	3	64
5	PPh ₃ (4 equiv)	10	3	53
6	dppm (2 equiv)	10	3	32
7	dppe (2 equiv)	10	3	90 (85 ^b)
8	dppe (2 equiv)	1	3	71
9	dppp (2 equiv)	10	3	71
10	dppb (2 equiv)	10	3	37
11	dtbbz (2 equiv)	10	3	47
12	dppf (2 equiv)	10	3	6
13	BINAP (2 equiv)	10	3	28
14	Xantphos (2 equiv)	10	3	15
15	Pt-Bu ₃ (2 equiv)	10	3	5
16	PCy ₃ (2 equiv)	10	3	12

bidentate phosphines

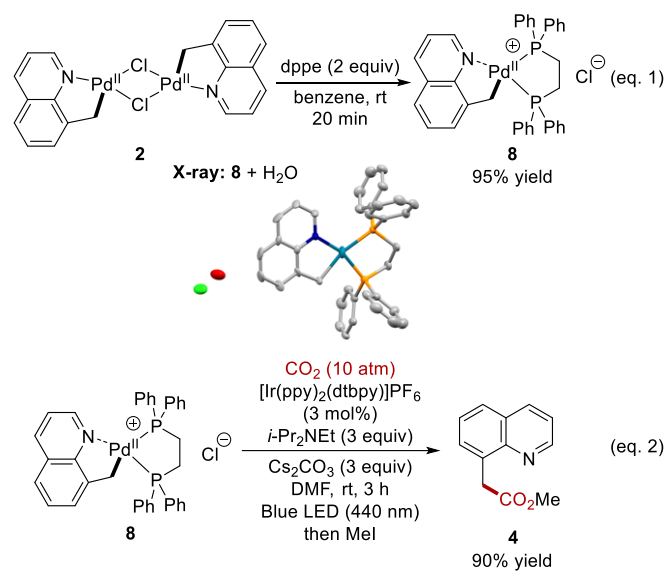
BINAP *Xantphos*

^a Yields were determined using ¹H NMR analysis with 1,1,2,2-tetrachloroethane as the internal standard. ^b Isolated yield.

2.2.5. Control experiments

Next, I synthesized a new dppe-coordinated palladium complex via the complexation of dimer **2** with dppe in benzene for 20 min (Scheme 2.2, eq. 1). The resulting solids were recrystallized in acetone, affording single crystals suitable for an X-ray crystallographic analysis.²⁴ The thus obtained molecular structure unequivocally revealed a cationic Pd complex with the chloride dissociated from the Pd center.

Scheme 2.2. Preparation of cationic Pd complex **8** and its reactivity.



I also experimentally examined the carboxylation of cationic Pd(II) species **8** under photoredox conditions (eq. 2). Under the optimized conditions, the corresponding carboxylate (**4**) was successfully obtained in 90% yield, which is the same as the yield listed in entry 7 of Table 2.2. This indicates that the cationic character of the complex may accelerate its reduction, leading to the promotion of the carboxylation.

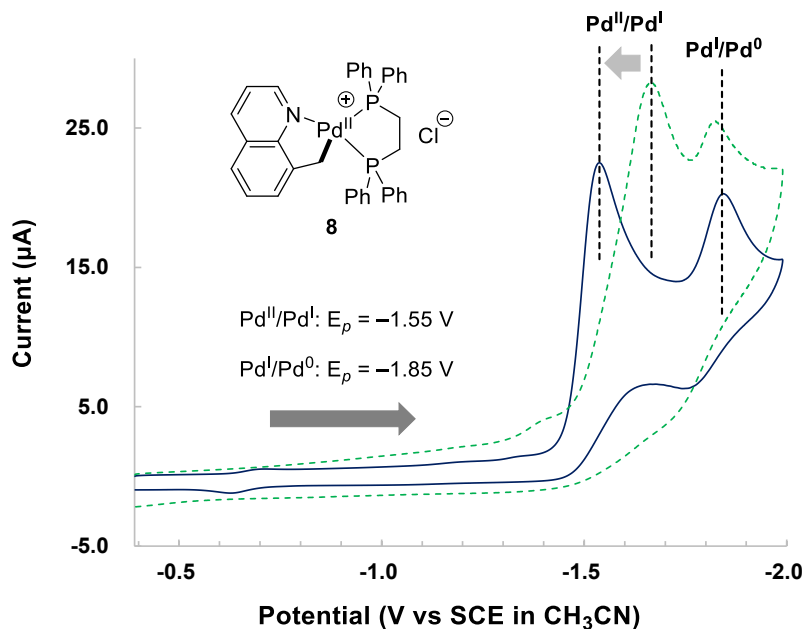


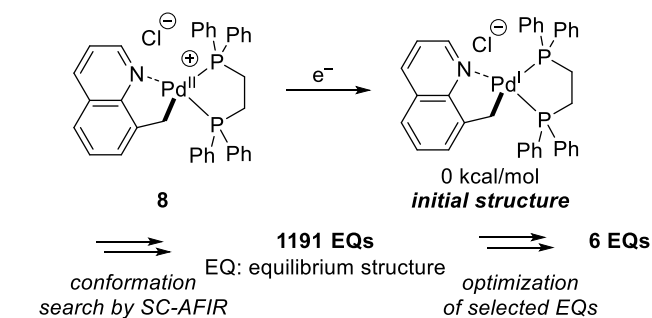
Figure 2.8. The cyclic voltammogram of **8**. The green dotted line represents the reduction potentials of **3** as shown in Figure 2.3.

To test this hypothesis, I measured the cyclic voltammogram of **8** (Figure 2.8). Although a similar Pd(I)/Pd(0) reductive potential was observed compared to **3**, the Pd(II)/Pd(I) reductive potential was greatly shifted to a lower voltage (from -1.68 V to -1.55 V). This indicates that the reduction of **8** is easier than that of **3** due to its cationic character.

2.2.6. Computational mechanistic study

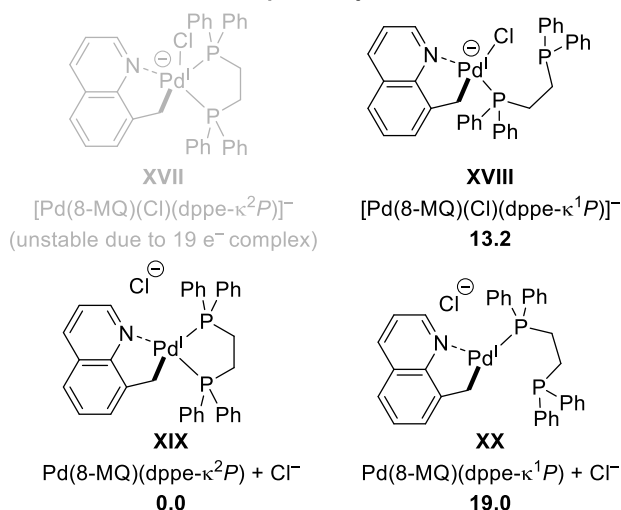
To confirm whether the higher yield obtained when using dppe is only due to the reductive potential of the cationic complex, I calculated the energy diagram for the carboxylation of palladacycle(II) **8** using the AFIR method. Similar to **3**, the coordination patterns using 8-MQ, Cl^- , and dppe were systematically explored to obtain the stable structures of the Pd(I) complexes. This search was started from the optimized structure **XIX**. The SC-AFIR search, with collision energy parameter $\gamma = 100$ kJ/mol, was terminated when the last 73 AFIR paths did not update the 73 local minima with the lowest electronic energies. This automated search eventually proposed 1191 structures, which were classified into 25 groups

according to their binding patterns. Reasonable structures from each group were selected and optimized at the ω B97X-D/Def2-SV(P)/DMF level of theory in a process similar to the calculations for the complexes **IV–IX**. Single-point calculations were performed at the ω B97X-D/Def2-TZVP/DMF level of theory. The final six coordination structures obtained are shown in Figure 2.9. Using these structures, reaction paths for the carboxylation were determined using the AFIR method.



6 EQs out of 8 possible structures

palladacycle



non-palladacycle

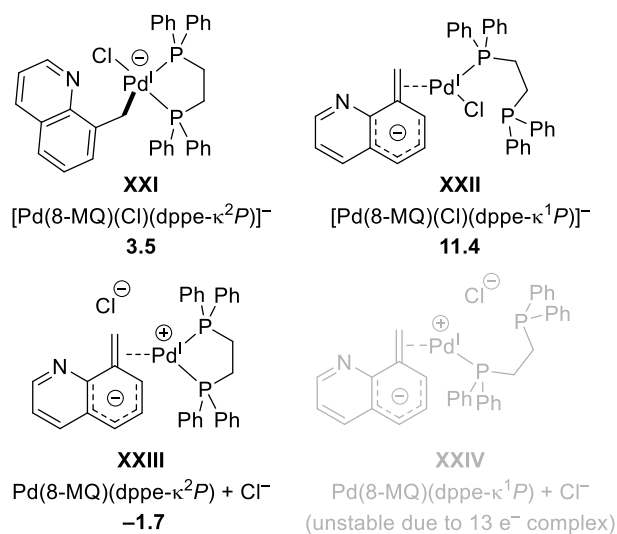


Figure 2.9. Six representative structures out of 1191 EQs. The Gibbs free energies of each EQ were calculated at the $\omega\text{B97X-D/Def2-TZVP/DMF} // \omega\text{B97X-D/Def2-SV(P)/DMF}$ level of theory and are shown relative to **XIX** in kcal/mol.

Palladacycle(II) **8** is reduced via a one-electron reduction to form **XIX** (Figure 2.10), whereby its square-planar orientation undergoes a change whilst its anion is delocalized to the aromatic ring, forming the most stable Pd(I) complex along the pathway, **XXIII**. The carboxylation of **XXIII** leads to the formation of Pd carboxylate **XXVI** via transition state **XXV**, in which the carbonyl carbon of CO₂ is coordinated to the Pd center. The activation energy of this transition state is $\Delta G^\ddagger = 26.0$ kcal/mol. Moreover, the slightly less stable palladium complex **XXI**, coordinated by Cl⁻, is carboxylated via transition state **XXVII**, in which CO₂ does not coordinate to Pd, to form carboxylate **XXVIII**. The activation energy of this carboxylation is $\Delta G^\ddagger = 34.9$ kcal/mol. The former value is similar to the activation energy when one molecule of PPh₃ is coordinated ($\Delta G^\ddagger = 26.7$ kcal/mol). Based on these results, I conclude that dppe does not reduce the activation energy of the desired carboxylation, and that the higher reaction yield with dppe should be attributed to the lower reduction potential of **8** that results from the bidentate coordination, which facilitates removal of the chloride ligand to generate a cationic complex. Iwasawa's recent computational studies of the Pd-catalyzed carboxylation of aryl halides and triflates demonstrated that the cationic character of the Pd(II) ligands significantly accelerates the carboxylation.^{20a}

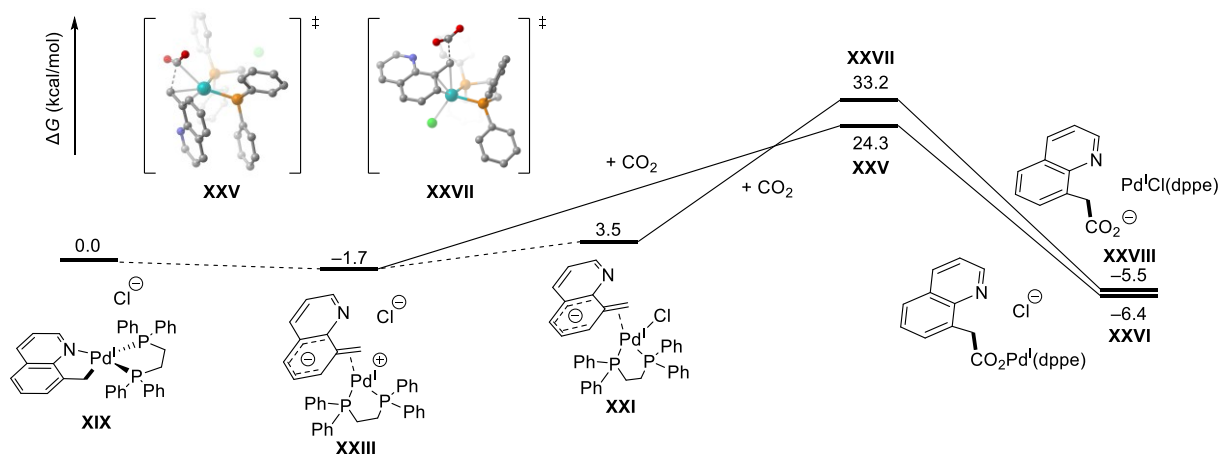
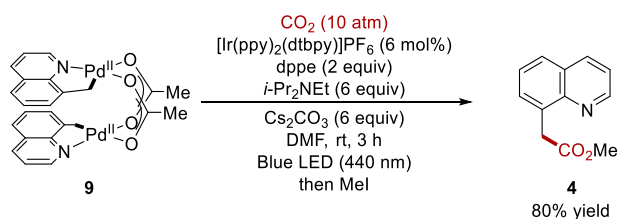


Figure 2.10. The calculated reaction diagram following the one-electron reduction of **8**. The Gibbs free energies relative to **XIX** are indicated in kcal/mol. The Gibbs free energies of the palladium intermediates for carboxylation and CO₂ (not shown) were calculated individually. Cartesian coordinates (x, y, z) of all structures are listed in the experimental section.

2.2.7. Carboxylation of acetate complex

Finally, I applied the optimal conditions to the carboxylation of dimer **9** which is generated initially from **1** via C(sp³)–H activation (Scheme 2.3). Dimer **9** is known to possess a bent structure due to the palladaphilic interaction between the two Pd centers.¹¹ The carboxylation proceeded smoothly when dppe was used as the ligand and **4** was obtained in an 80% yield. Although the yield was slightly lower than that obtained from **2** (90%), it is obvious that both dimeric compounds **2** and **9** could be carboxylated when these species are reduced by a photoredox catalyst. This is critical insight which will guide the future development of catalytic C(sp³)–H carboxylation reactions of 8-methylquinoline.

Scheme 2.3. Carboxylation of dimer **9**.



2.3. Conclusions

In summary, I have discovered a suitable reaction system for the insertion of CO₂ into a palladacycle(II) derived from 8-methylquinoline via C(sp³)–H activation, based on computational design that uses a reaction path search with the artificial force induced reaction (AFIR) method. The calculations uncovered that Pd(I) is a key reactive species for this carboxylation. Experimental studies using potential reductants such as Cp*₂Co and an Ir-based photoredox catalyst with a stoichiometric amount of sacrificial reductant furnished the carboxylated product in high yields. Electrochemical carboxylations also proceeded to some extent with the use of (+)Mg/(–)Pt electrodes. After screening several bidentate phosphine ligands under photoredox conditions, dppe was found to exhibit the best performance and this was rationalized using further calculations. Following a series of calculations with detailed experimentation has become a powerful tool for the development of new reactions. These findings provide guidelines for the future development of Pd-catalyzed C(sp³)–H carboxylations with CO₂. I am now

intensively studying a catalytic variant of this transformation from 8-methylquinoline with the aid of computational studies.

2.4. References

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Chapter 3. Development of a Synthetic Route to β -Amino Acids via a CO_2 -Coupled Electron Transfer Based on Theoretical Investigations of a Mechanistically Analogous Reaction

3.1. Introduction

3.1.1. β -Amino acid synthesis from CO_2

β -Amino acids and their analogues are important structural motifs in synthetic organic chemistry, especially for the synthesis of artificial peptides composed of β -amino acids.¹ Among the synthetic β -amino acids, cyclic β -amino acid frameworks and their polymeric helix structures, which were named ‘foldamers’ by Gellman,² have been the focus of particular attention. β -Amino acids can be synthesized using diverse methods, among which the Mannich reaction between imines and enolates stands out as a straightforward and reliable method for the nonstereoselective and stereoselective synthesis of β -amino acids.³ In these reactions, the carboxyl unit of the β -amino acids inherently comes from the substrate structure. Therefore, using carbon dioxide (CO_2) as a carboxylic acid unit for the synthesis of β -amino acids⁴ would provide a superior method owing to its abundance, low cost, low toxicity, and renewability. However, such transformations remain underdeveloped, even though analogous α -amino acids^{4f,5} and γ -amino acids⁶ can be synthesized from CO_2 using α -aminoalkylradical species after the oxidation of *tert*-amines or their reduced α -amino anions. The former species can be generated via the direct abstraction of a hydrogen atom next to a nitrogen atom, the so-called hydrogen-atom-transfer (HAT) process,^{6a} α -Aminoalkylradical/ α -amino anion thus generated can subsequently react with CO_2 to yield α -amino acids (Figure 3.1, eq. 1)⁵ or with an alkene followed by carboxylation with CO_2 to produce γ -amino acids (eq. 2).⁶ However, there are no reports on the synthesis of β -amino acids under photoredox conditions initiated by amine oxidation (eq. 3). During my study, Yu and coworkers reported a breakthrough in this area, namely the synthesis of β -amino acids using a dual photoredox/copper catalyst system. This novel reaction furnished regioisomeric carboxylic acids via an initial single-electron reduction of the substrate followed by copper-catalyzed amination (eq. 4)⁷. In sharp contrast to this study, the generation of an aminium radical

(radical cation) from a secondary amine via single-electron oxidation and subsequent attack on an alkene, followed by CO₂ addition, could pave the way for the one-step synthesis of β-amino acids from CO₂. This unprecedented approach based on an aminium radical in combination with CO₂ holds significant potential for the synthesis of β-amino acids (eq. 3).

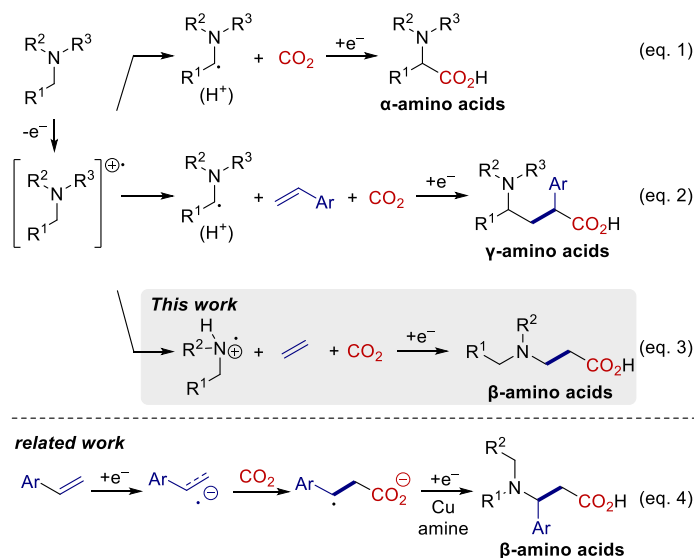


Figure 3.1. Amino acid synthesis from CO₂ under photoredox conditions.

3.1.2. ES/AFIR approach

Among the strategies employing aminium radicals for C–N-bond-forming reactions, photoredox catalysis stands out as a promising approach for the aforementioned purpose because it provides access to various types of amine- or amide-derived nitrogen-centered radicals, which can add to unsaturated functionalities, in a mild and versatile manner. Recently, I have reported a computational mechanistic study of the radical hydroamination developed by the Knowles group⁸ using quantum chemical calculations.⁹ This reaction involves a single-electron-transfer (SET) process, which is challenging to handle in quantum chemical calculations on account of the different electron states before and after the electron transfer. In the context of Marcus theory,¹⁰ the SET process between a photoredox catalyst and substrates can proceed via seam of crossings (SXs), where two different electronic states degenerate,¹¹ and nonadiabatic processes via an SX region.¹² In this study, I used the artificial force induced reaction (AFIR)

method¹³ with an energy-shift (ES) approach¹⁴ to explore multistate reaction path networks by modeling outer-sphere electron transfers including relatively large photoredox catalysts using the experimental redox potential.⁸ This ES/AFIR approach allowed a systematic analysis of the reaction mechanism for the entire photoredox catalytic cycle of Knowles hydroamination⁸ with amino alkene **1a** as a starting material in the presence of $[\text{Ir}(\text{ppy})_2(\text{dtbbpy})]\text{PF}_6$.^{8a} If intermediate twitterionic **IV** exists in the catalytic cycle, its C–N bond must be cleaved with an almost barrierless activation energy (0.05 kcal/mol) which is much smaller than the protonation of carbanion (1.8 kcal/mol) as confirmed by calculations (Figure 3.2, **IV**).⁹ However, a less stable SX leads to hydroamination product **2a** through a mechanism involving simultaneous reduction by Ir(II) and protonation by MeOH.⁸ This mechanism is known as the proton-coupled electron transfer (PCET).¹⁵

The minimum-energy SX (MESX) geometry in the PCET leading to hydroamination product **2a** is shown in Figure 3.2b. In this PCET, after receiving an electron, a proton is transferred from ammonium to the benzylic carbon via a proton-relay mechanism through a specific hydrogen-bond network formed by two molecules of MeOH. In other words, the presence of this specific conformational SX with MeOH molecules facilitates the formation of the product through the PCET.

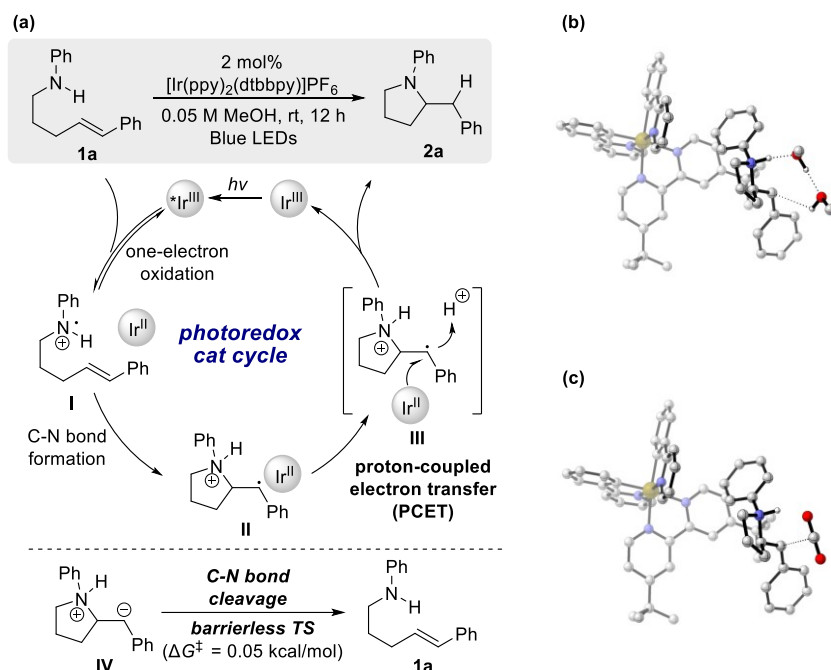


Figure 3.2. (a) Mechanism for the proton-coupled electron-transfer (PCET) for Knowles' radical hydroamination. (b) SX geometry leading to hydroamination products. (c) SX geometry constructed on the basis of the present assumptions to achieve a "CO₂-coupled electron transfer".

3.1.3. Design of CO₂-coupled electron transfer

This unexpected mechanism for Knowles' hydroamination led me to consider a novel pathway involving CO₂ instead of MeOH. In terms of the reaction mechanism, the addition of CO₂ to produce β-amino acids can be expected to operate in a concerted manner similar to PCET (Figure 3.2c). I have termed this process "CO₂-coupled electron transfer", in which carboxylation with CO₂ occurs simultaneously with a single-electron reduction. Hypothetically, such a previously unknown concerted one-electron reduction and carboxylation could occur if the aforementioned MeOH-facilitated mechanism for Knowles' hydroamination holds true. This hypothetical reaction would commence with the generation of an aminium radical (radical cation) from a secondary amine through a single-electron oxidation. Subsequently, the generated radical would attack an alkene and the addition of CO₂ would proceed via one-electron reduction and carboxylation to form β-amino acids under photoredox-catalyzed conditions (Figure 3.1, eq. 3).

Building on this notion, the present study showcases a protocol to synthesize β -amino acids through a photoredox-catalyzed radical reaction employing a CO_2 -coupled electron-transfer mechanism.

3.2. Results and discussion

3.2.1. MESX on force modified potential energy surface

First, I optimized the MESX geometry starting from the hand-made geometry by replacing the two MeOH molecules in the SX geometry (Figure 3.2b) with one CO_2 molecule (Figure 3.2c).¹³ In these calculations, the photoredox catalyst was represented by the ES approach¹⁴ using the experimental redox potential, i.e., the reduction potential of Ir(II) to Ir(III) for $[\text{Ir}(\text{ppy})_2(\text{dtbbpy})]\text{PF}_6$ of -1.51 V vs SCE (281.0 kJ/mol = 67.2 kcal/mol). It should be noted here that the ES approach to model photo-redox catalysts works only for outer-sphere electron transfer, which does not involve the interaction between catalyst and substrates. The $\omega\text{B97X-D}$ functional¹⁶ and the 6-311+G(d,p) basis set were used with the SMD¹⁷ solvent model for MeCN (indicated by the $\omega\text{B97X-D}/6\text{-}311\text{+G(d,p)}$ level). In the present study, all the geometry-optimization and reaction-path searches were conducted using the GRRM23 program,¹⁸ while all DFT energy and gradient calculations were performed using the Gaussian 16 program package.¹⁹

The mass-weighted steepest descent path in the ground state (the meta-IRC path) starting from the obtained MESX geometry led directly back to the reactant (Figure 3.3). Then, to see whether there is an SX region leading to CO_2 addition in the low energy region, I searched for MESX geometries on the force-modified (FM) potential energy surface²⁰ by applying a weak attractive force between the carbon atoms forming the C–C bond, as it is widely recognized that the nonadiabatic transition occurs not only at the minimum energy point but also at low-lying points within the corresponding SX hypersurface.²¹ Notably, these FM-MESX geometries do not correspond to the minimum energy points within the SX region but to one of the points within the potential-seam hyperspace where two different states are energetically degenerate because the same weak force was applied to both states in these calculations. Finally, I found SX points (denoted as FM-SX) that allowed the CO_2 addition via the meta-IRC calculation within the SX hypersurface. The lowest one within the obtained SX points leading to CO_2 addition exists

in a slightly higher energy region (~ 1 kcal) than the MESX point (*vide infra*). This result indicates that the carboxylation via an energetically slightly unstable region within the SX hyperspace contributes to the productive reaction process, which should be a CO₂-coupled electron transfer.

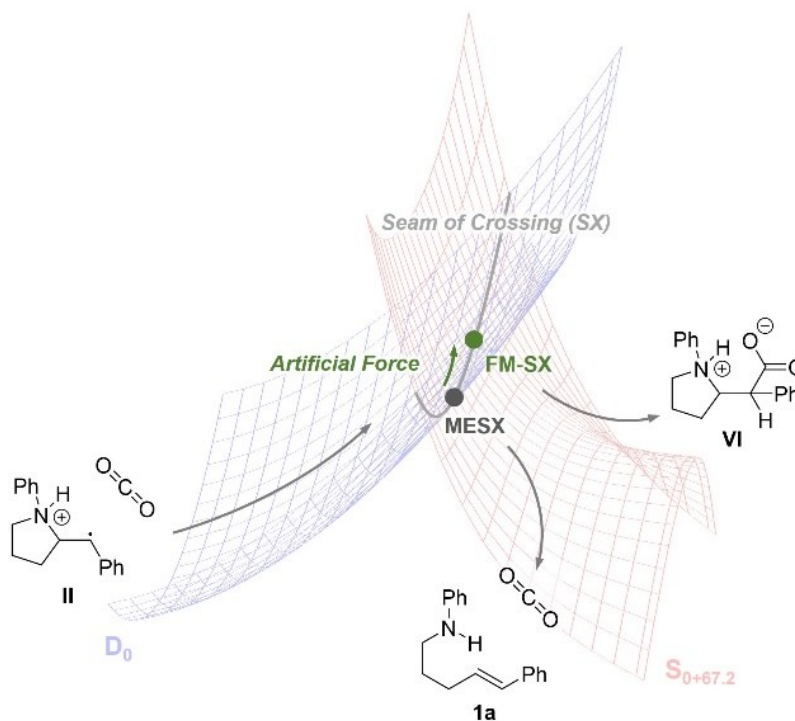


Figure 3.3. Schematic potential energy surfaces of the D₀ state and the energetically shifted S₀ state (S₀+67.2). The gray circle indicates the MESX point. The green circle indicates the lowest energy SX point among those leading to CO₂ addition, and the point is denoted by FM-SX. The black arrows indicate the meta-IRC path computed from MESX and FM-SX points in the S₀ state.

3.2.2. Path search of aminocarboxylation

Based on our previous mechanistic studies on radical hydroaminations of amino alkenes,⁹ I drew the energy diagram shown in Figure 3.4 using **1a** + CO₂, incorporating additional energy (the *Ir(III)-to-Ir(II) oxidation potential of +0.66 V vs SCE: 490.3 kJ/mol = 117.2 kcal/mol), which shifted the diagram along the black line (S₀+117.2) from the red line (S₀+67.2) (the aforementioned reduction potential of Ir(II) to Ir(III)) after light irradiation. In the figures, *Ir(III) indicates the triplet state of Ir(III), and visible-light-induced *Ir(III) generation is denoted by an arrow with *hν*. Next, the reaction path was searched using the

AFIR method under radical-cation conditions (D_0), represented by the blue line. Additionally, the pathway for another energy shift was calculated and is represented by the red line ($S_{0+67.2}$). These three pathways are interconnected, forming the reaction diagram for the reaction of **1a** with CO_2 as shown in Figure 3.4. In this context, the first amine oxidation occurred with a low $\Delta G^\ddagger$ (< 0.1 kcal/mol from EQ to the MESX point), followed by the formation of the C–N bond with a $\Delta G^\ddagger$ of 8.0 kcal/mol. Subsequent reduction followed by C–N bond cleavage took place with the lowest $\Delta G^\ddagger$ of 6.3 kcal/mol through the MESX geometry (shown as a gray circle), resulting in the regeneration of **1a**. However, subsequent carboxylation with CO_2 occurred with a $\Delta G^\ddagger$ of 6.6 kcal/mol to the *anti* product or a $\Delta G^\ddagger$ of 6.9 kcal/mol to the *syn* product through the FM-SX geometries (shown as green circles). Even if substrate **1a** is regenerated by the cleavage of the C–N bond, it will re-enter the catalytic cycle, and thus, carboxylation proceeds gradually.

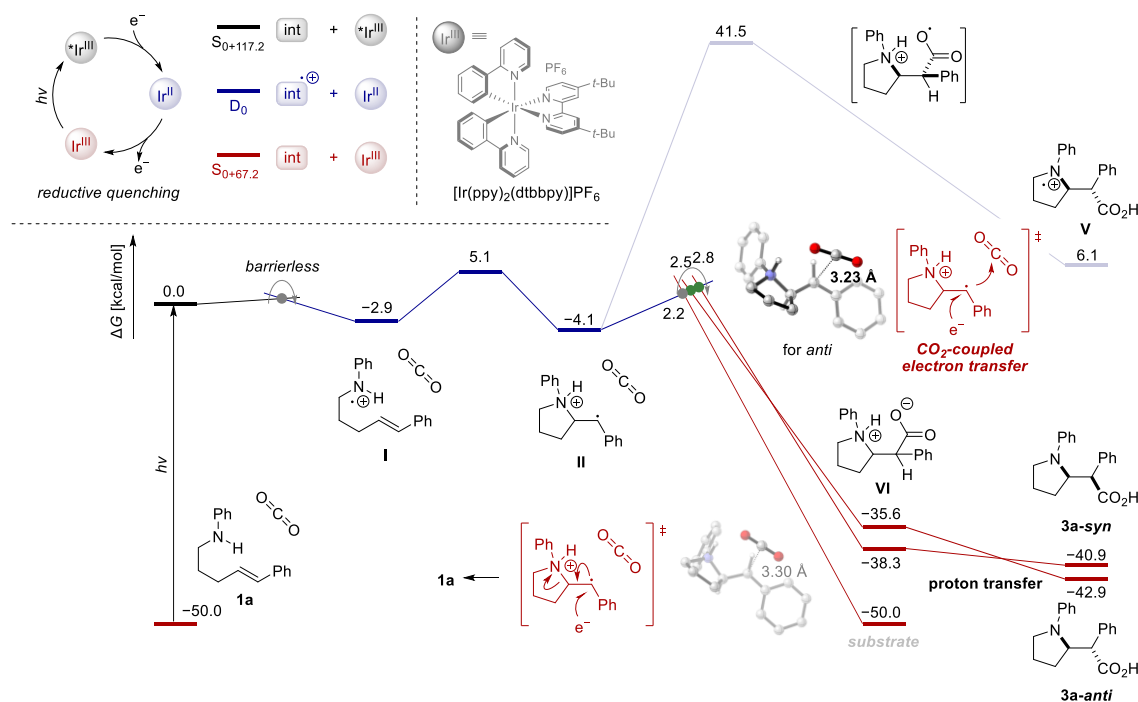


Figure 3.4. Reaction pathway for the reaction of **1a** and CO_2 under photoredox conditions using $[\text{Ir}(\text{ppy})_2(\text{dtbbpy})]\text{PF}_6$ as a photoredox catalyst. Gray circles indicate MESXs, while green circles indicate FM-SXs leading to CO_2 addition. Visible-light-induced $\text{Ir}(\text{III})$ generation is indicated by an arrow with $h\nu$. As indicated at the left top, the red, black, and blue lines represent states involving Ir^{III} , $\text{Ir}^{\text{III}*}$, and Ir^{II} , respectively.

I also found that the radical addition to CO₂ was considerably arduous ($\Delta G^\ddagger = 45.6$ kcal/mol) because the generated carboxylic radical is unstable. Nevertheless, in the presence of an electron, the ES calculations suggested that this process becomes feasible with a $\Delta G^\ddagger$ of 6.6 kcal/mol. This intriguing phenomenon is considered to be the CO₂-coupled electron transfer (*vide supra*). Accordingly, under photocatalytic conditions, the radical addition to CO₂ becomes achievable in the presence of an electron. With respect to the diastereoselectivity, **3a-anti** is preferentially formed over **3a-syn** due to the lower energy of the intersection of the former diastereomer.

Target β -amino acid **3a** exists in equilibrium with zwitterion **VI** due to the low activation barrier between these species (<0.1 kcal/mol). To reveal the decomposition pathways from β -amino acid **3**, I calculated these possibilities using the ES method (S_{0+117.2}) (Figure 3.5). A single-electron oxidation occurred followed by decarboxylation to afford the alkyl radical in an exergonic manner (from S_{0+117.2} to D₀). For this decarboxylation, **3a-anti** ($\Delta G^\ddagger = 20.1$ kcal/mol) is favored over **3a-syn** ($\Delta G^\ddagger = 23.8$ kcal/mol), which indicates that prolonging the reaction time would increase the amount of *syn* isomer (*vide infra*).

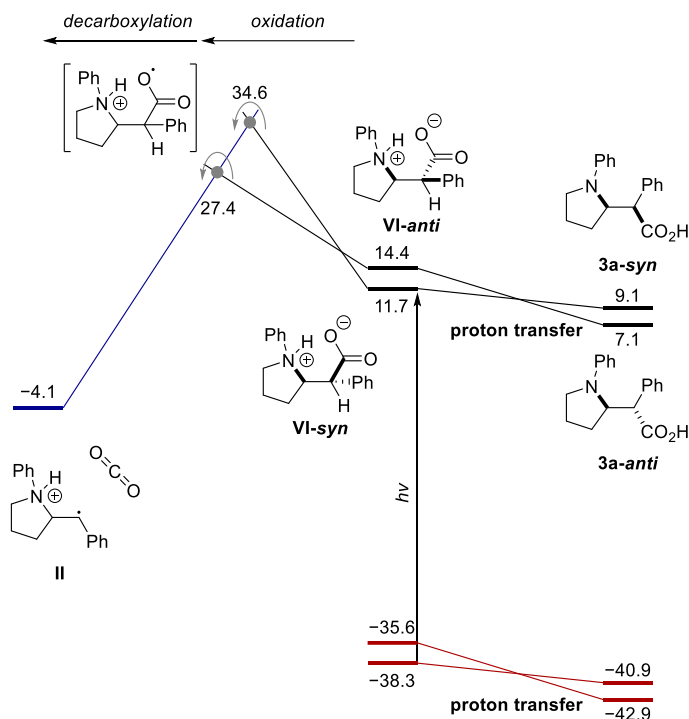
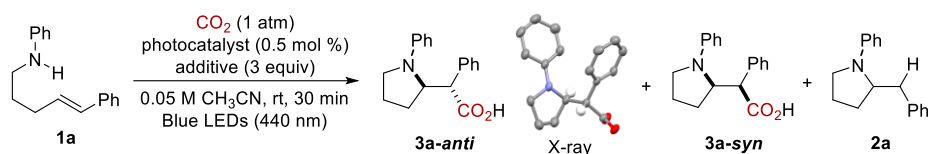


Figure 3.5. Reaction pathway for the decarboxylation of **3**. Red, black, and blue lines correspond to the three electronic states defined in Figure 3.4; gray circles indicate MESXs.

3.2.3. Experimental investigations

Accordingly, I started the experimental study using **1a** as the substrate (Table 3.1). First, photoredox catalysts such as $[\text{Ir}(\text{ppy})_2(\text{dtbbpy})]\text{PF}_6$, $\text{Ir}(\text{dFppy})_3$, and $[\text{Ru}(\text{bpy})_3](\text{PF}_6)_2$ were investigated (Table 3.1, entries 1–3), finding that $[\text{Ir}(\text{ppy})_2(\text{dtbbpy})]\text{PF}_6$ gave β -amino acid **3a** as theoretically predicted using its oxidation/reduction potentials, whereas the other two catalysts did not promote the radical amino carboxylation reaction (Table 3.1, entries 2 and 3). A single-crystal X-ray diffraction analysis (CCDC 2359995) confirmed that **3a-anti** is the major β -amino acid diastereomer, which is consistent with my calculation results. Next, I investigated several bases, which are generally employed in reductive carboxylation reactions with CO_2 .⁴ However, none of the bases tested, i.e., Cs_2CO_3 , $i\text{-Pr}_2\text{NEt}$, and NEt_3 , promoted the carboxylation (Table 3.1, entries 4–6), which is rare for CO_2 -incorporation reactions.⁴

Table 3.1. Condition Screening-1



entry	photocatalyst	additive	3a (%) ^a (<i>anti</i> / <i>syn</i>)	2a (%) ^a
1	[Ir(ppy) ₂ (dtbbpy)]PF ₆	-	46 (4.2:1)	49
2	Ir(dFppy) ₃	-	trace	trace
3	[Ru(bpy) ₃](PF ₆) ₂	-	nd	nd
4	[Ir(ppy) ₂ (dtbbpy)]PF ₆	Cs ₂ CO ₃	2	nd
5	[Ir(ppy) ₂ (dtbbpy)]PF ₆	<i>i</i> -Pr ₂ NEt	trace	nd
6	[Ir(ppy) ₂ (dtbbpy)]PF ₆	NEt ₃	trace	nd

^a Yields were determined using ¹H NMR analysis with 1,1,2,2-tetrachloroethane as the internal standard.

3.2.4. Mechanistic studies on basic conditions

To investigate the reason for the lack of reaction in the presence of bases, I calculated the pathways starting from R-CO₂⁻ (**VII**), which should be instantly formed after deprotonation of the acidic proton of β-amino acid **3a** by a base. The oxidation followed by decarboxylation to furnish alkyl radical **IX** from **VII** was firmly detected using the ES method (S₀+117.2) (Figure 3.6). The Δ*G*[‡] values for the oxidation of **VII** were very small (**VII-anti**: 0.0 kcal/mol; **VII-syn**: 0.6 kcal/mol), while those for the decarboxylation of radical intermediate **VIII** were reasonable (**VII-anti**: 12.9 kcal/mol; **VII-syn**: 13.3 kcal/mol). These results indicate that the decarboxylation of **3a** can be accelerated under basic conditions, which is consistent with the experimental outcome.

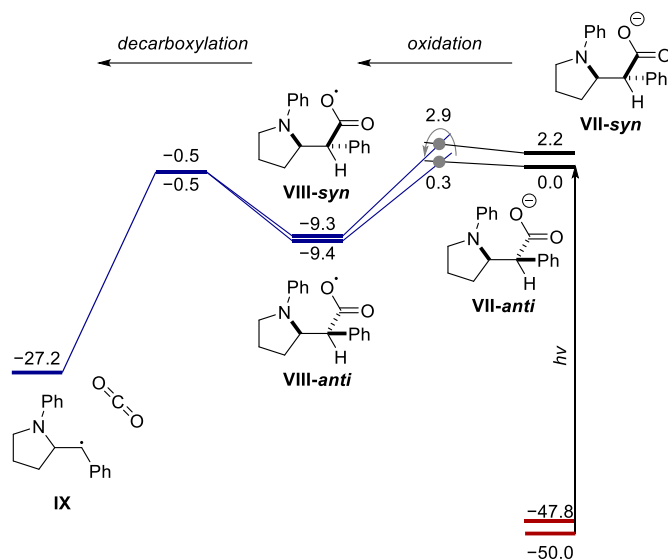


Figure 3.6. Reaction pathway for the decarboxylation of **VII**; red, black, and blue lines correspond to the three electronic states defined in Figure 3.4; gray circles indicate MESXs.

To experimentally confirm the oxidation tendency of each compound, I conducted cyclic-voltammetry (CV) measurements (Figure 3.7). Initially, I examined substrate **1a** to verify that the oxidation potential ($E_{p/2}$) was 0.72 V vs SCE (Figure 3.7a). The $E_{p/2}$ values of product **3a** and NEt_3 were 0.75 and 0.79 V, respectively (Figure 3.7a and 3.7b). However, when product **3a** in combination with 1 equiv of NEt_3 was subjected to CV, its potential shifted to 0.55 V (Figure 3.7d). This indicates that carboxylate **VII** derived from **3a** and NEt_3 is preferentially oxidized by the excited Ir(III) complex ($^*\text{Ir(III)}$), which has an oxidation potential of $E_{1/2} = 0.66$ V. These CV measurements also strongly support that **3a** is not obtained in the presence of a base due to the rapid and exergonic radical decarboxylation of **VII**.

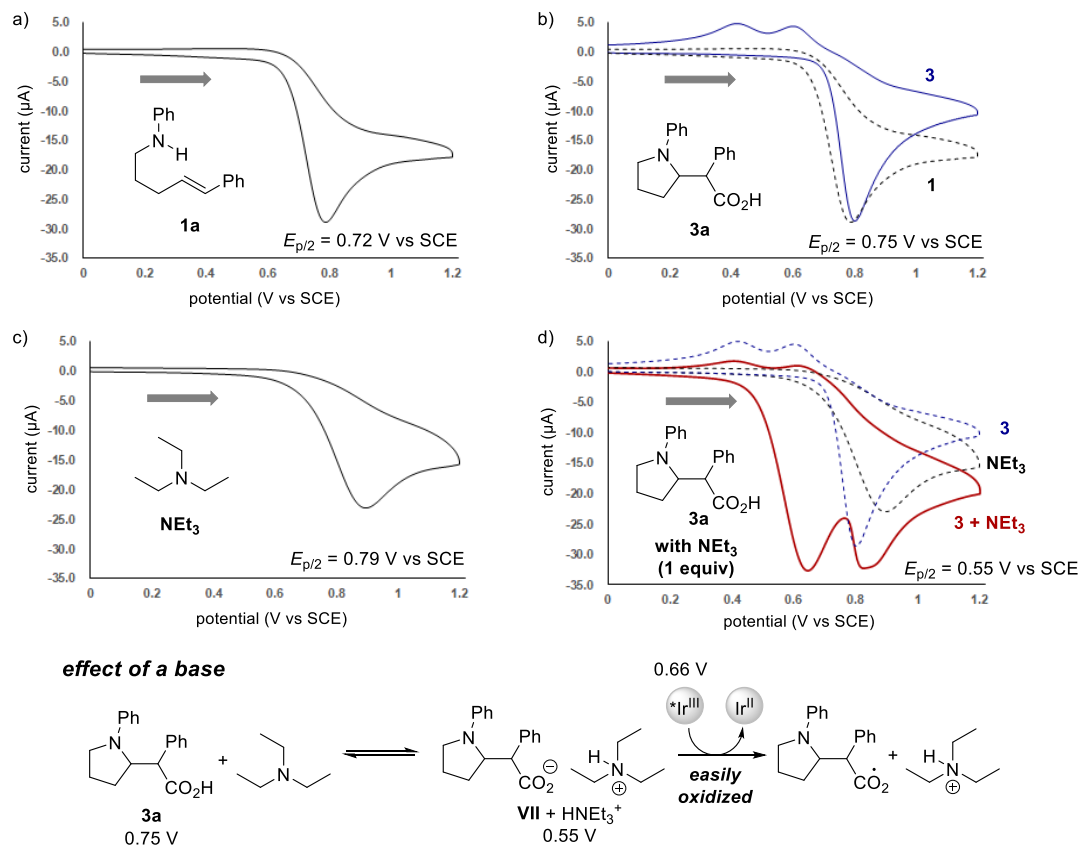


Figure 3.7. CV curves of each component.

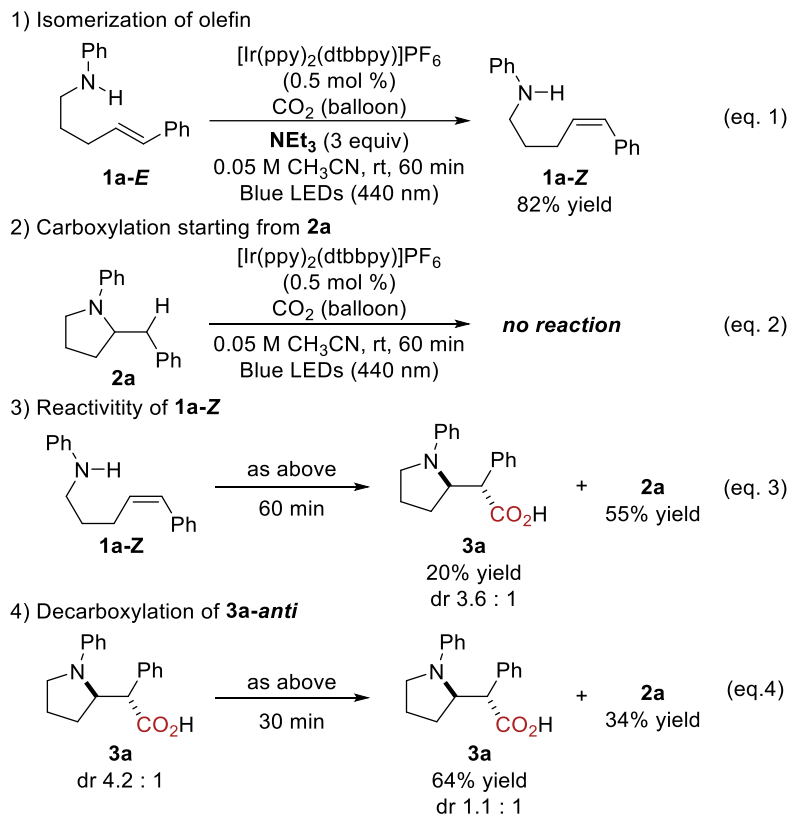


Figure 3.8. Control experiments.

3.2.5. Optimization of reaction conditions

According to the calculation results, I also conducted several control experiments (Figure 3.8). When **1a-E** was subjected to the reaction conditions in the presence of NEt_3 in order to avoid the desired cyclization, it readily isomerized to **1a-Z** under photoredox conditions under a CO_2 atmosphere (eq. 1), most likely via a known energy-transfer mechanism from $^*\text{Ir(III)}$.²² Next, I confirmed that the formation of **3a** was not observed from protonated **2a**, which remained intact under the photoredox conditions (eq. 2). Moreover, the reaction of **1a-Z** mainly gave protonated **2a**, although **3a** was only observed in 20% yield under identical photoredox conditions (eq. 3). This result indicates that **3a** should be obtained predominantly from **1a-E** before the isomerization to **1a-Z**. Next, when *anti*-rich **3a** was subjected to the reaction conditions under a CO_2 atmosphere, **3a-anti** decomposed preferentially to generate protonated **2a** in 34% yield, and the dr ratio changed accordingly from 4.2:1 to 1.1:1 (eq. 4). This is consistent with the

calculation result indicating that **3a-anti** is decarboxylates faster than **3a-syn**. These control experiments (eq. 1–4) suggest that under the reaction conditions, some of the generated amino acids decompose into the isomerized olefin **1a-Z** or protonated **2a**, neither of which is favorable for the target reaction.

Considering the results from the control experiments in combination with those of my calculations, I further optimized the reaction conditions (Table 3.2). To suppress the decarboxylation, the reaction was initially performed just for 5 min, leading to 40% yield of **3a** and 20% yield of **2a** (Table 3.2, entry 1). By extending the reaction time to 10 and 15 min, the yield increased up to 48% and 54%, respectively (Table 3.2, entries 2 and 3). Decreasing the temperature to 0 °C increased the formation of **3a** (Table 3.2, entry 4) and decreased that of protonated **2a**. Significant differences were not observed when using DMF instead of CH₃CN as the solvent for the carboxylation (Table 3.2, entry 5).

Lowering the temperature to –40 °C did not improve the yield, not even in combination with longer reaction times (Table 3.2, entries 6 and 7). However, increasing the pressure from 1 to 10 atm substantially enhanced the yield (in CH₃CN: 82%; in DMF: 86%) (Table 3.2, entries 8 and 9), which can be attributed to (i) the acceleration of the carboxylation step and (ii) the suppression of the protonation of **III** by another ammonium salt/carboxylic acid. Interestingly, prolonging the reaction time resulted in the formation of the opposite diastereomer **3a-syn** in 39% yield, together with protonated **2a** in 59% yield (Table 3.2, entry 10). This observation is strongly supported by the calculation results, which suggest that oxidation/decarboxylation of **3a-anti** is faster than that of **3a-syn** (Figure 3.5)

Table 3.2. Condition Screening-2

entry	pressure (atm)	solvent	temperature (°C)	time (min)	3a (%) ^a (<i>anti/syn</i>)	2a (%) ^a	TOF (min ⁻¹)
1	1	CH ₃ CN	rt	5	40 (4.0:1)	20	16
2	1	CH ₃ CN	rt	10	48 (4.5:1)	28	9.6
3	1	CH ₃ CN	rt	15	54 (4.3:1)	33	7.2
4	1	CH ₃ CN	0	15	67 (5.3:1)	19	8.9
5	1	DMF	0	15	63 (4.3:1)	nd	8.4
6	1	CH ₃ CN	-40	15	20 (7.9:1)	trace	2.7
7	1	CH ₃ CN	-40	80	55 (8.0:1)	trace	1.4
8	10	CH ₃ CN	rt	15	82 (4.3:1)	11	11
9	10	DMF	rt	15	86 (4.2:1)	nd	11
10 ^b	10	CH ₃ CN	rt	30	39 (1: 99)	59	2.6

^a Yields were determined using ¹H NMR analysis with 1,1,2,2-tetrachloroethane as the internal standard. ^b 2 mol% of the Ir cat.

3.2.6. Proposed mechanism

In accordance with the experimental and computational results, I would like to propose the feasible mechanism for the β -amino acid synthesis from amino alkene **1a** depicted in Figure 3.9. First, single-electron oxidation takes place to form **I**, before C–N bond formation occurs to generate **II**. These steps are identical to the initial steps of Knowles' hydroamination.^{8a,9} The single-electron reduction and carboxylation take place simultaneously via the CO₂-coupled electron-transfer mechanism (*vide supra*), in which the formation of **3a-anti** was faster than that of **3a-syn**. Moreover, the one-electron oxidation of **3a-anti** followed by decarboxylation to produce alkyl radical **II** was faster. Regenerated **II** enters the catalytic cycle again to produce **3a**. Prolonging the reaction time results in decomposition of **3a-anti**, increasing the amount of **3a-syn**. Intermediate **III** can also be decomposed reductively to generate starting **1a-E**. Protonated **2a** produced as a byproduct should be generated by protonation with an ammonium salt/carboxylic acid because an intramolecular proton transfer is sterically inaccessible.⁹ Alkene-isomerized **1a-Z** can be generated from **1a-E** via energy transfer from *Ir(III).

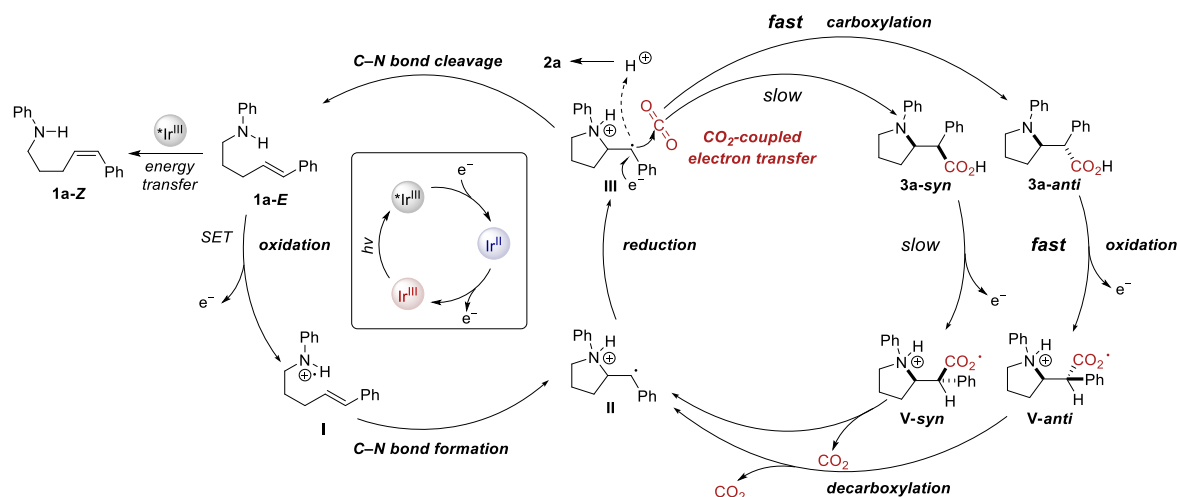


Figure 3.9. Plausible mechanism for the photoredox-catalyzed transformation.

3.2.7. Substrate scope

This protocol was successfully applied to several substrates bearing different substituents on the aryl group attached to the nitrogen atom (Figure 3.10). Not only **1a** with a simple phenyl substituent, but also **1b** with a *p*-chlorophenyl substituent were tolerated under the applied reaction conditions. However, the presence of a *p*-OMe-phenyl substituent led to a decrease in reactivity because its electron-donating ability can be expected to delay the C–N bond formation, which is observed in Knowles' hydroamination.^{8a} Various substituents on the styrenyl moiety, including *p*-Cl, *o*-Cl, and *p*-Br (**1d–1f**), promoted the reaction, achieving yields of up to 77%. It is also worth noting here that the Br group remained completely intact under the applied redox-neutral photoredox conditions. Moreover, an α -Me substitution on the styrenyl group (**1g**) was well tolerated for the production of a β -amino acid motif bearing a quaternary carbon center, as the stability of tertiary carbanion is not a concern in the concerted reduction–carboxylation mechanism. Furthermore, the C–N bond formation in **1h** and **1i** was significantly accelerated by Cl substitution on the aniline ring, affording **3h** and **3i**, both in 98% yield. I also attempted a one-carbon expansion with substrate **1j**, which resulted in the formation of six-membered β -amino acid **3j** in 11% yield with *anti*-selectivity.

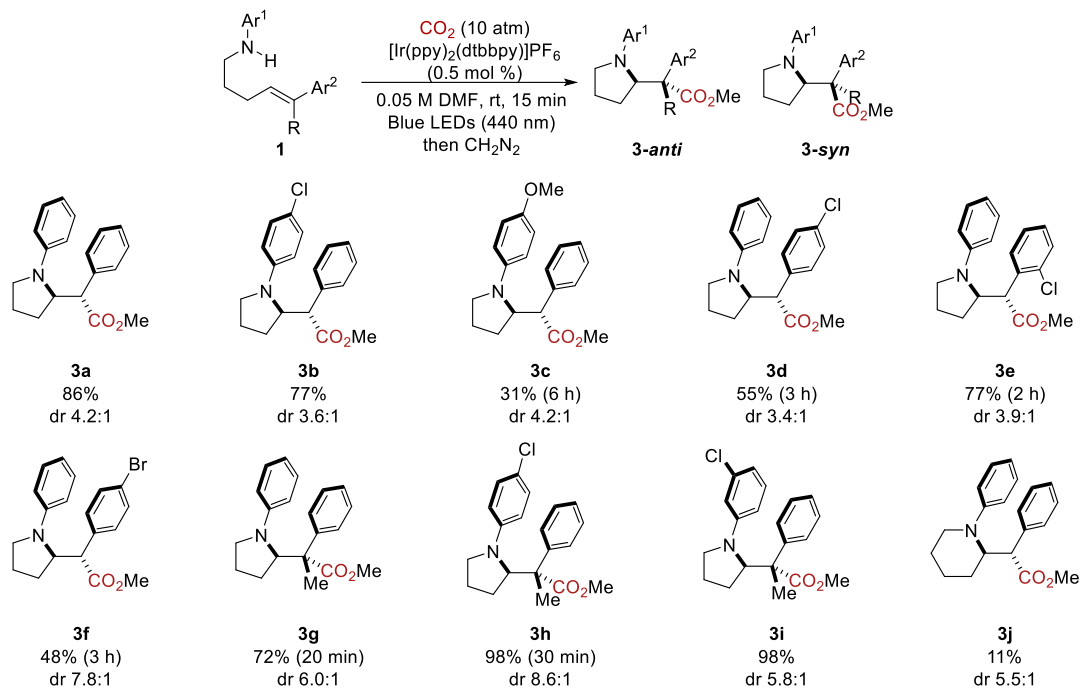


Figure 3.10. Substrate scope for the amino carboxylation.

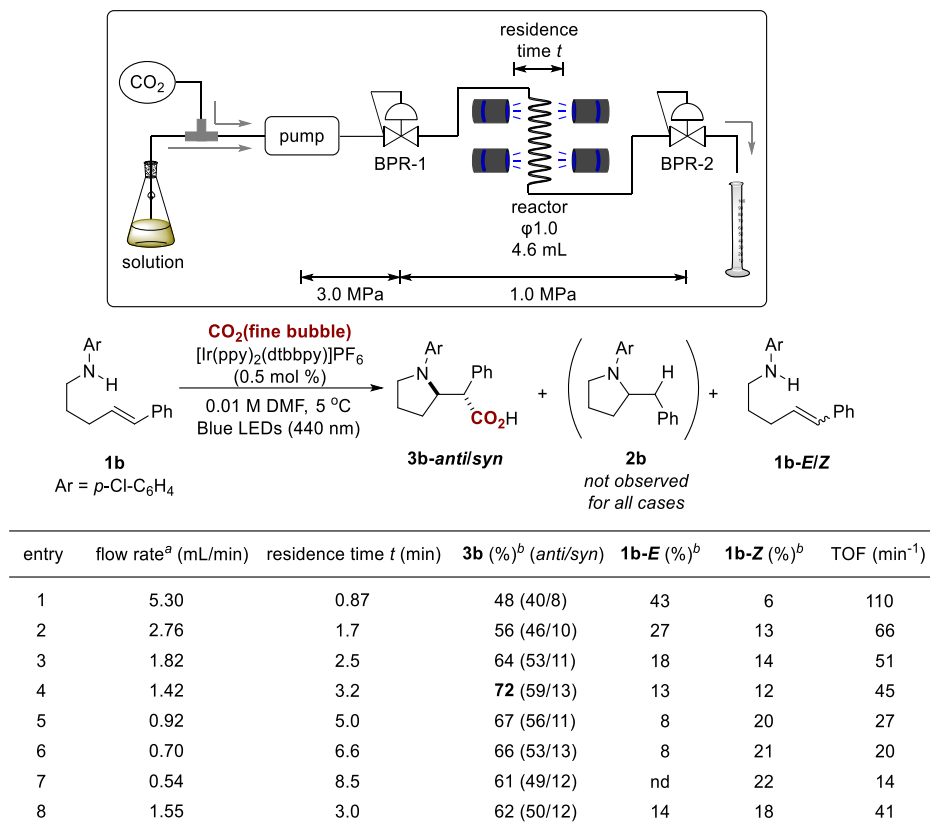
3.2.8. Extension to flow system

Finally, I conducted the reaction using a gas–liquid flow reactor equipped with a fine bubble generator (FBG-OS Type 1 PMT Inc., Japan) to improve the applicability of this β -amino acid synthesis, employing a previously reported fine-bubble-flow method (Table 3.3).²³ This method was expected to avoid the potential side reactions suggested by the calculations because it allows a uniform and short irradiation, promoting efficient reactions without an excessive oxidation/decarboxylation sequence.

Prior to the photoirradiation with blue LED lamps, a solution of amino alkene **1b** ($\text{Ar}^1 = p\text{-Cl-C}_6\text{H}_4$) and the $[\text{Ir}(\text{ppy})_2(\text{dtbbpy})]\text{PF}_6$ photocatalyst in DMF was circulated in the reactor to saturate the solution with CO_2 gas. Then, I turned the LED lamps on to start the reaction. By regulating the pressure difference from 3.0 MPa using a back pressure regulator (BPR-1) to 1.0 MPa using BPR-2, the fine-bubble-slug flow was generated.^{23a} The flow-rate ratio of CO_2 gas and pump (total rate at the exit of the system) was controlled by changing the flow rate of gas and pump while keeping a 1:2 ratio (gradient from

12:24 to 1.5:3.0). A residence time (t) of 0.87 min was too short for this reaction, and 43% of **1b** was recovered (Table 3.3, entry 1). By extending the residence time, the production of **3b** was improved and the recovery of **1b** decreased (Table 3.3, entries 2 and 3). The yield of **3b** was eventually maximized for a t of 3.2 min (Table 3.3, entry 4). The isolated yield after the methyl esterification with CH_2N_2 was 72%. For $t = 5$ min or more, the yield of **2b** decreased and that of isomerized alkene **1b-Z** increased to 22% (Table 3.3, entries 5–7) due to the favored progress of isomerization in the competitive reaction between carboxylation and isomerization under the extended t . According to these results, $t \approx 3$ min is an appropriate residential time. In terms of the TOF number, a more efficient TOF of $\sim 45 \text{ min}^{-1}$ was observed under the best conditions (Table 3.3, entry 4) compared with the batch system (11 min^{-1}) (Table 3.2, entry 9). In the absence of fine bubbles under 1.0 MPa pressure without using BPR-1, the yield decreased to 62% (Table 3.3, entry 8). To determine the solubility of CO_2 in DMF under fine-bubble conditions, I compared the control experiments conducted without fine bubble conditions. I found that the concentration was nearly doubled (123 mM vs. 67 mM) (for details, see the experimental section), indicating that the generation of fine bubbles is important for improving the yield because the solubility of CO_2 in DMF increases.

Table 3.3. Application to Gas Flow System



^a Flow rates were measured at the exit of the system. ^b Yields were determined using ¹H NMR analysis with 1,1,2,2-tetrachloroethane as the internal standard. ^c The isolated yield after the methyl esterification with CH₂N₂ was 72%. ^d BPR-1 was open.

3.3. Conclusion

In conclusion, my study showcases the successful development of a synthetic route to β-amino acids from CO₂, employing computational chemistry, namely the ES/AFIR method, as an efficient prediction tool. By using an Ir-based photoredox catalyst and irradiation from blue LED light for 15 min, high yields of several cyclic β-amino acids were achieved. One notable advantage of this method is its mild reaction conditions, eliminating the need for a base, which is typically required in reductive carboxylation processes. Moreover, I have demonstrated that this reaction can be efficiently carried out using a gas–liquid flow system, furnishing the desired product in 72% yield.

3.4. References

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Chapter 4. General Conclusion

In this thesis, I have focused on reaction development using quantum chemistry calculations. In Chapter 2, I developed a novel reaction: the carboxylation of a palladacycle(II) formed via $C(sp^3)-H$ activation, utilizing quantum chemical calculations as a predictive tool. This research centers on a key intermediate, the Pd(I) complex, generated via the one-electron reduction of palladacycle(II). Pd(I) complexes are typically very unstable, making it challenging to investigate their character and reactivity using experimental methods. Initially, an automated computational search was conducted to explore the properties and reactivity of these elusive Pd(I) intermediates. Following this, computational predictions of reactivity pathways for the carboxylation of CO_2 , starting from potential intermediates, were performed. Finally, the reactions were validated experimentally, confirming the predicted outcomes.

In Chapter 3, the development of catalytic olefin aminocarboxylation is presented. This reaction involves a one-electron reduction, a computationally demanding process due to the necessity of considering two electronic states for a single geometry. To address this challenge, a novel computational approach was introduced to locate representative crossing points. Using this method, crossing points for the concerted one-electron reduction and carboxylation were identified. The diastereoselectivity of the resulting β -amino acids was predicted based on kinetic considerations within the crossing region. Ultimately, the experimental verification of the reaction demonstrated the same diastereoselectivity as predicted computationally.

In these studies on reaction development, quantum chemical calculations were employed to analyze phenomena that are difficult to examine experimentally. This highlights one of the key advantages of quantum chemical analysis: the ability to observe atomic movements within a molecule. Such a microscopic perspective serves as a complement to the macroscopic viewpoint offered by experimental methods. However, to “predict” experimental results using computational analysis, a perspective like experimental methods is necessary. I hope that such a macroscale computational method will be developed, enabling us to predict chemical reactions without relying on prior experience.

Experimental Section

S2. Carboxylation of a Palladacycle Formed via C(sp³)-H Activation: Theory-Driven Reaction Design

S2.1. General

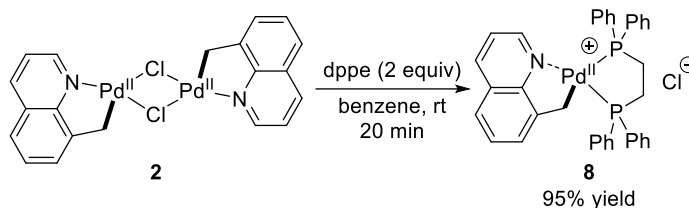
All manipulations were carried out under an atmosphere of nitrogen unless otherwise noted. Infrared (IR) spectra were recorded on a JASCO FT/IR 4600 Fourier transform infrared spectrophotometer. NMR spectra were recorded on a JEOL ESZ-400S spectrometer, operating at 400 MHz (¹H), 100 MHz (¹³C), and 162 MHz (³¹P). Chemical shifts in CDCl₃ were reported in the scale relative to CHCl₃ (7.26 ppm) for ¹H NMR and to CDCl₃ (77.16 ppm) for ¹³C NMR as internal references. ESI mass spectra were measured on a Thermo Scientific Exactive. Dry DMF was purified under argon using the Ultimate Solvent System (GlassContour: Nikko Hansen & Co., Ltd.). A cylinder of CO₂ was purchased from Hokkaido Air Water, Inc. A 45W PR160L-440 nm Kessil light was used as the light source under photoredox conditions. HPG-10 (Taiatsu Techno Corporation) was used as an autoclave which consists of a polycarbonate cylinder.

S2.2. Substrate Synthesis

8-Methylquinoline (**1**) is commercially available and used as received. Palladacycles **2** and **9** were prepared according to the reported conditions.¹ Cationic palladium complex **8** was prepared according to the modified reported procedure.²

¹ Wenzel, M. N.; Owens, P. K.; Bray, J. T. W.; Lynam, J. M.; Aguiar, P. M.; Reed, C.; Lee, J. D.; Hamilton, J. F.; Whitwood, A. C.; Fairlamb, I. J. *S. J. Am. Chem. Soc.* **2017**, *139*, 1177-1190.

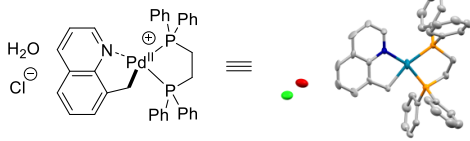
² Fornies, J.; Navarro, R.; Sicilia, V. *Polyhedron* **1988**, *7*, 2659-2665.



In an oven-dried flask were placed palladacycle **2** (113.6 mg, 0.2 mmol, 1 equiv) and dppe (159.4 mg, 0.4 mmol, 2 equiv) in benzene (10 mL). After the mixture was stirred for 20 min. the half of the solvent was removed under the reduced pressure. The addition of Et₂O (12 mL) facilitated the generation of precipitates, which were filtered to afford cationic palladium complex **8** (258.5 mg, 0.38 mmol) in 95% yield. Recrystallization was performed from acetone, giving a suitable block crystal, which could be used as crystallographic analysis.

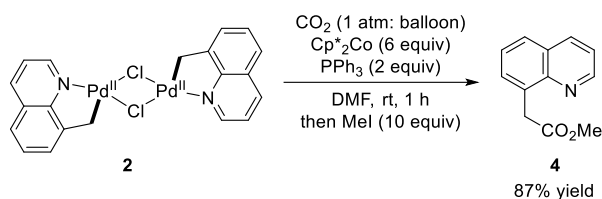
IR (neat): 3032, 2970, 1502, 1472, 1433, 1380, 1308, 1105, 1064, 990 cm⁻¹; ¹H NMR (400 MHz, CDCl₃) δ = 8.45 (dd, J = 8.5, 1.4 Hz, 1H), 8.35-8.33 (m, 1H), 7.77-7.69 (m, 9H), 7.63-7.52 (m, 14H), 7.33 (dd, J = 8.4, 4.9 Hz, 1H), 3.16 (dd, J = 8.0, 3.7 Hz, 2H), 2.83-2.55 (m, 4H) ppm; ¹³C NMR (100 MHz, CDCl₃) δ = 153.5 (dd, J = 5.8, 1.9 Hz), 152.4 (d, J = 6.7 Hz), 147.5 (d, J = 4.8 Hz), 140.1 (s), 133.3 (d, J = 13.5 Hz), 133.2 (d, J = 11.6 Hz), 132.4 (d, J = 1.9 Hz), 132.3 (d, J = 1.9 Hz), 131.2 (d, J = 9.6 Hz), 130.0 (d, J = 10.6 Hz), 130.0 (s), 129.6 (d, J = 10.6 Hz), 128.8 (s), 128.3 (d, J = 15.4 Hz), 127.8 (d, J = 33.7 Hz), 124.8 (s), 122.1 (d, J = 1.9 Hz), 39.0 (d, J = 83.8 Hz), 29.9 (dd, J = 34.7, 19.3 Hz), 26.3 (dd, J = 27.9, 9.6 Hz) ppm; ³¹P NMR (162 MHz, CDCl₃) δ = 56.8 (d, J = 26.0 Hz), 40.9 (d, J = 26.0 Hz); HRMS (ESI): m/z calcd for C₃₆H₃₂NP₂Pd [M⁺]: 642.10606, Found: 642.10650

S2.3. Data for Single Crystal X-ray Structural Analysis

Compound	
CCDC Name	CCDC 2088160
Empirical Formula	C ₃₆ H ₃₂ NP ₂ Pd, Cl, H ₂ O
Formula Weight	700.43
Crystal System	monoclinic
Crystal Size / mm	0.2 × 0.2 × 0.04
<i>a</i> / Å	20.8383(2)
<i>b</i> / Å	13.3739(1)
<i>c</i> / Å	25.6320(2)
α / °	90
β / °	111.154(1)
γ / °	90
<i>V</i> / Å ³	6662.00(11)
Space Group	I 1 2/a 1
<i>Z</i> value	8
<i>D</i> _{calc} / g cm ⁻³	1.397
Temperature / K	123
2 θ _{max} / °	68.249
μ (CuK α) / mm ⁻¹	6.357
No. of Reflections Measured	6096
No. of Observations (All reflections)	27784
Residuals: <i>R</i> ₁ (<i>I</i> > 2.00 σ (<i>I</i>))	0.0529
Residuals: <i>wR</i> ₂ (All reflections)	0.1160
Goodness of Fit Indicator (<i>GOF</i>)	1.269
Maximum peak in Final Diff. Map / Å ³	0.998
Minimum peak in Final Diff. Map / Å ³	-1.130

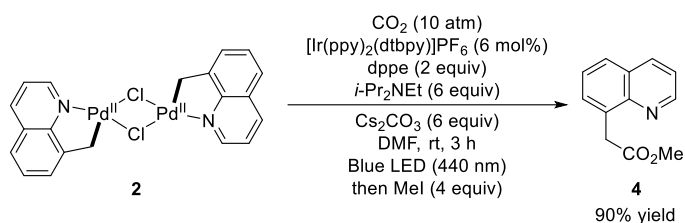
S2.4. General procedure for carboxylation

Thermal conditions



In an oven-dried test tube were placed palladacycle **2** (28.4 mg, 0.05 mmol, 1 equiv), Cp*₂Co (98.8 mg, 0.3 mmol, 6 equiv) taken from a glove box, and PPh₃ (26.2 mg, 0.1 mmol, 2 equiv) in DMF (2 mL). The test tube was filled with CO₂ (1 atm: balloon). The resulting mixture was stirred at room temperature for 1 h. After MeI (31 μL, 0.5 mmol, 10 equiv) was added and the mixture was stirred for a further 10 min. After the mixture was filtered off using Celite, the solvent was removed under reduced pressure. The yield of the product was determined by ¹H NMR spectroscopy using 1,1,2,2-tetrachloroethane as an internal standard (87% yield).

Photoredox conditions

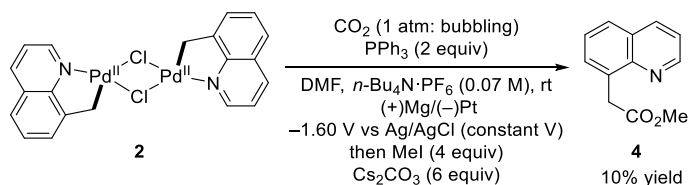


In an oven-dried test tube were placed palladacycle **2** (28.4 mg, 0.05 mmol, 1 equiv), [Ir(ppy)₂(dtbpy)]PF₆ (2.7 mg, 0.003 mmol, 6 mol%), dppe (39.8 mg, 0.1 mmol, 2 equiv), *i*-Pr₂NEt (52 μL, 0.3 mmol, 6 equiv), and Cs₂CO₃ (97.7 mg, 0.3 mmol, 6 equiv) in DMF (2 mL). The test tube was placed in an autoclave and then CO₂ was introduced into the tube (10 atm). The resulting mixture was stirred at room temperature under visible light irradiation using a 45W PR160L-440 nm Kessil light for 3 h. After MeI (12 μL, 0.2 mmol, 4 equiv) was added and the mixture was stirred for further 10 min. After the

mixture was filtered off using Celite, the solvent was removed under reduced pressure. The yield of the product was determined by ^1H NMR spectroscopy using 1,1,2,2-tetrachloroethane as an internal standard (90% yield). The residue was purified by silica-gel column chromatography (the eluent: Hex/AcOEt = 4/1) to afford methyl 2-(quinolin-8-yl)acetate (**4**) (17.1 mg, 0.085 mmol) in 85% yield.

IR (neat): 2951, 1738, 1595, 1500, 1435, 1343, 1261, 1173, 1002, 796 cm^{-1} ; ^1H NMR (400 MHz, CDCl_3) δ = 8.92 (dd, J = 4.2, 1.7 Hz, 1H), 8.15 (dd, J = 8.2, 1.6 Hz, 1H), 7.77 (dd, J = 8.2, 1.4 Hz, 1H), 7.65 (dd, J = 7.1, 0.7 Hz, 1H), 7.51 (dd, J = 8.0, 7.1 Hz, 1H), 7.41 (dd, J = 8.2, 4.1 Hz, 1H), 4.30 (s, 2H), 3.71 (s, 3H) ppm; ^{13}C NMR (100 MHz, CDCl_3) δ = 172.9, 149.9, 146.8, 136.4, 133.5, 130.5, 128.5, 127.6, 126.4, 121.3, 52.1, 37.1 ppm; HRMS (EI): m/z calcd for $\text{C}_{12}\text{H}_{11}\text{NO}_2$ [M^+]: 201.0790, Found: 201.0790.

Electrochemical conditions



In an oven-dried test tube were placed PPh_3 (26.2 mg, 0.1 mmol, 2 equiv) and $n\text{-Bu}_4\text{N}^+\text{PF}_6^-$ (54.2 mg, 0.14 mmol, 0.07 M) in DMF (2 mL). After bubbling CO_2 for 30 min, palladacycle **2** (28.4 mg, 0.05 mmol, 1 equiv) was added to the resulting mixture, which was electrolyzed at a constant voltage (-1.60 V vs Ag/AgCl) under continuous CO_2 flow (anode: Mg; cathode: Pt plated). The resulting mixture was stirred until the system reached 2 F/mol. After MeI (12 μL , 0.2 mmol, 4 equiv) and Cs_2CO_3 (97.7 mg, 0.3 mmol, 6 equiv) were added and the mixture was stirred for further 10 min. After the mixture was filtered off using Celite, the solvent was removed under reduced pressure. The yield of the product was determined by ^1H NMR spectroscopy using 1,1,2,2-tetrachloroethane as an internal standard (10% yield).

S2.5. Cyclic Voltammetry Measurements

Cyclic voltammetry (CV) was performed with an ALS/CH Instruments Electrochemical Analyzer using a glassy carbon working electrode, a platinum wire as the counter electrode and a saturated calomel reference electrode. The scan rate for the experiment was $100 \text{ mV}\cdot\text{s}^{-1}$. The scan direction was negative. The cyclic voltammetry was carried out with the 100 mM CH_3CN solution of $n\text{-Bu}_4\text{N}\cdot\text{PF}_6$ containing 1 mM of the **3** or **8** under a nitrogen gas atmosphere at room temperature (Figure S2.1).

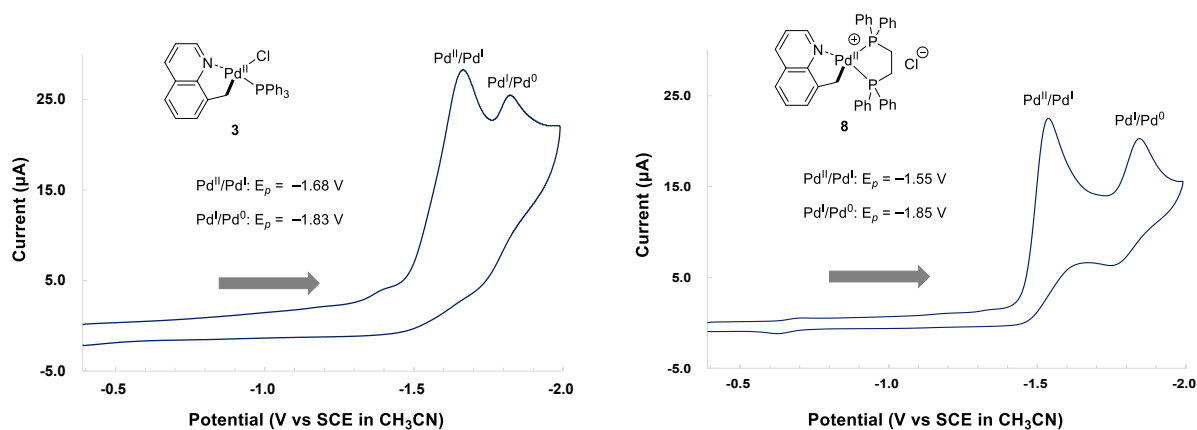


Figure S2.1. Cyclic voltammograms of **3** and **8** in CH_3CN .

S2.6. Details for Quantum Chemical Calculations

Exploration for the potential structures of Pd(I) species derived from **3** and PPh₃ (Figure 2.5)

The potential structures of Pd(I) species bearing PPh₃ which would be generated through single electron reduction of the palladium complex **3** were searched by the single component artificial force induced reaction (SC-AFIR) method implemented in the developer version of the GRRM program,³ where GFN1-xTB was used for the electronic structure calculation with the ORCA 4.2.0 program.^{4,5} The value of γ was set as 100 kJ/mol, and the maximum number of fragment pairs to which the artificial force is applied was set as 1 (SC-AFIR1). The AFIR calculation for the palladium complex **3** and additional PPh₃ as the input molecules was continued until when the electronic energies from the lowest local minima to 80th were not updated in the latest 80 AFIR paths. This automated search provided 1048 structures, where selected 6 complexes **IV–IX** were then used for density functional theory (DFT) calculations with the Gaussian 16 program. Based on the obtained structures, these geometries were optimized by using ω B97X-D functional, Def2-SV(P) basis set with the Grid=FineGrid option in DMF, as modelled by the CPCM method.^{6,7} Single-point calculations were performed at the ω B97X-D/Def2-TZVP level of theory with the Grid=FineGrid option in DMF, as modelled by the CPCM method. The Gibbs free energy values at 298.15 K and 1 atm were estimated by assuming ideal-gas, rigid-rotor, and harmonic vibrational models, where all the harmonic frequencies smaller than 100 cm⁻¹ were set as 100 cm⁻¹ as suggested in the literature.⁸

Exploration for the potential structures of Pd(I) species derived from **8** (Figure 2.9).

The calculation method for the **3** and PPh₃ was applied for the palladium complex **8** bearing dppe as well, where the calculation was continued until when the electronic energies from the lowest local

³ Maeda, S.; Harabuchi, Y.; Takagi, M.; Saita, K.; Suzuki, K.; Ichino, T.; Sumiya, Y.; Sugiyama, K.; Ono, Y. *J. Comput. Chem.* **2018**, *39*, 233.

⁴ (a) Grimme, S.; Bannwarth, C.; Shushkov, P. *J. Chem. Theory Comput.* **2017**, *13*, 1989. (b) Grimme, S.; Bannwarth, C. *J. Chem. Phys.* **2016**, *145*, 054103-1.

⁵ Neese, F.; Wennmohs, F.; Becker, U.; Riplinger, C. *J. Chem. Phys.* **2020**, *152*, 224108-1.

⁶ Barone, V.; Cossi, M. *J. Phys. Chem. A* **1998**, *102*, 1995.

⁷ Cossi, M.; Rega, N.; Scalmani, G.; Barone, V. *J. Comput. Chem.* **2003**, *24*, 669.

⁸ Ribeiro, R. F.; Marenich, A. V.; Cramer, C. J.; Truhlar, D. G. *J. Phys. Chem. B*, **2011**, *115*, 14556.

minima to 73rd were not updated in the latest 73 AFIR paths. This automated search provided 1191 structures, where selected 6 complexes shown in Figure 2.9 were then used for DFT calculations with the Gaussian 16 program. Based on the obtained structures, these geometries were optimized at the same level of theory for those of **3** and PPh₃.

Investigation of reaction pathways for carboxylation of the palladium complexes (Figure 2.4, 2.6, and 2.10).

Reaction pathways were calculated using the developer version of the GRRM program combined with the Gaussian 16 program. Geometry optimizations were performed at the ω B97X-D/Def2-SV(P) level of theory with the Grid=FineGrid option in DMF, as modelled by the CPCM method. Single-point calculations were performed at the ω B97X-D/Def2-TZVP level of theory with the Grid=FineGrid option in DMF, as modelled by the CPCM method. The structures of the palladium complexes after the geometry optimization at the same level of theory for the DFT calculation shown in figures 2.5 and 2.9 were used as the initial components for calculation by the AFIR method, where the value of γ was set as 100 or 150 kJ/mol for the artificial force between the two carbon atoms of the palladium complexes and CO₂ that were involved in the C–C bond forming step. All AFIR paths were then reoptimized by the LUP method.^{9,10} The Gibbs free energy values were obtained as described above. All TSs were also confirmed to connect reactants and products by intrinsic reaction coordinate (IRC) calculations. The Gibbs free energies of the palladium intermediates for carboxylation and CO₂ shown in figures 2.4, 2.6, and 2.10 were calculated individually.

3

Free Energy = -2064.86309111239

C	7.465342944156	-11.026413193859	-2.413081048386
C	6.635039015674	-11.788621259595	-3.276717341582
C	7.222573800305	-11.122050781645	-1.019232361308
H	6.793145177694	-11.738194825360	-4.357959242710
C	5.645280695207	-12.578964129972	-2.744667185078

⁹ Choi, C.; Elber, R. *J. Chem. Phys.* **1991**, *94*, 751.

¹⁰ Ayala, P. Y.; Schlegel, H. B.; *J. Chem. Phys.* **1997**, *107*, 375.

N	6.228779468913	-11.922900563331	-0.519529203571
H	4.990274494339	-13.178112915847	-3.380169165146
C	5.473612022807	-12.619474710662	-1.342266268579
H	4.700676159743	-13.236666437128	-0.873668835565
C	9.270002838372	-9.487445910717	-1.942407816307
C	8.516581321909	-10.183844434409	-2.859840357036
C	9.008707738493	-9.595282435632	-0.553730144574
H	8.714688588828	-10.098883482351	-3.931732285124
H	9.621731939416	-9.025852208603	0.151802882332
C	7.993493476376	-10.400025334736	-0.075471640598
H	10.080969250762	-8.838045120022	-2.283556944260
C	7.644628164266	-10.548610931754	1.385448864985
H	8.528248880026	-10.880538917013	1.960681375330
H	7.350046737277	-9.566835035309	1.798075115199
Pd	6.110336833924	-11.876354542813	1.597933810526
P	6.161962202377	-11.661275864397	3.880666217515
C	7.570463499428	-10.713712393417	4.572174740580
C	8.685633415564	-11.352188540139	5.125267370992
C	7.570297361673	-9.315515325383	4.460343460891
C	9.781641688593	-10.604644185548	5.561160225185
C	8.662571310173	-8.571063094234	4.898974467399
C	9.773066124216	-9.215001606185	5.449062164826
H	8.708074933825	-12.440756628886	5.224640602794
H	6.704976852585	-8.798099836018	4.034615120651
H	10.645578113899	-11.115600024120	5.994957884541
H	8.646357276284	-7.481452062055	4.808643776930
H	10.631718973007	-8.631079201959	5.792173329008
C	6.274524214029	-13.287040116495	4.716099464387
C	7.008074553968	-14.306217674416	4.093787057375
C	5.687475000699	-13.527966450186	5.963272109297
C	7.163164632389	-15.543876398712	4.715927081881
C	5.835721007480	-14.770584663236	6.580414284410
C	6.574752789885	-15.778268701906	5.960070797501
H	7.461624748052	-14.131878149362	3.112885651090
H	5.104327055878	-12.748553307553	6.460862412324
H	7.739184660448	-16.331389624991	4.222338300589
H	5.368176164711	-14.950185417156	7.552464301701
H	6.689830347825	-16.751452806461	6.445657415639
C	4.693701567780	-10.834383986108	4.601151134616
C	4.754415951383	-10.203221221048	5.852879504303

C	3.478983347226	-10.857013684703	3.903240023812
C	3.618735283547	-9.604994804823	6.395946662629
C	2.344205340343	-10.257596051669	4.450911610613
C	2.411852730640	-9.630232264542	5.694939357881
H	5.694130358975	-10.172316176307	6.411190565774
H	3.418714155820	-11.364155327748	2.935826012287
H	3.679308000120	-9.115575324793	7.371814717467
H	1.400812241002	-10.280283974389	3.898360819564
H	1.521861085184	-9.158222197517	6.120698580031
Cl	4.283109602438	-13.503727840768	1.693351537528

I

Free Energy = -2253.40322525824

C	7.429159528411	-11.203315272180	-2.489079526269
C	6.799822980945	-12.237870423276	-3.228097295025
C	7.144769814080	-11.109970390544	-1.101360199197
H	7.001193197807	-12.332308166240	-4.298974948677
C	5.944608206152	-13.103409575412	-2.592761609773
N	6.288846556815	-11.996328252924	-0.497630818058
H	5.440028039178	-13.909700039193	-3.128190434716
C	5.716553873857	-12.945445955336	-1.210006479513
H	5.046307097157	-13.617569026992	-0.667202790099
C	8.869925889035	-9.269381340937	-2.305492328417
C	8.311940825812	-10.259268457039	-3.078046356180
C	8.575503621912	-9.183033434301	-0.923606823314
H	8.530173862657	-10.332802233317	-4.146705861784
H	9.025697575981	-8.382279862136	-0.329632038880
C	7.733311682772	-10.085908855314	-0.309295840123
H	9.547800870231	-8.538398041442	-2.754099484749
C	7.370118634875	-10.014674986233	1.131475217113
H	7.880987505948	-10.863208545679	1.673332069842
H	7.816856682791	-9.157568271019	1.653530142842
Pd	6.048666603434	-11.763264670539	1.612382214159
P	6.070515919016	-11.635455012050	3.921946873967
C	7.536123898732	-10.752253378788	4.578065587394
C	8.569890360715	-11.439421383658	5.228423181112
C	7.635780207021	-9.362014390315	4.409440095147
C	9.686998750337	-10.747608952766	5.697620456365
C	8.752354523605	-8.677229255663	4.883855415303
C	9.781673170607	-9.367234657977	5.526702446289

H	8.512607966751	-12.518654964180	5.383852110217
H	6.837429527435	-8.822915492484	3.892947503920
H	10.485536252123	-11.295712351460	6.204987865920
H	8.818723867555	-7.594404457625	4.747003747842
H	10.657664745206	-8.827749660140	5.897457251043
C	6.187907549562	-13.295162587640	4.673476709964
C	7.045485483448	-14.242564003861	4.095999693048
C	5.482774270769	-13.619544714140	5.836106193282
C	7.205281477301	-15.493453707968	4.685752219087
C	5.637605435026	-14.878833734549	6.418959912265
C	6.499714883393	-15.813935718063	5.848506824971
H	7.592721149926	-14.004433783158	3.178230550869
H	4.805092239702	-12.894624044729	6.294502270202
H	7.879881495734	-16.224743532581	4.232531509401
H	5.080034087766	-15.126027219475	7.326425955855
H	6.621914529784	-16.798437933607	6.308665379373
C	4.617144226310	-10.836413320128	4.668958648023
C	4.717994656639	-10.163015868904	5.893014576149
C	3.373960254862	-10.942593568221	4.033163462276
C	3.582554795214	-9.599126900490	6.473806206013
C	2.242353489471	-10.378752564542	4.619201826092
C	2.345144381972	-9.705904839214	5.838001009974
H	5.682727107392	-10.074494975303	6.399785159797
H	3.290820375897	-11.469870737482	3.078991224607
H	3.667866814586	-9.074471441006	7.429149709153
H	1.274504980069	-10.462987265948	4.117806948878
H	1.456303435908	-9.260923603936	6.293917773323
Cl	4.544627762865	-13.553811198100	1.802223864235
C	5.632214968528	-9.231496227111	1.232861186362
O	5.426431129270	-8.762664142451	2.332130986841
O	5.124743369673	-9.222288979181	0.136832803378

II

Free Energy = -2253.45077715740

C	6.820193746625	-11.162825165472	-2.683638182601
C	5.522611343596	-11.378843725558	-3.211354936444
C	7.010205723380	-11.208545869611	-1.267479155385
H	5.373831017650	-11.336204838693	-4.293942655750
C	4.478355855733	-11.634499446423	-2.363113233015
N	5.937135234667	-11.489952050563	-0.452628843212

H	3.462681481304	-11.803232620102	-2.724722442479
C	4.742689759549	-11.688652673891	-0.982743611773
H	3.934424708599	-11.923627126725	-0.287132577960
C	9.161144402080	-10.680307211680	-3.033741765996
C	7.912429359263	-10.899632781720	-3.551777222484
C	9.349593100827	-10.708577370076	-1.634844392800
H	7.733608530391	-10.875119914830	-4.629982137818
H	10.350397447115	-10.518332790278	-1.237542181892
C	8.325183207254	-10.962740867499	-0.743016525378
H	10.010879877740	-10.476963961337	-3.690111874316
C	8.636917293540	-10.894550498059	0.733194686740
H	8.306478870232	-11.807810316546	1.255529354017
H	9.724834278538	-10.812376531039	0.860308921049
Pd	5.892008255590	-11.575716510800	1.716121884820
P	5.853616463169	-11.607560622391	4.008254517638
C	6.986798404320	-10.368806806976	4.724391433132
C	8.216186313950	-10.733886792807	5.283255690648
C	6.640375881354	-9.011907488868	4.646832797556
C	9.087620071295	-9.753888064088	5.761842180055
C	7.508349901479	-8.038200226250	5.131859039729
C	8.735957765008	-8.407258562266	5.687242395571
H	8.503650381918	-11.785579191551	5.357989268863
H	5.686650978559	-8.712237481676	4.204607763912
H	10.044465869239	-10.050193682678	6.199996143013
H	7.228627278536	-6.983124349404	5.068686712294
H	9.419712624496	-7.641105692362	6.063417471341
C	6.382242506015	-13.202092760257	4.719720853713
C	7.439680788929	-13.887740889694	4.106114599291
C	5.794981794806	-13.730353484545	5.874030413851
C	7.914192381685	-15.078516498063	4.650019182156
C	6.266059357783	-14.929780059700	6.410848291970
C	7.326151808980	-15.602128035526	5.803334043204
H	7.898571281530	-13.491024234332	3.195640812541
H	4.962896919345	-13.214734731733	6.360857577887
H	8.742777404266	-15.602992469993	4.166743590279
H	5.798866748120	-15.339106145742	7.310568840833
H	7.694565486445	-16.540250477095	6.227778042874
C	4.217929769809	-11.223886096532	4.717029798583
C	4.105370187214	-10.658873827148	5.996149940345
C	3.058733963782	-11.526112940258	3.990631891079

C	2.848211263898	-10.400813552437	6.539235906650
C	1.803143814564	-11.265926740647	4.539131068688
C	1.696057238038	-10.702904454989	5.811095115854
H	5.001191999052	-10.414847089223	6.574063319129
H	3.139434978293	-11.977094431067	2.997951094003
H	2.769166061069	-9.958553942638	7.535927673793
H	0.902887159850	-11.502979431101	3.965788807891
H	0.710567946616	-10.497482846946	6.238262870518
Cl	4.824520914956	-13.662263022436	1.680612259843
C	7.997032464902	-9.636392985829	1.345385519980
O	6.770232922159	-9.742971973926	1.741921390669
O	8.624520895728	-8.590893485021	1.381069844905

IV

Free Energy = -2064.95045773525

C	6.525452432639	-11.881753227018	2.141322070523
C	5.617443264534	-12.132158677798	1.077670841743
C	7.125457622563	-13.013352830264	2.763898693286
H	5.152941851592	-11.286349083444	0.560519851731
C	5.313363443591	-13.426442420309	0.725019733034
N	6.757684175684	-14.280415935922	2.433871522078
H	4.608586726305	-13.646949370893	-0.080524560895
C	5.893810392701	-14.482658044331	1.464258638042
H	5.613802530056	-15.525147905995	1.273076403881
C	7.660133899650	-10.446207051659	3.716387750843
C	6.815820186409	-10.579901780327	2.632316815491
C	8.291162897191	-11.563264363506	4.303108168170
H	6.350967394629	-9.708989719271	2.161366988245
H	8.984346142020	-11.407634553170	5.135903735367
C	8.093370843066	-12.861528082894	3.827503786046
H	7.868377850997	-9.449587455925	4.119650842548
C	8.750856921765	-14.051217153806	4.354359383476
H	9.333326166626	-14.590850253537	3.581485401563
H	9.386380777499	-13.831910380270	5.227468625892
Pd	7.257129424233	-15.633463936581	4.431401747865
P	7.120851781351	-15.837395768679	6.738298534792
C	7.542480909764	-14.288245221401	7.635815102060
C	8.396721684290	-14.231936304958	8.743017117928
C	6.972584489579	-13.100184933447	7.157738714270
C	8.668601986749	-13.011094708005	9.365308110647

C	7.232639317834	-11.883753963864	7.785108337854
C	8.084949550609	-11.836173286861	8.890835288559
H	8.857135150000	-15.145645189007	9.129424957072
H	6.332971160317	-13.127680390822	6.269455781376
H	9.341446301656	-12.980781469243	10.227408248201
H	6.781560056228	-10.965888765194	7.397300525832
H	8.298325312527	-10.880768385390	9.379016145352
C	8.306526388805	-17.053114869910	7.453191292656
C	9.552699591675	-17.194596233507	6.824280480652
C	8.028648445843	-17.828730092351	8.585818326174
C	10.504503786304	-18.082289078961	7.325211648872
C	8.977852876367	-18.723760442096	9.082365509800
C	10.218025876519	-18.850549215585	8.455722527348
H	9.771334925297	-16.606765426670	5.925820328511
H	7.062554246597	-17.735921525696	9.089891133562
H	11.472186972313	-18.181600886886	6.825029505242
H	8.745386675261	-19.324549215761	9.966573053961
H	10.960796510508	-19.553214581545	8.844614651228
C	5.534306178649	-16.330733194934	7.535405296870
C	5.065556208992	-15.792206183402	8.741560412906
C	4.766823194311	-17.307113628306	6.881800673983
C	3.859096207720	-16.230982690655	9.290550064823
C	3.567706879046	-17.751842317012	7.438270140821
C	3.110513974850	-17.215381868629	8.643769796331
H	5.645956348415	-15.025483689183	9.263150918282
H	5.105886612711	-17.707288509194	5.918261047799
H	3.503840037858	-15.801420693896	10.231940550353
H	2.980353250531	-18.516358583297	6.920891104301
H	2.167155725753	-17.560657821042	9.077018381637
Cl	6.095180885040	-17.723253239661	3.467875934005

V

Free Energy = -3101.03937406131

C	7.479894174262	-10.955681600593	-2.390279873073
C	6.551185666473	-11.656034191282	-3.218438308283
C	7.312726915989	-11.045220289760	-0.970890504911
H	6.651661479067	-11.620163975508	-4.307038058537
C	5.549534970579	-12.432167155507	-2.594281579096
N	6.243376741041	-11.715360086379	-0.398001126925
H	4.854304605953	-13.031743942000	-3.189457552050

C	5.430203632309	-12.444838061727	-1.221152464865
H	4.653075329896	-13.040250532047	-0.737664797671
C	9.448317957845	-9.554161832735	-1.993820610902
C	8.561629490996	-10.183119841689	-2.871100617607
C	9.293345573386	-9.694985569576	-0.612405416574
H	8.695710801169	-10.082089741883	-3.953602340259
H	10.002407493558	-9.221509680471	0.075485562639
C	8.232360446155	-10.454558360828	-0.095898113574
H	10.273729777089	-8.955502754135	-2.392895671888
C	8.043445244541	-10.721065899560	1.374307341309
H	8.780293205207	-11.461169285294	1.740360087722
H	8.193033710036	-9.801497362010	1.969949145369
Pd	6.150164694906	-11.484076054783	1.682107195473
P	6.564616878077	-11.247256670074	3.955605092997
C	8.338507642204	-11.383534479481	4.420913445333
C	8.935168393902	-12.646116727928	4.535477676951
C	9.137710517123	-10.240431529719	4.551654247026
C	10.300587550093	-12.760201468368	4.793805814626
C	10.503580730840	-10.356899279301	4.810651047050
C	11.088248398766	-11.616698911327	4.936048459575
H	8.345538842344	-13.555706694463	4.394337309692
H	8.697869661755	-9.244737043194	4.450132513910
H	10.751932827704	-13.752477334380	4.881326742502
H	11.112004144017	-9.453947365503	4.912673782163
H	12.158965632267	-11.709029868512	5.138698489638
C	5.769971742186	-12.562481848519	4.962330126216
C	5.703997639661	-13.843880920403	4.397870582882
C	5.213516042668	-12.345779839249	6.229103645624
C	5.074657621828	-14.883612682562	5.082349486244
C	4.588507161176	-13.388455967820	6.911769179948
C	4.508400125570	-14.657991765138	6.336792722970
H	6.157018878173	-14.054870511378	3.420311835264
H	5.225820968159	-11.354095950191	6.684751074892
H	5.022335022891	-15.873039095735	4.619034705626
H	4.144919147193	-13.200898487019	7.893586949783
H	4.004768962840	-15.470817166394	6.867906595697
C	6.046712583581	-9.647259385059	4.671823556956
C	6.392780413281	-9.262876464453	5.977897219499
C	5.287810388512	-8.773796333503	3.886434170047
C	5.954783392448	-8.045840305316	6.493282596336

C	4.849337529384	-7.553470527055	4.402307810569
C	5.175381582003	-7.192251140839	5.707706471963
H	7.022238514137	-9.909790087921	6.595782538684
H	5.038070100665	-9.047769912140	2.858136146087
H	6.225785070905	-7.760355815235	7.513395581508
H	4.248446010849	-6.887040956636	3.777918388096
H	4.830025410846	-6.237967158992	6.115479091896
P	3.733126749979	-11.922416656705	1.797500635263
C	2.777053442750	-11.120955537165	3.151332654198
C	2.634079901558	-11.766841266935	4.386189741872
C	2.250797956215	-9.831203645375	3.000749241595
C	1.997425768303	-11.129927965087	5.450384595100
C	1.612744122981	-9.195457617701	4.064730871104
C	1.489000672701	-9.840126412733	5.295424889464
H	3.014531120426	-12.782132252089	4.523928249904
H	2.338188492991	-9.306902096354	2.045641610535
H	1.902013748732	-11.649548214913	6.408030057230
H	1.211046781294	-8.187510118602	3.928280070753
H	0.992058317884	-9.340591797807	6.131901832140
C	3.173762641653	-13.664197858609	1.849786461996
C	1.864297427967	-14.033421438670	2.195215644831
C	4.106945120333	-14.661824037629	1.547445016772
C	1.497235380188	-15.377263002505	2.228032365690
C	3.737569582263	-16.007172267001	1.583070268473
C	2.434356309031	-16.367812898776	1.921240499138
H	1.125150684599	-13.269397055705	2.453357408130
H	5.151039225210	-14.416943769031	1.318543617449
H	0.474229618622	-15.652847747805	2.499336013711
H	4.490509797477	-16.768706847829	1.361549973640
H	2.146456799946	-17.422610229759	1.956321341312
C	2.949206692897	-11.196012761816	0.298620376953
C	1.857536519751	-11.782450224319	-0.350081956706
C	3.489464227135	-10.009617536313	-0.217155173415
C	1.316000698854	-11.194252125023	-1.493814474315
C	2.942059211304	-9.415831902560	-1.352638982055
C	1.855762775301	-10.010409340394	-1.996846141856
H	1.427536719154	-12.715424671938	0.022433569592
H	4.365485343676	-9.556125734817	0.256507869468
H	0.467544282556	-11.668389202909	-1.995192169793
H	3.376818435635	-8.492291091764	-1.744785141479

H	1.432249335398	-9.552389213230	-2.895214865518
Cl	7.651253943736	-15.086069593543	1.574118785309

VI

Free Energy = -2064.94854094216

C	5.275914495139	-13.076047394467	-0.041544887209
C	4.501660293722	-14.048936159887	-0.726743689120
C	5.453263088889	-13.248353148163	1.357807886052
H	4.365129354445	-13.960641819944	-1.808837839158
C	3.917052935411	-15.076575100818	-0.025160451424
N	4.791935717562	-14.232055135684	2.040253563200
H	3.312386136907	-15.837344047575	-0.523448409092
C	4.064375126303	-15.109843809448	1.378942101115
H	3.545059146786	-15.867954247148	1.973304390150
C	6.517387679297	-11.007522118044	0.088090630142
C	5.833550132646	-11.930975173328	-0.672480116373
C	6.742505989977	-11.215369610918	1.468015393056
H	5.689197001400	-11.786501225992	-1.746682795268
H	7.339033148339	-10.487921421162	2.027614787849
C	6.277773598634	-12.350463107425	2.124696156660
H	6.924811194629	-10.109313335717	-0.386032937975
C	6.558784921307	-12.685893538174	3.527169341524
H	7.205613838377	-13.578978609268	3.621155638480
H	6.985720393603	-11.846042619859	4.097518201054
Pd	4.759702161729	-13.713582185880	4.197798432260
P	4.548576793363	-13.053795002014	6.369086584334
C	4.633495855434	-11.225625900036	6.576582298407
C	4.843293253162	-10.626504816273	7.827816564848
C	4.452225359558	-10.412447003608	5.450959978330
C	4.860325521459	-9.237138073863	7.942894171088
C	4.466891503215	-9.021102156022	5.570464268781
C	4.669336113900	-8.430844618733	6.817833236270
H	5.011648975604	-11.225650759827	8.732544480124
H	4.310990354867	-10.877161015625	4.469622383284
H	5.024981324103	-8.785160623957	8.925770627435
H	4.324332914628	-8.398555282562	4.682463785191
H	4.684043794841	-7.341065942505	6.914230600606
C	5.937500216786	-13.663784441647	7.403216753739
C	7.156804656068	-12.973619910513	7.420851078352
C	5.835756529368	-14.877796512570	8.094511905308

C	8.244875197731	-13.476365346214	8.133815372213
C	6.923714147022	-15.379532273892	8.808567543606
C	8.130731898163	-14.679276673167	8.832247652690
H	7.258673948705	-12.027321713965	6.881289892523
H	4.894437833380	-15.435678151126	8.088043472461
H	9.187925030390	-12.922320414862	8.144831832573
H	6.825707492123	-16.324661559964	9.350317265791
H	8.983010248746	-15.071431522027	9.394425522903
C	3.048068188278	-13.503825781002	7.338102461412
C	2.968722118945	-13.361229322078	8.732238307408
C	1.930300592775	-13.967487654318	6.634006732387
C	1.783753867633	-13.670775330919	9.398092657020
C	0.743667849527	-14.274012921872	7.303796054293
C	0.668409642957	-14.123663564223	8.688306979153
H	3.825690438201	-13.016265819567	9.326822664771
H	1.992342118024	-14.091567068457	5.546628654381
H	1.736462863617	-13.551078645865	10.484820214948
H	-0.122165470651	-14.634199057310	6.740834902506
H	-0.259272802452	-14.363327322717	9.216447362062
Cl	5.257660484383	-11.991907538753	11.213859701954

VII

Free Energy = -3101.04771403214

C	6.926678912690	-12.270740421621	2.209261436102
C	6.973837266939	-11.186860052723	1.295873465244
C	5.675352781336	-12.943610573365	2.357276945289
H	7.915888196048	-10.645539198826	1.159486168292
C	5.843406279562	-10.823505181467	0.598054914613
N	4.587006342972	-12.578623517002	1.646571757541
H	5.851561436449	-9.988849607878	-0.107523918856
C	4.662681818181	-11.565521694591	0.810048762550
H	3.743828753307	-11.306631049449	0.267539392460
C	7.940610969902	-13.759821544720	3.830980216275
C	8.058375016295	-12.680212060533	2.969585581208
C	6.728484392975	-14.442011994234	3.985510622767
H	9.006457006363	-12.147916504137	2.851707026951
H	6.678449993120	-15.300810332117	4.662231642635
C	5.547754066786	-14.057573729865	3.299076321887
H	8.812602704180	-14.092452041360	4.404006502900
C	4.298339577242	-14.731001982085	3.466294128068

H	3.578696581049	-14.612630012031	2.652732373122
H	4.344483565951	-15.735870602423	3.904971099013
Pd	3.826747464030	-13.393920659722	5.127208585823
P	4.480033395272	-11.688749363172	6.710180750073
C	5.188003296571	-10.126607307459	6.031055219493
C	5.891213679267	-10.229439734643	4.826632498991
C	5.129494046058	-8.886328690203	6.678119537945
C	6.511081363287	-9.114343143846	4.264804547256
C	5.734681734003	-7.765149622437	6.110178892989
C	6.424151512583	-7.875434665808	4.900766470285
H	5.946010868040	-11.197431160873	4.319591605406
H	4.604600961145	-8.784827486152	7.632389418317
H	7.051342695561	-9.215049679216	3.319115711786
H	5.669884256151	-6.798744588788	6.618526901605
H	6.896477936911	-6.994552661860	4.456407548393
C	5.859404592150	-12.107215521440	7.863356347213
C	6.816880064947	-13.017896707958	7.402286653904
C	6.051019877286	-11.492116987026	9.107970654260
C	7.943137783331	-13.316414391038	8.170205492070
C	7.170357576323	-11.798482047318	9.881912307022
C	8.118693247487	-12.711838840016	9.415187193986
H	6.683041985535	-13.488315204501	6.423234067597
H	5.322765567293	-10.765609361681	9.481156474862
H	8.683322043543	-14.028819599285	7.794190249378
H	7.305527043842	-11.316363599425	10.854525649995
H	8.996581438547	-12.949835986688	10.023085568232
C	3.122290904718	-11.133393427989	7.810149457292
C	2.250253960656	-10.115322308058	7.400402991981
C	2.813328663578	-11.856949671531	8.971810300260
C	1.106539006251	-9.818082486583	8.140524516398
C	1.671814290349	-11.555745083098	9.714302217005
C	0.814253413292	-10.534966058906	9.300791574082
H	2.454484004103	-9.550673724435	6.486768348114
H	3.462671165149	-12.675147630816	9.297122793507
H	0.435821098686	-9.024548639064	7.798529899558
H	1.447923866316	-12.128764901688	10.618721402611
H	-0.085282266468	-10.304386136332	9.878660969152
P	1.735852139003	-12.633151814056	4.251949962495
C	0.212572787360	-13.020562090214	5.220949731444
C	0.316852363699	-13.059228443304	6.617053340993

C	-1.042588598575	-13.237227626362	4.633891983679
C	-0.803117210781	-13.306580903317	7.410940670937
C	-2.162541527465	-13.492545852590	5.425974270153
C	-2.045929242228	-13.527663250763	6.816971760768
H	1.285755388890	-12.887378844070	7.092448887716
H	-1.154137563718	-13.202724647084	3.546713470347
H	-0.697337553728	-13.327757999875	8.499425319484
H	-3.133980782474	-13.660975620077	4.951960458889
H	-2.924887002684	-13.728781695386	7.436459583253
C	1.247897282517	-13.209694075830	2.575929736488
C	1.105504471331	-12.357752897081	1.476755351447
C	1.071792970430	-14.588570048882	2.388906370690
C	0.793442367163	-12.871996890593	0.216229143568
C	0.749738058944	-15.102718564088	1.134902183265
C	0.613492334457	-14.243709300163	0.041250057262
H	1.245511166680	-11.280427527990	1.596952405113
H	1.195060957312	-15.271187419455	3.236951015282
H	0.689538352610	-12.191251276892	-0.633949574060
H	0.611723323254	-16.180319432561	1.007620215245
H	0.368994238290	-14.646031780235	-0.946108224707
C	1.628343365902	-10.802040977779	4.096686140870
C	0.500079981421	-10.052478733922	4.450823486760
C	2.776306953295	-10.130101204482	3.658592780338
C	0.529978195319	-8.658595618054	4.387015009205
C	2.806795188032	-8.738962760695	3.586626373845
C	1.684288341288	-7.998308915896	3.961531717440
H	-0.405829728974	-10.553392948737	4.802138931237
H	3.662712575123	-10.708172075677	3.385357695245
H	-0.353608774889	-8.084444257501	4.681134066946
H	3.720787350331	-8.235310507125	3.258380879512
H	1.709120983882	-6.905313795660	3.923363723746
Cl	3.739993427776	-15.485488644087	6.943576841087

VIII

Free Energy = -2064.96139650302

C	4.964835898207	-14.839262955453	0.763559959252
C	5.516880699050	-16.139583910766	0.671419453059
C	5.603229105692	-13.923426673086	1.658030828858
H	5.053125712552	-16.870786163341	0.001096164062
C	6.628085004707	-16.473482742909	1.420827075302

N	6.694008993821	-14.268279504553	2.367989189835
H	7.072076547983	-17.470943727840	1.368131417981
C	7.185306112776	-15.491661195938	2.257885784859
H	8.072450412849	-15.722594226739	2.861429733166
C	3.355472666161	-13.127175394019	0.115740893018
C	3.828596566441	-14.432286073295	0.004327614365
C	3.946236367070	-12.213382726513	0.984615243221
H	3.357863420562	-15.147368168707	-0.676462874164
H	3.555092033617	-11.193006845608	1.052111070251
C	5.048407874644	-12.572176224530	1.828257409311
H	2.500684517487	-12.809930459128	-0.490814845882
C	5.628364192014	-11.648180302574	2.753220525644
H	6.650961586461	-11.837285133151	3.097778678138
H	5.382061739349	-10.584671272249	2.624810117598
Pd	4.195001478494	-12.589760758615	3.989513291747
P	4.947648723073	-11.821607980603	6.034410696373
C	5.948612899755	-10.282536887108	5.953017864475
C	7.229069273509	-10.151665524083	6.500822975809
C	5.383565152125	-9.190743076411	5.277430229888
C	7.928348845105	-8.947399830652	6.382562438444
C	6.074268216347	-7.986253413538	5.170562523976
C	7.352144030278	-7.862566940995	5.722948976936
H	7.691460118370	-10.992640664397	7.025302963544
H	4.392493204768	-9.292166630476	4.821615197167
H	8.929559853346	-8.858342550013	6.814136122080
H	5.618420443638	-7.141571277436	4.646089104774
H	7.899386458033	-6.919791746755	5.632965558458
C	6.105491864189	-13.037432009430	6.789160116761
C	6.887411573729	-13.818964651924	5.924277911116
C	6.243835613990	-13.207472415810	8.172732029569
C	7.798653617743	-14.741746958528	6.437986969733
C	7.151041135569	-14.137112150533	8.683920377976
C	7.932257169840	-14.903950768769	7.818404571226
H	6.776064614011	-13.715409749194	4.837508992508
H	5.639336275520	-12.610811535660	8.861947648637
H	8.402221962978	-15.345241437893	5.753623551771
H	7.247629014865	-14.262310687254	9.766268656683
H	8.642389031894	-15.632914090261	8.219745589237
C	3.775891913015	-11.456682306284	7.405040498245
C	3.996965616459	-10.466597073010	8.372258473839

C	2.607450309484	-12.229253033941	7.472150768329
C	3.069904230208	-10.259838976641	9.394890748097
C	1.686037845672	-12.025635421784	8.499691576785
C	1.914867136987	-11.040900364960	9.462439306983
H	4.900696128658	-9.851133003281	8.331829417812
H	2.412433987123	-12.984678714897	6.701267739009
H	3.252484215493	-9.483923084143	10.144104396883
H	0.777364332014	-12.633371504674	8.542529350479
H	1.188082600081	-10.876671861203	10.263425400676
Cl	2.278428086190	-14.161064722452	4.303582335119

IX

Free Energy = -3101.05748898679

C	6.652147942699	-14.346039430401	-1.192126968177
C	6.847309911922	-15.747444064909	-1.184722419671
C	7.276172614825	-13.595905292821	-0.147774443528
H	6.375017807441	-16.357022636945	-1.961712012275
C	7.623710716231	-16.331200213670	-0.203150481875
N	8.039092347482	-14.185152478599	0.791748683768
H	7.787493154564	-17.411311031352	-0.172576016747
C	8.205998849984	-15.498012667029	0.767127448197
H	8.834121905401	-15.928806951402	1.556485318717
C	5.752616854007	-12.299755247010	-2.164690869282
C	5.877481209678	-13.684898544789	-2.190577775298
C	6.336535512643	-11.539302586394	-1.156803653577
H	5.406453939179	-14.278673821342	-2.979018263417
H	6.206616349439	-10.453294129638	-1.149793872534
C	7.067177832810	-12.139241663742	-0.077253368081
H	5.176071530108	-11.795331557344	-2.945770073982
C	7.658999135384	-11.361930191760	0.961482972906
H	8.476045424938	-11.798260390634	1.543682105510
H	7.730718640770	-10.277952323194	0.801701429628
Pd	5.759578225800	-11.866415220458	1.818351603246
P	6.180845898730	-11.390947444508	4.090847532932
C	7.955337689130	-11.149228410542	4.504445561322
C	8.676731917631	-11.992537375444	5.355557976379
C	8.618545287789	-10.076690058617	3.889020090207
C	10.035994107425	-11.765365296497	5.590081824979
C	9.969045188644	-9.842601253058	4.132307482492
C	10.683837477708	-10.690681056873	4.983090388769

H	8.180697020792	-12.835043532081	5.845505276081
H	8.068704631709	-9.418755977460	3.208200291868
H	10.588934585266	-12.433470972525	6.256705470494
H	10.469697661234	-8.998321577633	3.649667999930
H	11.746848970719	-10.513058881615	5.169427417038
C	5.684740433262	-12.801102704752	5.161585903399
C	5.854453656948	-14.091062250957	4.640006238230
C	5.074298425147	-12.650852445261	6.412252243756
C	5.408817104151	-15.208471799363	5.343089536920
C	4.623048957894	-13.768660201843	7.115755327757
C	4.782456815775	-15.047833501624	6.580433350662
H	6.317389499093	-14.220479866822	3.656533169737
H	4.921685261876	-11.654709817140	6.835392939713
H	5.531366270336	-16.204718637216	4.908639489512
H	4.133488480422	-13.636227323167	8.084825011654
H	4.414818124563	-15.921119448632	7.126816907647
C	5.399429147156	-9.940866380856	4.902978080621
C	5.947689000686	-9.336943881165	6.044682738954
C	4.200376382933	-9.445472403505	4.378281114364
C	5.300864102592	-8.263935495985	6.655236033827
C	3.552977680747	-8.371321260082	4.990932191713
C	4.099702342752	-7.780405682417	6.129448451437
H	6.887201768546	-9.709168987585	6.464282712945
H	3.777369252430	-9.881569927756	3.470444499832
H	5.737165053821	-7.801426831008	7.545215638002
H	2.621047990458	-7.991139410702	4.563055250417
H	3.594877978919	-6.935129201893	6.606439200213
P	3.575267303597	-12.839676604918	1.686132996205
C	2.336877290409	-12.127789543762	2.847850261419
C	2.411192579080	-12.483350732762	4.203078535744
C	1.427177607335	-11.136637398749	2.462490023587
C	1.600947611061	-11.861241267018	5.149343592493
C	0.619437543943	-10.508150848586	3.412794176617
C	0.704764331833	-10.865060001218	4.757867426529
H	3.111303444976	-13.257381442481	4.527817395530
H	1.349142360121	-10.833758388367	1.415383580994
H	1.680897013911	-12.151578609466	6.201017369246
H	-0.082442787307	-9.732157953386	3.094015278159
H	0.074267350895	-10.367550768475	5.500271249685
C	3.514242468182	-14.638736243692	2.052816583269

C	2.391732866084	-15.281619659646	2.590816971750
C	4.647640955160	-15.400705968404	1.747165547619
C	2.413170862922	-16.654724389359	2.835249098371
C	4.667150051560	-16.775531235417	1.978225584534
C	3.551150016528	-17.404407540384	2.530622819640
H	1.490534687343	-14.709000604354	2.827340450318
H	5.532469535786	-14.909927003980	1.332815816337
H	1.532897204465	-17.142234996292	3.263837820990
H	5.564322796260	-17.351043596342	1.733405860030
H	3.566497608606	-18.480848487437	2.724299287567
C	2.765448417265	-12.726274091070	0.037624616552
C	2.183486799228	-13.827420290812	-0.604010026123
C	2.794757721141	-11.489746048837	-0.624805749584
C	1.634666618141	-13.693730528688	-1.880837354568
C	2.226660381759	-11.355939893630	-1.891130793869
C	1.650181431372	-12.457032036103	-2.526338320499
H	2.159658264348	-14.804160385656	-0.113904232869
H	3.263164980785	-10.613303701496	-0.154944917214
H	1.189312706022	-14.564490686236	-2.370962048822
H	2.251905505872	-10.382883496116	-2.390845983104
H	1.216395669196	-12.352740122600	-3.525287163436
Cl	4.251009081522	-8.475407694250	0.798321260530

XI

Free Energy = -3289.62550387049

C	7.082567192858	-11.980633041081	-1.391884171125
C	7.618673108332	-13.288294561146	-1.541404084790
C	7.402129395575	-11.272301295591	-0.196958995425
H	7.389605464276	-13.859790699123	-2.446521467184
C	8.389078880342	-13.821237938832	-0.538966306575
N	8.194299439987	-11.812246531230	0.765450106255
H	8.800326030053	-14.831860872555	-0.599817721366
C	8.653029618198	-13.032233564263	0.608840552339
H	9.254250555548	-13.463294414810	1.422517543574
C	5.706614810369	-10.136991915083	-2.144280409312
C	6.222675839112	-11.394743948007	-2.359781281105
C	6.030306350593	-9.415860657226	-0.976819476533
H	5.976107348634	-11.957967552942	-3.264485832182
H	5.612172766988	-8.416973245436	-0.827227362466
C	6.861105886486	-9.944157455558	0.014802259354

H	5.037572595011	-9.684825393808	-2.882056390393
C	7.164784178865	-9.182787829039	1.237644071017
H	7.986211457041	-9.577602306086	1.844194872741
H	7.331327560380	-8.121057035952	1.005854582495
Pd	5.421422236762	-10.518785558728	1.949363772124
P	6.286426641861	-11.277757844925	4.051673412630
C	8.101538033365	-11.123301045862	4.251281572445
C	8.957061116939	-12.221630358792	4.116774336733
C	8.654128692988	-9.845980459238	4.433156511310
C	10.340971318206	-12.050875822547	4.171217543533
C	10.036490550232	-9.680306441872	4.500624658745
C	10.885701696226	-10.782847506823	4.369104046007
H	8.579242562510	-13.232957746481	3.945917933812
H	7.995535206219	-8.975360707283	4.498977864758
H	10.969727019309	-12.935634599715	4.034948385276
H	10.455013299451	-8.680059795172	4.647406845677
H	11.970603365854	-10.648031242468	4.414473532661
C	5.970977919713	-13.056154648552	4.358707058886
C	6.117509361757	-13.925538545786	3.271293063984
C	5.552207323587	-13.572029050876	5.591090929776
C	5.854539552359	-15.286807583971	3.406884294849
C	5.272781913616	-14.932117644075	5.724131489334
C	5.420520072079	-15.791262795274	4.633046316635
H	6.440846202086	-13.529787822660	2.304247480552
H	5.417253651866	-12.910193379520	6.450272502027
H	5.977655613709	-15.948935202255	2.545557312576
H	4.931375034876	-15.322706537571	6.687063840875
H	5.197624280293	-16.856540997656	4.741108335062
C	5.596803281543	-10.435128656023	5.522694009033
C	6.255835602024	-10.419763776857	6.759802962952
C	4.347661390754	-9.814713589430	5.407508770856
C	5.666772598263	-9.804422803365	7.863794632917
C	3.754745986850	-9.205207264902	6.512788323062
C	4.413360223303	-9.199794814588	7.742451946553
H	7.236816371074	-10.892921063325	6.864036753844
H	3.833484982120	-9.803456936489	4.441886357297
H	6.188734946964	-9.798083898201	8.824848493077
H	2.775271554549	-8.730560361650	6.407474581917
H	3.952174297967	-8.718901866374	8.609955804005
P	3.400329986650	-11.769512681119	1.631771143255

C	2.334446010595	-11.752411705897	3.122037380272
C	2.568571844837	-12.661931244777	4.162731421449
C	1.397120496218	-10.728848582096	3.312024890642
C	1.879822754789	-12.549265426504	5.368759247510
C	0.710854728022	-10.616167165407	4.521777720659
C	0.951549118190	-11.524000942099	5.553646205218
H	3.297328621064	-13.466890416310	4.038838007694
H	1.203325382528	-10.003944571128	2.515771636560
H	2.078394682139	-13.266594827280	6.170214710365
H	-0.017063397261	-9.811179782577	4.656950173271
H	0.417617821857	-11.430276631198	6.503398319623
C	3.527057842251	-13.528397566343	1.140266722845
C	2.610512267612	-14.518782525004	1.512541851200
C	4.602560405829	-13.872312661304	0.313367891826
C	2.782232285635	-15.833465603022	1.077512845654
C	4.768970315696	-15.181640291219	-0.131123544210
C	3.860692439827	-16.167716687701	0.257480894649
H	1.757087289036	-14.272432166356	2.149976932079
H	5.328341723532	-13.106044515673	0.026810474319
H	2.065221890658	-16.600888631793	1.381952188947
H	5.619703277871	-15.433170073981	-0.770611389009
H	3.994599650880	-17.200041678665	-0.077877748141
C	2.334780027949	-11.045535876751	0.319601978025
C	1.320223471302	-11.778897091311	-0.311811784682
C	2.547501150501	-9.712141804541	-0.051726980265
C	0.533576984516	-11.186465181794	-1.298324605212
C	1.754456803958	-9.118890476986	-1.035822700832
C	0.749244202601	-9.854804145217	-1.662031694728
H	1.142774387981	-12.823857944720	-0.041215539132
H	3.338939300917	-9.129870235848	0.430977451981
H	-0.252495657045	-11.768710449531	-1.787620061619
H	1.929951199531	-8.076293655654	-1.315679230951
H	0.132082296827	-9.392810677487	-2.438026843681
Cl	10.024744701223	-15.527151168187	2.930321197567
C	5.714509830578	-8.146406320532	2.387002041317
O	4.785569855820	-7.863530096966	1.668971909097
O	6.271643578084	-7.830062423076	3.400042218056

XII

Free Energy = -3289.67389130879

C	6.874696314802	-12.082148134703	-1.481324129468
C	7.193912994957	-13.430644461128	-1.791170298150
C	7.544314359983	-11.482677486742	-0.374809677320
H	6.706199261655	-13.913870032346	-2.643553117567
C	8.086297095598	-14.111804369200	-1.002945427638
N	8.420129329593	-12.184546147589	0.394406041102
H	8.342463956720	-15.155394876355	-1.201679320562
C	8.666826127666	-13.440730589269	0.104188680626
H	9.344426703917	-13.979322477021	0.784805491780
C	5.632132597360	-10.043804194093	-1.852866216650
C	5.905472369063	-11.340944768268	-2.208511570968
C	6.334526292195	-9.430268608741	-0.786395441050
H	5.383459399495	-11.819800153549	-3.042168683507
H	6.116870602671	-8.384788167887	-0.548909815891
C	7.283038898847	-10.110143493604	-0.046736050189
H	4.878757112285	-9.468873306878	-2.398217640747
C	8.100346535201	-9.433153845154	1.027029267878
H	8.401388432110	-10.188106042567	1.771184010667
H	9.029958407944	-9.038757089548	0.581981842316
Pd	5.137873056128	-10.385821807590	2.155228302675
P	6.056762105221	-11.326457796666	4.154459651213
C	7.841662819903	-10.951720830165	4.332762776275
C	8.844189410151	-11.890818466364	4.070431512737
C	8.204892735946	-9.624359932320	4.609483366354
C	10.186784966112	-11.508408812659	4.072127148690
C	9.544757884349	-9.245862054505	4.614004267212
C	10.540979668844	-10.186869251546	4.338514583161
H	8.619306518926	-12.936538700418	3.844888016668
H	7.433796689997	-8.874202111534	4.804703264433
H	10.932756080186	-12.275288177283	3.843084634739
H	9.810107701572	-8.205143623454	4.820303816376
H	11.592854967458	-9.885764373058	4.331911521579
C	5.951255029349	-13.145248496196	4.301401809307
C	6.331453076716	-13.890294135988	3.177679698710
C	5.480349441179	-13.815872350669	5.436888100069
C	6.272809668217	-15.281720145005	3.194466260213
C	5.392689628699	-15.208201846273	5.442404465294
C	5.793457416702	-15.943408522345	4.325140533320
H	6.682042935490	-13.375438953953	2.277293883204
H	5.160271351082	-13.254670051197	6.318539246443

H	6.590340153937	-15.845661183601	2.313674961818
H	5.010155123607	-15.721278931661	6.329141494899
H	5.727335400702	-17.035074173403	4.335690025715
C	5.327908115261	-10.650910351259	5.690047854185
C	5.957243562036	-10.813580274568	6.933853587920
C	4.117350544796	-9.952234853287	5.623192964383
C	5.373563497053	-10.301381215395	8.090136415813
C	3.533794050062	-9.437447198453	6.781934443770
C	4.158660784351	-9.614194354629	8.015326579144
H	6.913146824993	-11.342366815358	6.999562517735
H	3.622696185326	-9.808058445872	4.657416463495
H	5.869747503483	-10.436223061774	9.055262432593
H	2.585117881493	-8.898162897977	6.715302182355
H	3.702506607044	-9.210464938540	8.923746339013
P	3.275992607197	-11.740826303081	1.715136729820
C	2.153500515125	-11.714765749206	3.164075447731
C	2.400995978850	-12.576930981684	4.241573376016
C	1.155987283649	-10.740499066971	3.288429013071
C	1.662206406446	-12.472127692040	5.417299878270
C	0.421694032219	-10.631971255990	4.470777484516
C	0.672489718383	-11.495772771417	5.537210271789
H	3.180290742174	-13.340004303043	4.169086688410
H	0.949639762453	-10.052473033772	2.463272552419
H	1.871271409513	-13.152593527646	6.247543757512
H	-0.352894138438	-9.864684310235	4.556061230515
H	0.098877017955	-11.405602404580	6.463855963140
C	3.444026477121	-13.509193514609	1.277905810422
C	2.526213044809	-14.494140359311	1.664188838665
C	4.525122341295	-13.866574444632	0.464818732300
C	2.701856072940	-15.817073089700	1.257653713351
C	4.691706232989	-15.184355016187	0.045428733785
C	3.784123065865	-16.164170814423	0.448604811655
H	1.664790355508	-14.235555485414	2.285334377386
H	5.249901580309	-13.104668544103	0.164057208863
H	1.983535083668	-16.578914925296	1.572649511123
H	5.544152881446	-15.449362742545	-0.585131692440
H	3.921543483664	-17.202046347092	0.132538533649
C	2.267308831974	-11.063239145325	0.334695038637
C	1.382095458551	-11.855726612054	-0.408584225690
C	2.404798210343	-9.707736692961	0.007268529318

C	0.651221856148	-11.300690279023	-1.458420158265
C	1.667237716693	-9.150456053906	-1.037404050244
C	0.792163767064	-9.947900937648	-1.774728322654
H	1.264318600786	-12.917998759232	-0.176884608597
H	3.098331344890	-9.074691243396	0.570770225430
H	-0.030454028211	-11.931027479837	-2.036219068700
H	1.786494143257	-8.090951534752	-1.279633736116
H	0.221243903481	-9.515986751959	-2.601534834448
Cl	10.448133843070	-15.001317183530	2.913869063986
C	7.402255936608	-8.288208186762	1.768897462073
O	6.249175358137	-8.544868047546	2.267383150380
O	7.973271434092	-7.203985993155	1.877877241294

XIII

Free Energy = -3289.62236786712

C	6.912741096715	-15.792508889939	3.256720311330
C	8.053978598841	-16.378377152996	3.866363979762
C	6.738443035731	-14.386280675530	3.415442010563
H	8.213164794393	-17.457684228110	3.775336127541
C	8.946870013115	-15.587342977588	4.547652173697
N	7.639862469240	-13.625635906568	4.085032484076
H	9.835875417851	-16.008121965929	5.023900907260
C	8.691854421279	-14.197868939831	4.619864456672
H	9.393520773992	-13.544323037124	5.154017029894
C	4.924333770345	-15.901620642749	1.888278619197
C	5.979111498117	-16.548550275038	2.495250694432
C	4.729414197750	-14.515535123582	2.045362190693
H	6.125776169666	-17.626587980106	2.382945761308
H	3.878402359195	-14.040171605872	1.550925731654
C	5.578478010666	-13.730055194322	2.838342095453
H	4.212514248697	-16.468690670997	1.279810484717
C	5.367539105240	-12.327928913252	3.050983337194
H	6.012779067083	-11.799864098978	3.746340848153
H	4.487673276680	-11.818731572992	2.660097319052
Pd	3.718493004365	-13.289442257937	4.632907616361
P	4.796396244790	-12.400677385491	6.556251065398
C	5.604773529229	-10.799520527851	6.168284893541
C	6.926761183446	-10.477875685748	6.486633720494
C	4.848934103683	-9.890913778193	5.409879253727
C	7.480103443967	-9.266170714595	6.061155582334

C	5.392309809751	-8.677685829496	5.001488488808
C	6.715978279497	-8.363511376961	5.323819068167
H	7.543571903679	-11.176094052780	7.058583634057
H	3.828408102767	-10.153693977804	5.110499761830
H	8.519931771008	-9.032259460412	6.307252172320
H	4.786735738260	-7.985932194895	4.408438061366
H	7.153495847463	-7.418346849840	4.989723729467
C	6.026598944031	-13.357200123814	7.529588949707
C	6.476989488510	-14.582549036518	7.029558895001
C	6.488686449923	-12.919691067509	8.780775147808
C	7.381854687979	-15.356307247446	7.760025573912
C	7.396976583699	-13.686422274647	9.506763311045
C	7.845474864584	-14.908145578147	8.995700806162
H	6.111176742719	-14.938240946650	6.061557541419
H	6.130619728799	-11.971943958685	9.195789527637
H	7.726967378263	-16.311327947150	7.354143052847
H	7.753957579193	-13.332881455109	10.478416870029
H	8.553642605104	-15.513724192060	9.568780349119
C	3.606853411068	-11.954411914117	7.892643417817
C	3.468452492821	-10.668824887250	8.426562520359
C	2.777929671412	-12.981911355205	8.370023334753
C	2.519426387476	-10.414931163151	9.420753557603
C	1.840111622962	-12.729511690249	9.368052131373
C	1.706638821005	-11.442734176239	9.896469050928
H	4.101646342406	-9.851801826263	8.070631106282
H	2.851509807865	-13.982230448692	7.929008478223
H	2.420270183948	-9.404465466001	9.827918791935
H	1.198361828652	-13.539332972076	9.727061249952
H	0.963882301223	-11.241493213185	10.673804107111
P	1.763049218274	-12.511477567833	3.398201249721
C	0.314096639962	-12.129931049482	4.467756281746
C	0.555511196660	-11.826310852247	5.812986392131
C	-1.003374879142	-12.096429240316	3.990584647355
C	-0.494290637648	-11.484319116714	6.666739116354
C	-2.054154069826	-11.761121194877	4.843923684569
C	-1.801962898949	-11.452450423489	6.182850294705
H	1.578591555252	-11.859304388342	6.198172692589
H	-1.217834240734	-12.333634785827	2.944744456819
H	-0.282564395621	-11.252348052236	7.714473054058
H	-3.077923986801	-11.740094753248	4.459263786003

H	-2.628188513254	-11.189994299930	6.849938552365
C	1.047164503245	-13.571319333861	2.078274128242
C	0.384970443888	-13.079770973666	0.944734519577
C	1.179306351519	-14.957843690209	2.241991540309
C	-0.130840132387	-13.958109514251	-0.008799882978
C	0.655635587910	-15.835010481236	1.292025264638
C	0.004246194956	-15.336852644338	0.162553689895
H	0.271517839853	-12.002013904922	0.796523894289
H	1.696592032343	-15.349223506593	3.125532914642
H	-0.640498788606	-13.561109120414	-0.891328704203
H	0.766291582850	-16.914151825183	1.431823818797
H	-0.397151392095	-16.024473372340	-0.587590992190
C	2.067342682447	-10.901585872113	2.561505941585
C	1.803730508183	-9.690218311426	3.215114300644
C	2.751568846851	-10.866641799000	1.336273180820
C	2.219075599069	-8.477946831426	2.662299722847
C	3.166210662821	-9.655713825632	0.784089573446
C	2.904725156918	-8.455985246474	1.447281226984
H	1.274589317626	-9.687602167990	4.172508231962
H	2.980515744466	-11.795212004967	0.804550128837
H	2.005656632168	-7.543263646835	3.188831401280
H	3.703272834084	-9.654439059116	-0.168579717138
H	3.234850721798	-7.506148712632	1.017512692174
Cl	2.752322363942	-15.486276776979	5.625108246155
C	6.277214752053	-11.389285922727	1.307839035424
O	6.778853197719	-10.407223850257	1.750945210200
O	6.005376897297	-12.082305132937	0.382971264749

XIV

Free Energy = -3289.66796141644

C	7.484021130599	-15.685362798619	3.436614006342
C	8.734124079967	-16.259653075051	3.790384096756
C	7.421411218398	-14.266216933111	3.287361542626
H	8.810352322517	-17.344808851278	3.912151813050
C	9.821612072806	-15.447696077823	3.986976698771
N	8.521075199181	-13.484306367179	3.482795406457
H	10.797095168331	-15.852830139392	4.266534168345
C	9.652680204335	-14.049561703678	3.819149971863
H	10.510504521550	-13.381892613649	3.974414280457
C	5.128756554837	-15.854381840687	2.926811191980

C	6.314551109543	-16.468671049752	3.254086112330
C	5.071157554724	-14.451480756756	2.765855348227
H	6.373711213571	-17.553517657763	3.382976960358
H	4.122321614710	-13.985840823654	2.489084783043
C	6.178927579003	-13.643132614780	2.938168295314
H	4.219327055463	-16.446902288127	2.789538678060
C	6.087277391514	-12.163644851198	2.736644637383
H	6.931517077634	-11.651622034223	3.213519615641
H	5.166325037973	-11.796620905320	3.223714896923
Pd	3.029065096275	-12.994787760235	5.093705800325
P	4.686861328961	-12.389974772987	6.676637699884
C	5.726475657922	-11.047906931133	5.987826266672
C	7.121584849116	-11.040746330634	6.067132828642
C	5.073032876887	-10.016339377878	5.295382644865
C	7.853214272373	-10.013909058457	5.466348998265
C	5.802720555425	-8.989342201677	4.704881912870
C	7.197683118426	-8.988913519570	4.786572392854
H	7.648209809003	-11.845317664296	6.587533354659
H	3.980975852577	-10.025319798010	5.194605532593
H	8.945168743227	-10.022781632230	5.526709870699
H	5.279766295745	-8.196715099152	4.162534773398
H	7.773510389774	-8.189411752922	4.311779721921
C	5.874596162353	-13.609268283628	7.339885176752
C	6.227939582613	-14.693143500872	6.526805639602
C	6.456384781689	-13.481044556286	8.608019073022
C	7.158145492562	-15.631946503702	6.972848772324
C	7.386284115985	-14.420437173147	9.051811628571
C	7.739395236120	-15.495757020476	8.233984975235
H	5.768187904156	-14.804793411913	5.539702991629
H	6.184947248701	-12.643125826097	9.256862197917
H	7.425249219979	-16.475575591047	6.330989600495
H	7.837502691412	-14.311638667945	10.042039727545
H	8.467143976611	-16.233505394499	8.583789099140
C	3.930318829853	-11.639123679597	8.168118542560
C	4.453701402040	-10.495861634758	8.783762095041
C	2.783924542915	-12.245723674149	8.702450062993
C	3.843036833306	-9.968265566519	9.922105097960
C	2.179519347821	-11.719659431566	9.843842663010
C	2.707318194441	-10.579711062828	10.454224439252
H	5.343276867478	-10.009632353516	8.373192824188

H	2.362414821591	-13.131705458583	8.214599052403
H	4.258485952581	-9.073923072692	10.394893122725
H	1.285913907532	-12.198173207044	10.254393431564
H	2.228683266369	-10.163999386370	11.345485320054
P	1.380299357254	-12.532848235866	3.460717199911
C	-0.338475025334	-12.414583165125	4.072151062237
C	-0.536521143325	-12.215837885617	5.444866651245
C	-1.447974916510	-12.484115613357	3.219956014295
C	-1.826256874827	-12.077729293635	5.958272904622
C	-2.736864524973	-12.353460644108	3.735800139859
C	-2.927289965155	-12.148211767435	5.104001066905
H	0.327443015876	-12.169132640190	6.116232663010
H	-1.309013662418	-12.644578787865	2.146734336790
H	-1.970752206512	-11.920186920759	7.030551197573
H	-3.597933429344	-12.411303642610	3.064092516404
H	-3.939113037165	-12.045677473331	5.506492816538
C	1.297286478524	-13.570477854838	1.961708978730
C	1.047786392004	-13.062397510206	0.680944060721
C	1.510960249159	-14.946154721482	2.129139700967
C	1.018139047133	-13.920007896749	-0.418946678306
C	1.472135963594	-15.802055432953	1.029286799186
C	1.230300921351	-15.288633953101	-0.246360039127
H	0.885103676441	-11.990813850543	0.534884704900
H	1.718443655112	-15.343322653223	3.129222059703
H	0.830585448236	-13.514285391242	-1.416908960576
H	1.642592115976	-16.873198934479	1.168276058180
H	1.211199362667	-15.958301331216	-1.110909399813
C	1.801744424175	-10.841698874797	2.898243971374
C	1.189013288723	-9.716198788015	3.464364835718
C	2.902388833826	-10.667902916702	2.046062603706
C	1.676008473540	-8.437861236237	3.187196481881
C	3.389460402633	-9.389945508315	1.775475454752
C	2.779244164866	-8.272368678524	2.348511484855
H	0.333879382661	-9.831599473823	4.136750529514
H	3.403958095764	-11.527513640083	1.587251192879
H	1.191402884159	-7.566261216448	3.636338884596
H	4.271989172812	-9.286167198665	1.138091336169
H	3.167540033880	-7.270031268746	2.145575912287
Cl	2.151806851602	-15.110513002904	6.069768756957
C	5.969276484552	-11.692890667956	1.253782278728

O	6.510063301724	-10.598159445670	0.990180598422
O	5.288085722277	-12.405351589019	0.484114652082

XV

Free Energy = -2253.53573682721

C	5.872532480847	-14.342769823299	1.533097668846
C	7.100900027959	-14.981082670602	1.854018726702
C	5.675877684737	-13.016764315498	2.018002205344
H	7.278234739132	-16.004284681257	1.508226118365
C	8.045610732522	-14.308190905268	2.588316648264
N	6.634152745867	-12.367219861083	2.728006416645
H	8.999178892866	-14.770301940905	2.854425961956
C	7.758527077455	-12.982666980854	2.997504808333
H	8.499444096368	-12.419782487975	3.579752247781
C	3.704859395644	-14.292309890417	0.463088628245
C	4.863171732746	-14.973915151932	0.756483834904
C	3.490825201140	-12.984461614976	0.951242941858
H	5.028437287075	-15.991512785996	0.390800011194
H	2.550121373172	-12.472708833702	0.730289011067
C	4.428030944359	-12.334467876341	1.752492183795
H	2.930418974494	-14.766380336860	-0.147099471893
C	4.145121910407	-11.010876126119	2.346420538448
H	5.012019615128	-10.533215037112	2.813192628617
H	3.687344269365	-10.340085996245	1.604513110110
Pd	3.309164687217	-12.390694219654	3.996219228164
P	4.729472615729	-11.937982546743	5.836193275536
C	6.054614770850	-10.692503844156	5.625508519753
C	7.398481203957	-10.941900767307	5.922299840977
C	5.686510733051	-9.442962455151	5.104865077040
C	8.363256898690	-9.957301470395	5.700149350471
C	6.650701976434	-8.459140225076	4.893031630412
C	7.992285027427	-8.714548489597	5.186683140461
H	7.704752071755	-11.911924656569	6.322814411060
H	4.640089944417	-9.249823336416	4.843005080932
H	9.412269667314	-10.165328250018	5.930126135857
H	6.353734302400	-7.488677204474	4.484646112054
H	8.749383831925	-7.944330098213	5.012796637048
C	5.613750998701	-13.418123741241	6.462030693651
C	5.969351170508	-14.414378864419	5.544158233774
C	5.968999122768	-13.573589951878	7.808406450250

C	6.685291372684	-15.537096925309	5.958471986300
C	6.675973265115	-14.701579311458	8.225301977066
C	7.039104272222	-15.682693041018	7.300497038295
H	5.679247013732	-14.314444740280	4.494027822182
H	5.694361943773	-12.808935914901	8.541046837971
H	6.961758845209	-16.302617329301	5.228060486335
H	6.944595164443	-14.814543974166	9.279479706305
H	7.594440598422	-16.566049564918	7.628835027449
C	3.813659367615	-11.342664158217	7.313580481521
C	4.293757036801	-10.342287952283	8.167698356211
C	2.575914728166	-11.943034621546	7.589623149700
C	3.548788587564	-9.949839910208	9.281752564422
C	1.838500994346	-11.555435323615	8.707189815851
C	2.322222757977	-10.555974511208	9.554477606656
H	5.256222519763	-9.863454898578	7.966793948091
H	2.191362330042	-12.720563220260	6.919553043842
H	3.932474687089	-9.166351356431	9.941550413930
H	0.875666723768	-12.031822573073	8.913123933240
H	1.740170285077	-10.247025705239	10.427662997685
Cl	2.090210282878	-14.398308220964	4.756142614207
C	2.379444474926	-10.459192977403	3.288388330417
O	2.599829946140	-9.433714468076	3.890477161705
O	1.446152875864	-11.037574954667	2.758020643648

XVI

Free Energy = -2253.58613804446

C	5.659824172192	-14.508681116333	1.779178272767
C	6.701253201774	-15.405921098210	2.136426370756
C	5.838203526273	-13.128231765352	2.090595193222
H	6.590477069436	-16.471627719242	1.913341692039
C	7.825776195072	-14.924637780808	2.756787676856
N	6.963092382366	-12.678949573389	2.710052867980
H	8.645073414821	-15.584671744318	3.051081506327
C	7.900373339914	-13.535832470674	3.027366781138
H	8.786705607865	-13.131732351999	3.533793199701
C	3.516654055908	-14.018607014601	0.777283340106
C	4.475890301276	-14.938151856323	1.122709704275
C	3.692675862259	-12.648110970159	1.086411116117
H	4.348121936143	-16.000124894453	0.893440923326
H	2.907130879104	-11.940868977985	0.804925857215

C	4.815932878576	-12.182888532093	1.743170921762
H	2.604844808047	-14.338819319263	0.265448280878
C	5.015101006901	-10.717389064598	2.033470512091
H	5.735300800168	-10.618852029338	2.861517168416
H	5.474439473218	-10.223734389096	1.159734260097
Pd	3.009350249278	-12.403020242350	4.185676430990
P	4.543332278366	-11.974610050528	5.911100576508
C	5.636913361615	-10.542168231590	5.603469448069
C	7.020562703225	-10.661336021107	5.437545667193
C	5.028042943179	-9.297205762717	5.383933788587
C	7.782470057523	-9.554134226371	5.059622741873
C	5.788342257542	-8.193297140097	5.008938016586
C	7.169664732942	-8.320837845974	4.841275733473
H	7.511451722317	-11.625683858881	5.587802590945
H	3.944117060535	-9.194916373703	5.486134663618
H	8.862847525996	-9.662173578886	4.927460763213
H	5.298369257373	-7.231650807518	4.833300269886
H	7.767696341779	-7.456417589822	4.538226187374
C	5.678212536015	-13.338240066694	6.379156265859
C	5.746878373621	-14.471302712155	5.563507379872
C	6.465424920967	-13.279793829558	7.539362661647
C	6.589757965783	-15.532806775542	5.899941065268
C	7.312147114670	-14.334952232864	7.870237673162
C	7.373632294418	-15.465728987441	7.049973918902
H	5.125387547712	-14.528402949770	4.665103520419
H	6.418552968040	-12.401511380049	8.191232775680
H	6.632353023633	-16.414793719135	5.255123093324
H	7.923619538073	-14.278915785659	8.775403896666
H	8.034392800762	-16.296691975267	7.313722137762
C	3.735688290400	-11.595496675395	7.519964264070
C	4.165428734320	-10.585770220089	8.389162847071
C	2.645644356323	-12.398378444885	7.889497201145
C	3.515711604810	-10.380995427405	9.608145906948
C	2.004505557045	-12.198171589049	9.110996947860
C	2.436332665330	-11.186457014150	9.971994322339
H	5.013072577269	-9.949786147420	8.118358165734
H	2.301611810279	-13.186384644990	7.209867717285
H	3.859059683155	-9.587835169832	10.278530525479
H	1.157722821734	-12.832107434068	9.389813414230
H	1.929286807148	-11.025332274714	10.927698717594

Cl	2.120720571697	-14.609955111422	4.707104515711
C	3.761260492689	-9.914954035337	2.419154147526
O	3.638971353151	-8.773434891122	1.968811628093
O	2.933103259469	-10.460978952920	3.223300165589

XVIII

Free Energy = -2716.46634030096

C	2.967834333236	-1.884057341503	3.241179955530
C	2.552008849205	-2.821330668073	4.235373283375
C	2.064876423606	-0.825516782268	2.909277912702
H	3.213835397663	-3.642977734332	4.525108381518
C	1.272291268999	-2.666657512349	4.817183356164
N	0.808646779233	-0.728755062580	3.471280478506
H	0.919170310787	-3.370522253516	5.577384357037
C	0.441991119135	-1.638567496288	4.419407031605
H	-0.565498974846	-1.512865394750	4.824962879507
C	4.499145632542	-0.999339693886	1.544771169660
C	4.189172400348	-1.942526582166	2.529866539206
C	3.614124101345	0.043729527544	1.256946655019
H	4.888508594529	-2.756801720144	2.749694246701
H	3.866730681857	0.790178681501	0.495854572018
C	2.400429844564	0.148068664711	1.953355872977
H	5.445590789921	-1.078460285019	0.999427311952
C	1.417817225253	1.270626953862	1.794605771847
H	1.621818425961	2.068261766899	2.542585484461
H	1.486314290685	1.739165498057	0.799852208252
Pd	-0.411395429530	0.645775447806	2.461511657195
P	-3.573555658254	-1.246947650621	0.344527239550
C	-4.457132947024	-2.128159083206	-1.025630464101
C	-5.714634401532	-1.667004981830	-1.450959842089
C	-3.988267746340	-3.338112145396	-1.559802024468
C	-6.456105020936	-2.366429918857	-2.402979547774
C	-4.732892382617	-4.044741752895	-2.505972737189
C	-5.966387078354	-3.558872808901	-2.938547005986
H	-6.140045153855	-0.749069553962	-1.031899926345
H	-3.024217976815	-3.741253359309	-1.238378589483
H	-7.427167868413	-1.977283252354	-2.723330807149
H	-4.339415536800	-4.982338590671	-2.910144183768
H	-6.547526406195	-4.109705516138	-3.683676045336
C	-1.847401297595	-1.846797760854	0.109151403666

C	-1.182993056619	-2.394521182941	1.212693063032
C	-1.172142346276	-1.782178704239	-1.119046861298
C	0.127100846403	-2.864995711764	1.098073583547
C	0.135017428285	-2.248612119079	-1.237386878631
C	0.788513437213	-2.787987948652	-0.125098358735
H	-1.683276799290	-2.425667957011	2.184028578548
H	-1.670205519248	-1.361273970852	-1.998505697919
H	0.637362031542	-3.264346350144	1.979110615165
H	0.650724330614	-2.182150948461	-2.200035923017
H	1.820045583697	-3.142099247096	-0.213547489054
P	-1.528154353421	2.034964454517	1.041774838321
C	-0.849956387614	2.342642798731	-0.634239987921
C	-1.206321311753	3.483307030396	-1.366557454491
C	-0.040585322157	1.372203613308	-1.234313839694
C	-0.751739546561	3.651157553517	-2.673964686625
C	0.407392551025	1.534957373716	-2.545410838759
C	0.055526604181	2.676562706842	-3.265620637436
H	-1.840915041319	4.252043280377	-0.914391546949
H	0.238415145680	0.477588464734	-0.671355833135
H	-1.030606122421	4.547862838275	-3.234651427491
H	1.037123631840	0.765970468675	-3.001840575553
H	0.411655120699	2.810020218521	-4.291178772274
C	-1.630351837151	3.709338171094	1.780159170096
C	-2.788337591573	4.185509828721	2.405112188632
C	-0.468625331535	4.496262444072	1.806554906562
C	-2.787393888132	5.431757878284	3.036472584910
C	-0.470612463989	5.740449905724	2.432070468527
C	-1.632133063858	6.211698272984	3.049786655673
H	-3.704823081688	3.590301441506	2.412827752976
H	0.447656698538	4.132435810018	1.330417636772
H	-3.699656326619	5.792982471370	3.519509427443
H	0.440672528229	6.345162976347	2.439749546382
H	-1.634005623762	7.187622913127	3.543264805553
C	-3.524420947137	0.488178737907	-0.360446895446
H	-2.820491739829	0.548873039282	-1.209044675267
H	-4.526211536474	0.649708580028	-0.790106924720
C	-3.289077802432	1.624812338984	0.646119880353
H	-3.781528274154	1.404117189847	1.607300701902
H	-3.729873769103	2.551137381892	0.237547685611
Cl	-2.487673710429	0.170757282033	3.741389948186

XIX

Free Energy = -2716.48735146408

C	7.941812501236	-8.938229103154	-1.480568552341
C	7.306277280343	-9.325906575443	-2.700285511907
C	7.440504998232	-9.486393997750	-0.255267117380
H	7.666382347762	-8.929530360315	-3.654157928586
C	6.216785932773	-10.221566466920	-2.638292799353
N	6.353839794366	-10.350065159196	-0.233349652626
H	5.705116668674	-10.543049404993	-3.550541205633
C	5.774940808354	-10.702439705621	-1.423617869303
H	4.930960489285	-11.393912861934	-1.363595055791
C	9.596520004952	-7.701236429737	-0.168343471912
C	9.029531655177	-8.040538414286	-1.399368606906
C	9.099873534015	-8.256535792290	1.012920340721
H	9.422744176321	-7.605405628482	-2.324668558215
H	9.551690119201	-7.997498439312	1.976798645473
C	8.024782104837	-9.159298817840	0.977324648808
H	10.435031881285	-6.997867844859	-0.132249140942
C	7.466814908906	-9.832285943940	2.206588394166
H	8.199949650125	-10.545512259996	2.633937720117
H	7.244534564789	-9.098753587773	3.005714011036
Pd	5.823767488554	-10.966338676347	1.671913173602
P	5.379419799688	-11.425860450715	3.871883345267
C	4.279570197498	-10.189785891834	4.650394153877
C	4.098504816263	-8.948272490028	4.031454605460
C	3.603213606666	-10.463286953528	5.848360223560
C	3.248078244116	-7.995678484022	4.594101750016
C	2.751598764009	-9.513183942324	6.407977171364
C	2.571233110926	-8.278352555629	5.779697794509
H	4.616255389465	-8.731928821979	3.092102856759
H	3.740691211660	-11.422780735409	6.356744071745
H	3.109019681421	-7.031759179785	4.097233884082
H	2.226269707381	-9.737292751662	7.340416656503
H	1.898519245804	-7.535346453135	6.217404925793
C	6.803377088172	-11.573311834517	5.005817497017
C	7.725193623046	-12.610352039814	4.794257390326
C	7.041454734848	-10.632249991079	6.013451288626
C	8.855080990632	-12.710817987050	5.604520478783
C	8.178436020734	-10.735393168436	6.817178839692

C	9.084079973951	-11.776262823929	6.617701797018
H	7.581692074615	-13.327180300762	3.974077996005
H	6.339735218063	-9.810653544524	6.179673455085
H	9.569890621895	-13.521338718052	5.435140961336
H	8.354125352414	-9.994808503122	7.602497974500
H	9.974601905688	-11.856997633770	7.247656841633
P	3.962400785487	-12.439433812200	1.340385632927
C	3.634402487197	-13.375477365695	-0.192641346828
C	4.612922603175	-14.266530541747	-0.662061163272
C	2.479516105287	-13.156019987857	-0.953351924758
C	4.420607847834	-14.936010179646	-1.869990630895
C	2.297909812194	-13.823266145858	-2.165710743830
C	3.266291400479	-14.715462745006	-2.625215971260
H	5.535058792782	-14.429991065092	-0.087916502752
H	1.713984887050	-12.457292205486	-0.604735184766
H	5.184163862101	-15.632497575448	-2.228550455206
H	1.391972917566	-13.643374675870	-2.751450684479
H	3.123956099734	-15.237225362749	-3.575945242854
C	2.372854354351	-11.644246397378	1.770035209363
C	1.320924217408	-12.342816020903	2.378004713302
C	2.224974676545	-10.275508156380	1.513700818070
C	0.147183211689	-11.679165762351	2.731706271162
C	1.047046015361	-9.613054169527	1.857737527256
C	0.009414385694	-10.313573799159	2.472912486710
H	1.412358110476	-13.413337901154	2.583228068290
H	3.049335420388	-9.720755981698	1.053941373332
H	-0.664936434899	-12.230583128807	3.213679519979
H	0.945426799273	-8.543099680329	1.657224902370
H	-0.911014041379	-9.794143949502	2.754304709387
C	4.240342735872	-13.713348692414	2.646188061457
H	3.425997872824	-14.455397846211	2.684598027715
H	5.172899395269	-14.223262475535	2.336270976614
C	4.445018578430	-13.043994690460	4.010789831036
H	4.996770988910	-13.713291649367	4.689923705026
H	3.474542388978	-12.825465187794	4.485024905030
Cl	7.566124983265	-14.411147241723	1.571186291721

XX

Free Energy = -2716.45711464110

C	-0.318178913489	0.484966295849	4.951326908003
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C	0.685275329366	-0.498315860172	4.746117137202
C	-1.406502008088	0.516406108292	4.038559207717
H	1.531158958089	-0.554164708787	5.438178682801
C	0.591292903203	-1.353204232089	3.675546116620
N	-1.452659455600	-0.325160563997	2.962369444711
H	1.348841931565	-2.116264615884	3.484014065286
C	-0.502142044647	-1.215107842817	2.788744831663
H	-0.580236960300	-1.853921523239	1.903634707358
C	-1.235822542400	2.415169019835	6.074694214839
C	-0.252666437439	1.457591624449	5.985025924861
C	-2.330228572659	2.421745661762	5.175852658722
H	0.588866107791	1.442245720147	6.683492789805
H	-3.103528318609	3.188940452467	5.286553808939
C	-2.459813876410	1.480141011423	4.168469853202
H	-1.182833615481	3.179583927436	6.855793821754
C	-3.597691338170	1.413450511257	3.207577638742
H	-4.328973516976	0.652683380464	3.556586775649
H	-4.129685064686	2.381683132089	3.162715948144
Pd	-2.941284765163	0.501157143211	1.420778246778
P	-2.597159775542	-0.581829345649	-0.672464164480
C	-4.215050822079	-0.844605564802	-1.521179414588
C	-5.267959338215	0.040949990868	-1.257381863677
C	-4.412110419117	-1.873205282582	-2.452590864226
C	-6.492985711524	-0.093961245981	-1.912813316510
C	-5.637673838724	-2.013201719661	-3.103703675367
C	-6.680088474063	-1.123088075867	-2.836173390841
H	-5.129587848913	0.845703197384	-0.525548864975
H	-3.603571266323	-2.578126562855	-2.670378991044
H	-7.305055330447	0.605808917553	-1.695784559962
H	-5.779060233608	-2.822259773229	-3.826183394749
H	-7.641414857876	-1.235267368006	-3.345807661610
C	-1.916561550254	-2.279945337055	-0.599534453830
C	-2.376138827530	-3.119116816340	0.427580121314
C	-0.955929506143	-2.764470478038	-1.491446993115
C	-1.886768625243	-4.417605057059	0.555865305086
C	-0.454561191100	-4.060669675361	-1.353274537715
C	-0.917546516514	-4.890911304116	-0.333788519696
H	-3.116506359006	-2.745615603155	1.144464783994
H	-0.555442578542	-2.162829312035	-2.313522503867
H	-2.254391104283	-5.060248192039	1.361078267802

H	0.309742477500	-4.395372533841	-2.060616154118
H	-0.522154746028	-5.905213886105	-0.224904536356
P	0.607530210059	0.525334999431	-0.293866397769
C	2.332315783526	0.961489407179	-0.804212003723
C	3.006788945513	0.067249178242	-1.653519091540
C	3.019867112547	2.092574115621	-0.343187925121
C	4.325694336690	0.309764204330	-2.036168559069
C	4.345831204520	2.325145231774	-0.716810300235
C	5.004451471453	1.435870954807	-1.565397816937
H	2.497546168520	-0.816692218093	-2.059870563295
H	2.521948024025	2.809234182461	0.315546917850
H	4.824458398527	-0.392374280731	-2.711601271913
H	4.862763207866	3.214488740335	-0.343806895403
H	6.041887585510	1.619929287622	-1.859899931854
C	0.066828273064	2.059625111708	0.558826998462
C	0.440685964556	2.205556899339	1.903139281189
C	-0.718266867414	3.059607164311	-0.028372251459
C	0.052519675982	3.321821244080	2.639677572213
C	-1.124594794684	4.171808469610	0.712601802299
C	-0.738819821810	4.306994431604	2.046314723777
H	1.036845500681	1.424094333101	2.387620263046
H	-1.026859376818	2.981970357866	-1.074136396101
H	0.346051063627	3.408063395572	3.689925139415
H	-1.746173728409	4.938399533565	0.240527960298
H	-1.060949531543	5.176458097089	2.626754591156
C	-1.712341732311	0.290185523244	-2.057949849792
H	-1.914706839628	-0.262029513231	-2.992248492108
H	-2.284875967177	1.231434034976	-2.131538304969
C	-0.205151365639	0.593100838872	-1.965558965446
H	0.001178850645	1.565900912392	-2.444965983186
H	0.346262336194	-0.159210855172	-2.561274468625
Cl	1.377886393934	-2.155944450932	-4.015610114697

XXI

Free Energy = -2716.48176656634

C	-4.641294385048	-1.240986990197	2.694017854309
C	-5.926572992384	-1.279133801920	2.100601638963
C	-3.870612890601	-0.053853972986	2.509358179818
H	-6.534346898260	-2.183337212308	2.205580081597
C	-6.390841796441	-0.194156708236	1.388880593101

N	-4.361194629712	1.007711172717	1.837181459519
H	-7.373407910592	-0.201901616825	0.910395845609
C	-5.561806104023	0.940543951551	1.295341227692
H	-5.907059413724	1.829369794404	0.751533490369
C	-2.841037338725	-2.248577535665	3.977957979523
C	-4.115053137365	-2.338787328906	3.434357432834
C	-2.058616428869	-1.106243743380	3.806837729150
H	-4.723128221921	-3.239000228235	3.560583420122
H	-1.064473120260	-1.059034798184	4.260165771961
C	-2.506702364224	0.024013665581	3.055942794806
H	-2.438719667243	-3.086341427515	4.556845650395
C	-1.708990734906	1.201213102791	2.925753626432
H	-2.218363436235	2.134530549950	2.665875629151
H	-0.873737002189	1.311902298635	3.630098943746
Pd	-1.096896978353	0.215066353001	1.092914793700
P	-1.779183896682	-0.938543544128	-0.874657032752
C	-3.288015622228	-1.990228739223	-0.877572402075
C	-3.415752046956	-2.939188685741	0.144277070312
C	-4.293726943025	-1.903421175705	-1.850445783350
C	-4.508449980981	-3.804424127553	0.179376575194
C	-5.397918215098	-2.754787307382	-1.803519583302
C	-5.503784663103	-3.712519844965	-0.793209338127
H	-2.662338073780	-2.986328223675	0.937299101985
H	-4.227169045248	-1.171018398040	-2.659037112835
H	-4.591942986517	-4.537882623733	0.986379253538
H	-6.177860599837	-2.672427741972	-2.566083374280
H	-6.367786843386	-4.382635798312	-0.760642593424
C	-0.630518355403	-1.986285386939	-1.870599563176
C	-0.033638070762	-3.078451231427	-1.221815834292
C	-0.314111419024	-1.751485237910	-3.214466953647
C	0.840293645085	-3.924096813306	-1.902513308885
C	0.572247013451	-2.590261691205	-3.894046222461
C	1.148008588387	-3.680402708373	-3.242906471489
H	-0.249958617753	-3.267815647863	-0.165363728402
H	-0.754244461930	-0.910640377883	-3.756236720427
H	1.290696286808	-4.773582194158	-1.381064311375
H	0.807958280610	-2.389409007188	-4.943148441784
H	1.839234001733	-4.338084847523	-3.777584590838
P	-0.698593019509	2.084826992175	-0.281126168161
C	0.942935513718	2.869928717803	-0.539127243571

C	1.086517961033	4.078080551746	-1.237924956305
C	2.082164210493	2.221144311723	-0.046647100371
C	2.350537029069	4.628294888094	-1.442660026426
C	3.348503413273	2.774648590965	-0.255986864532
C	3.484759048574	3.976140810857	-0.950841062930
H	0.202606263867	4.597803546346	-1.621809711121
H	1.978615472605	1.279854303182	0.509974927509
H	2.452467400169	5.572259779381	-1.985990764876
H	4.233806712102	2.264324616064	0.134802525577
H	4.476306904055	4.410960499788	-1.108101864049
C	-1.767088338002	3.539558205484	0.034505764471
C	-1.479699827422	4.309561102256	1.172826252192
C	-2.899328389719	3.857757550780	-0.724280100962
C	-2.292647741434	5.381178804524	1.532579419670
C	-3.721120276936	4.927453739328	-0.358380809790
C	-3.420171952554	5.692291742219	0.767640795181
H	-0.607835935986	4.062026713370	1.788227651218
H	-3.159652508062	3.276925565349	-1.613402568620
H	-2.049777135327	5.973253445487	2.419756401751
H	-4.601866286801	5.162970951603	-0.962931969041
H	-4.064259728226	6.529170797444	1.052365291253
C	-2.219479169367	0.463618496891	-2.009455355004
H	-2.428328752518	0.127800508663	-3.038231537861
H	-3.162437934836	0.876700813479	-1.608944314841
C	-1.120040649276	1.530527933739	-2.006395570206
H	-1.385619879367	2.383412452739	-2.654137279162
H	-0.181624771977	1.107931540645	-2.407782099391
Cl	1.491790299055	-0.888480629186	1.883679529478

XXII

Free Energy = -2716.46921011338

C	2.246499412937	-1.953054323251	1.106565055056
C	2.628313011981	-1.877336498959	-0.252775545121
C	2.151538246163	-0.721105345673	1.826236300082
H	2.689986513479	-2.798640676426	-0.841368056124
C	2.912777407699	-0.651328714031	-0.822696105838
N	2.476250649150	0.455203852733	1.262526833170
H	3.198976295437	-0.562530829681	-1.873763325926
C	2.834797820243	0.492915416496	-0.009721068601
H	3.069199290260	1.481800818776	-0.422595887483

C	1.590269207316	-3.204626006675	3.093013256921
C	1.967216459627	-3.191919377651	1.755603974411
C	1.448786052551	-2.022987019050	3.813553821489
H	2.051891175796	-4.121786793028	1.187280266712
H	1.150257538342	-2.058262147340	4.866051839361
C	1.664043272556	-0.730778811981	3.217138327237
H	1.388126366907	-4.160061888328	3.586639714317
C	1.522263787667	0.464145975917	3.986838336306
H	1.984125037635	1.384754640462	3.613081758972
H	1.496642759409	0.363629160776	5.080117901659
Pd	-0.384876578760	0.146085357237	3.065504016336
P	-1.618894647207	-0.906336606040	1.339958297360
C	-3.433792751993	-0.694328723925	1.084440018668
C	-4.128242465556	-1.395555560468	0.088049304092
C	-4.121682122751	0.238971910978	1.868112550088
C	-5.483047629279	-1.155785258661	-0.133231942853
C	-5.482655483312	0.474020741169	1.650803028510
C	-6.162719419474	-0.216377190347	0.648187192353
H	-3.604427080192	-2.135079690997	-0.527437379253
H	-3.584266747620	0.787536717423	2.650926668425
H	-6.012884456239	-1.703254968432	-0.918292938706
H	-6.012316433850	1.206573896569	2.266932115703
H	-7.226067243777	-0.027102548847	0.474433484230
C	-1.491453080514	-2.741742859170	1.434674756395
C	-1.868268604771	-3.319927286133	2.656858798830
C	-1.025965014422	-3.579869639831	0.417061209019
C	-1.803316064311	-4.696811454907	2.849301925042
C	-0.952218602987	-4.961811448838	0.609504585626
C	-1.342626294206	-5.524860483084	1.822264018049
H	-2.205083421562	-2.675699095709	3.476788621485
H	-0.692647378030	-3.170617043038	-0.539125445723
H	-2.103544200743	-5.127107462199	3.809192786861
H	-0.578583480364	-5.599419115083	-0.197132262945
H	-1.281262752286	-6.606614273719	1.972803496240
P	-1.587135183025	2.296857322590	0.066368407546
C	0.064372565365	3.025780946884	-0.285646216528
C	0.598372418846	3.176388964050	-1.575103165057
C	0.820119369144	3.461508790018	0.809066425006
C	1.849589976250	3.759537867648	-1.762859102930
C	2.075081686795	4.045814521135	0.625464636202

C	2.589956919859	4.197815755132	-0.660612785947
H	0.025625847762	2.851762284489	-2.449828357069
H	0.423983197677	3.332988400695	1.821748876180
H	2.251659400589	3.874576223697	-2.773622899366
H	2.653252640812	4.376146450164	1.493048912702
H	3.572592689835	4.655337528333	-0.808322531870
C	-2.744478300718	3.339446896863	-0.922110581716
C	-2.420089785290	4.601399410020	-1.437134019007
C	-4.066758214556	2.881615810232	-1.062250683611
C	-3.381578671885	5.372621722852	-2.095263199858
C	-5.023618549707	3.646914668136	-1.725908433333
C	-4.683589041457	4.897091604145	-2.248007708835
H	-1.405520634778	4.994953210744	-1.328428517042
H	-4.363758610911	1.915295748387	-0.638266359063
H	-3.105835930247	6.353302063929	-2.494357112972
H	-6.043643908456	3.265100175659	-1.829505478086
H	-5.433741897392	5.500518994928	-2.767226979334
C	-0.969917982039	-0.486365801746	-0.357677116564
H	0.122530252631	-0.373751717626	-0.252973585983
H	-1.143304109829	-1.325179920024	-1.050810314500
C	-1.593291168963	0.759394071873	-0.991697818233
H	-2.651993757283	0.555261703492	-1.220268494889
H	-1.100262249944	0.959543232867	-1.958447347927
Cl	-1.860398857907	1.691544678373	4.441485908197

XXIII

Free Energy = -2716.48998483449

C	6.939369959770	-11.866110755925	-1.702958423164
C	7.132144580198	-13.084130262291	-2.389779790373
C	7.737594488470	-11.638931252042	-0.539514069603
H	6.519626176902	-13.304755973482	-3.269602137074
C	8.079579523126	-13.984828178356	-1.942319644587
N	8.674141506455	-12.515350392630	-0.137688217551
H	8.241903245505	-14.939605897922	-2.448679398453
C	8.835745010917	-13.644676462180	-0.810201391884
H	9.602602661554	-14.333865995438	-0.435121754815
C	5.875229613292	-9.685081721807	-1.445679360095
C	5.997604606812	-10.884252558388	-2.137626263429
C	6.613241498937	-9.440080890059	-0.289268802850
H	5.400610619564	-11.082597378528	-3.032123111105

H	6.497991863100	-8.488997378616	0.239984112327
C	7.512708031228	-10.422401606332	0.264010004447
H	5.178579015823	-8.921172983930	-1.805422419073
C	8.199359159432	-10.185156862519	1.497065324234
H	9.072173619224	-10.802739537166	1.733075530953
H	8.247882018584	-9.150691568884	1.861130950897
Pd	6.344891743177	-11.178721844697	1.981181137256
P	5.643059832159	-11.306217092999	4.238107173092
C	4.770668993475	-9.768713269922	4.738966189187
C	5.045676819066	-8.578276380534	4.055832377012
C	3.821309506132	-9.754131278847	5.771316190183
C	4.379894210477	-7.397285773128	4.388652867874
C	3.152068147427	-8.577287291176	6.102018682253
C	3.429091487590	-7.396456299243	5.408777566065
H	5.780889603869	-8.580476624149	3.244206044788
H	3.600097806827	-10.669003550030	6.330026320079
H	4.602179563611	-6.475714783906	3.843453359397
H	2.410254878700	-8.581280018191	6.905543281799
H	2.901898634558	-6.473426348672	5.666585109135
C	6.699786234857	-11.689386270386	5.691132111576
C	7.318583053594	-12.948608353397	5.754607758421
C	6.970241623635	-10.746827010105	6.691958142681
C	8.168741485452	-13.259831237181	6.815301596005
C	7.828281504583	-11.061526219008	7.747709872732
C	8.425777260295	-12.319772438292	7.816103875705
H	7.162286737184	-13.689639587433	4.958426190624
H	6.508319537177	-9.756452427446	6.656118068716
H	8.642537682629	-14.245363128711	6.853792478419
H	8.027260112715	-10.315271326907	8.522516345014
H	9.096331230663	-12.566856002758	8.644313323186
P	4.369472254647	-12.421780255956	1.553193698708
C	4.190072395605	-13.567400072935	0.139826379785
C	4.923669679780	-14.763579499874	0.120988627179
C	3.437284603398	-13.211482864392	-0.987854173638
C	4.876285428833	-15.595957710406	-0.996977790099
C	3.399611365036	-14.044770819478	-2.105943354248
C	4.114869273444	-15.242892253302	-2.111800921725
H	5.565884514979	-15.037781967778	0.967985687259
H	2.874775292541	-12.273150784919	-0.999188697656
H	5.451937087320	-16.526531236250	-0.999752997544

H	2.806842981485	-13.753397124120	-2.978193300241
H	4.084907503749	-15.896970168250	-2.988262054841
C	2.818239212774	-11.442874120518	1.573883478788
C	1.554711668343	-12.048777470807	1.639246526941
C	2.903879928830	-10.046199667114	1.601683884459
C	0.402729157335	-11.271005262119	1.737412143149
C	1.750877640625	-9.264871583599	1.704683047918
C	0.500260620086	-9.876814827983	1.775049412069
H	1.466298798589	-13.139733302689	1.610689591801
H	3.885980493766	-9.565971859426	1.551311286443
H	-0.577221556093	-11.753779962593	1.790172030987
H	1.834731442932	-8.174800516298	1.734370892096
H	-0.404862653666	-9.268215305641	1.858441425863
C	4.207713986751	-13.477658384543	3.064599132622
H	3.268464985062	-14.057347908618	3.051437328710
H	5.061736819236	-14.181047450444	3.037415925334
C	4.281856909867	-12.605565070180	4.323438880167
H	4.434497365098	-13.233043719067	5.216512084194
H	3.328662327054	-12.068292099392	4.462326544162
Cl	7.383328658853	-15.139559470683	2.826752341972

XXV

Free Energy = -2905.06543828956

C	6.777609203950	-11.866230705092	-1.288251658739
C	7.452994347587	-13.093724992794	-1.493836799801
C	7.195460651635	-11.062046897929	-0.189712456432
H	7.152067998799	-13.738470852002	-2.324600613424
C	8.467022583024	-13.462286934119	-0.643100635576
N	8.200338850583	-11.442783466963	0.634120537584
H	9.001124911028	-14.406921347997	-0.767447473315
C	8.800926751131	-12.592800919650	0.417486794375
H	9.604036535598	-12.867131325304	1.113033733049
C	5.131240887075	-10.200473825172	-1.927284383777
C	5.722160189581	-11.428727812575	-2.137312889865
C	5.541564280770	-9.377996634776	-0.864637947089
H	5.404435808778	-12.072895605451	-2.961963515398
H	5.072163452474	-8.400856058954	-0.721166760559
C	6.535277130828	-9.782965655628	0.052332449227
H	4.333252312145	-9.856570362817	-2.591521323497
C	6.953764729040	-8.905476787869	1.146991100612

H	7.869836936566	-9.209485237883	1.663128871523
H	6.997885811539	-7.853706922550	0.832375099607
Pd	5.336141258722	-10.407622181414	1.920362080044
P	4.926581848280	-10.884783304158	4.210204916111
C	4.691671246884	-9.670536936329	5.555002060371
C	5.423045421628	-9.688985413311	6.747472996301
C	3.747894675028	-8.653717579545	5.347361465854
C	5.205007943424	-8.712916377317	7.721981420438
C	3.523228162571	-7.687663947793	6.325229168721
C	4.252388030190	-7.715190824914	7.516672301692
H	6.169802562922	-10.467693190561	6.923948283692
H	3.197465909104	-8.601333540254	4.402078487011
H	5.782673727492	-8.737458832470	8.650489324743
H	2.781158148191	-6.902871821332	6.152793057017
H	4.080992508802	-6.953541026197	8.282772800508
C	6.134126050218	-12.120365389458	4.815521768262
C	7.346065895506	-12.269104244899	4.126344746561
C	5.850132107831	-12.960130748356	5.904043354683
C	8.266965635662	-13.241685610380	4.520329616110
C	6.774286238476	-13.930433327398	6.290993534723
C	7.981398088424	-14.073846905817	5.602878198683
H	7.564971492501	-11.637859609051	3.257279844219
H	4.904225157909	-12.868201725974	6.459410514227
H	9.207979650279	-13.351765861935	3.973976007078
H	6.544500242689	-14.584551993891	7.137505443617
H	8.700194714570	-14.839188526285	5.909969974965
P	3.958034191621	-12.294267766494	1.505552444093
C	4.680660458004	-13.787283402051	0.731675221510
C	5.723289133787	-14.437073049340	1.409776737472
C	4.281655188570	-14.269015740523	-0.520243076894
C	6.318292670767	-15.574153350922	0.868815411605
C	4.885569264607	-15.403066405917	-1.064443933994
C	5.896077204779	-16.064895683173	-0.367534405680
H	6.085636930466	-14.051267204633	2.369066502235
H	3.492281045037	-13.761189403190	-1.080329494768
H	7.126779176819	-16.071351636363	1.412101335787
H	4.559658329046	-15.771648940067	-2.041332903238
H	6.364832968173	-16.955974391543	-0.794403668221
C	2.399779594673	-11.967838481198	0.603906587256
C	1.406271173880	-12.949803596396	0.465977362012

C	2.181532454895	-10.697105938676	0.059365119579
C	0.222395715133	-12.665588970946	-0.210412062848
C	0.993804613827	-10.411454257586	-0.617352280351
C	0.015327208592	-11.394812994840	-0.754233811550
H	1.558003935806	-13.950889404430	0.881964594863
H	2.946977215569	-9.922885647105	0.165293602030
H	-0.543606870980	-13.439176125982	-0.313627577494
H	0.835850044877	-9.415063646300	-1.039091894394
H	-0.915327463667	-11.172714359780	-1.284157503463
C	3.383215264276	-12.929632607191	3.163133061794
H	2.404317218873	-13.424300716741	3.053850391093
H	4.098532498655	-13.703121997601	3.489666056930
C	3.319889386427	-11.808549103782	4.197310788072
H	3.079767990323	-12.196153748402	5.206848353285
H	2.542592836175	-11.070951326666	3.926813555876
Cl	2.724249231901	-12.850018653417	7.654862330364
C	5.688956598629	-7.964194631218	2.537936519690
O	4.646773630542	-7.670765426684	2.009347830002
O	6.414029297655	-7.706618290026	3.455493333753

XXVI

Free Energy = -2905.11424341492

C	7.111453591384	-11.971606378323	-1.005706658537
C	7.784495983395	-13.205860627438	-1.183789292138
C	7.621407810073	-11.073156338774	-0.024440922963
H	7.417552445474	-13.912959438696	-1.933080531426
C	8.875946969546	-13.498857332795	-0.405637845635
N	8.696573862524	-11.391737713865	0.745125997809
H	9.414952378977	-14.443409662382	-0.508517430198
C	9.284916621017	-12.549712151217	0.560879805856
H	10.146097390712	-12.772761014099	1.203863653814
C	5.370844794130	-10.396824915896	-1.577995988032
C	5.971964370913	-11.611905463424	-1.775343094787
C	5.892797559998	-9.486859625367	-0.621589581056
H	5.588308083014	-12.318660127305	-2.516122069847
H	5.417773134680	-8.507053234977	-0.518947834965
C	7.000524011099	-9.788734269446	0.152095606746
H	4.490987788591	-10.112120036763	-2.161137428521
C	7.629244558160	-8.773741940262	1.075477758641
H	8.136526273223	-9.304983428436	1.897747989249

H	8.418544487422	-8.224556300007	0.533841415951
Pd	4.900670162669	-10.265415133332	1.990797806968
P	4.728106730329	-10.927910013963	4.266652928201
C	4.539107145638	-9.769494737648	5.664137659680
C	5.301053686596	-9.836822645301	6.836786922592
C	3.594442913991	-8.741420505464	5.520041642406
C	5.112981055427	-8.896573724636	7.851426722313
C	3.399953872360	-7.811462289365	6.539085887412
C	4.161017294987	-7.886884129270	7.707880209181
H	6.045840829961	-10.627183359248	6.964483720225
H	3.009214455527	-8.660990420456	4.597198231947
H	5.713517285780	-8.957979149394	8.763518565069
H	2.656191277300	-7.019022189670	6.416819875867
H	4.015075894377	-7.152679952804	8.505311729364
C	6.041828301902	-12.118064283387	4.714724724603
C	7.232606665270	-12.096672472894	3.973884990318
C	5.866217159989	-13.090002040938	5.711981197623
C	8.236552523999	-13.032955003659	4.221576352445
C	6.872687672590	-14.026696566927	5.950872270378
C	8.055372400749	-14.002581798868	5.208178995936
H	7.374027326414	-11.359486144602	3.175939027352
H	4.944484364472	-13.123117606317	6.313279012307
H	9.158115474607	-13.007746962132	3.633655366908
H	6.728378763099	-14.785870918317	6.725507017069
H	8.836978451897	-14.744126253672	5.397866193603
P	3.736780487612	-12.249930186249	1.540421593873
C	4.533981363756	-13.693390736272	0.739260564668
C	5.611280389179	-14.305047707588	1.398803513351
C	4.128349159186	-14.191657625852	-0.503650290997
C	6.236025199543	-15.420745725328	0.847520890536
C	4.763712077674	-15.302754033011	-1.059919543648
C	5.809151317697	-15.927788327868	-0.380921135686
H	5.976294208072	-13.907649084595	2.351994016524
H	3.306870725204	-13.716733707372	-1.046213128782
H	7.071551953355	-15.887956561783	1.376074293236
H	4.431979995516	-15.684902333565	-2.029569390353
H	6.301080520664	-16.802491952674	-0.815488257091
C	2.168837975800	-12.003712305684	0.626324587757
C	1.192164480141	-13.007837572873	0.540392694436
C	1.934437350870	-10.773081141546	0.000898082252

C	0.006555931224	-12.782777181812	-0.155423484848
C	0.746387025313	-10.547224610516	-0.697078928631
C	-0.218029950706	-11.550701151472	-0.775203331021
H	1.357072295002	-13.982061502072	1.011338261664
H	2.685730257901	-9.979136377420	0.061191515025
H	-0.746903658407	-13.572982677773	-0.214557479477
H	0.576006065891	-9.580672235009	-1.179016784573
H	-1.150602429382	-11.374399726517	-1.318682844295
C	3.213358914730	-12.971418558603	3.183465959617
H	2.237441884325	-13.471542506316	3.075797306684
H	3.944035131125	-13.755599614513	3.442437205166
C	3.167521243507	-11.921929123263	4.292274879210
H	3.006822709959	-12.386129576869	5.285503437942
H	2.346809281899	-11.202724830013	4.118784685321
Cl	2.887874457788	-13.179472006222	7.696808473856
C	6.674506968940	-7.747962339975	1.707095866401
O	5.558975479383	-8.195233313311	2.145289291597
O	7.041832071527	-6.577474605981	1.799942475812

XXVII

Free Energy = -2905.05116049098

C	-0.282539999940	-1.109674217768	4.965429263765
C	-0.202732047186	-2.303052896392	5.723638430726
C	-1.350866517692	-0.999583759146	4.031156087843
H	0.609049446156	-2.423672487859	6.448160677334
C	-1.143696704837	-3.292227902651	5.546349014514
N	-2.272383397340	-1.977932730999	3.882284413831
H	-1.108584265677	-4.224265596603	6.115755462807
C	-2.170719024199	-3.073223779031	4.603751610336
H	-2.938608206279	-3.841528892295	4.446073145960
C	0.519554088763	1.092443679316	4.364220124829
C	0.654431819873	-0.041843638866	5.121415982444
C	-0.524633553855	1.221216374450	3.412120386010
H	1.461934873295	-0.144750566014	5.851983796468
H	-0.672819961401	2.184499557190	2.917911692831
C	-1.481447807487	0.202777536505	3.216268014040
H	1.224986211746	1.920351728366	4.484268488856
C	-2.589644247675	0.388739148430	2.331076936808
H	-3.193235853890	-0.466134831768	2.028451443313
H	-2.673824475300	1.314023905807	1.756232828693

Pd	-0.406766787599	-0.036426572200	1.109133145579
P	-1.392124412938	-1.153685401693	-0.720419608028
C	-2.820937029310	-2.297316577191	-0.555160499091
C	-3.073627857021	-2.870982313624	0.695218625293
C	-3.630757057758	-2.647725454778	-1.645993468258
C	-4.122637411543	-3.779185479651	0.857078096112
C	-4.680721611570	-3.549643422982	-1.482594312710
C	-4.927530722961	-4.118196175049	-0.229600132828
H	-2.456944444169	-2.599591918666	1.558181335872
H	-3.440319515667	-2.224152367970	-2.637085697386
H	-4.308969793277	-4.220711267142	1.840440094448
H	-5.307283733027	-3.815693576410	-2.338909274451
H	-5.748853107735	-4.829855618497	-0.104442676510
C	-0.320402985449	-2.116544328378	-1.858840026832
C	0.222239042304	-3.311383931160	-1.360325527006
C	0.006353657382	-1.720222893835	-3.160634681952
C	1.060190409051	-4.095841988524	-2.148003810346
C	0.856110907361	-2.502215585991	-3.948256798092
C	1.383554251291	-3.690461855225	-3.445978718725
H	-0.020103263164	-3.634491142249	-0.342657047760
H	-0.402420818808	-0.800640210034	-3.587384893881
H	1.469574124245	-5.026756836968	-1.745056065195
H	1.099800247523	-2.178294329011	-4.964218443558
H	2.045783766667	-4.303077640187	-4.064429146537
P	-0.441792603987	2.022755575962	-0.264687899223
C	0.992485192265	3.047568725920	-0.783636500698
C	1.026959252200	3.789904985663	-1.973107039158
C	2.097507919077	3.092560822574	0.076167585183
C	2.147429103139	4.554117921777	-2.296430084200
C	3.214647993921	3.868597727657	-0.240049740541
C	3.242374742186	4.596552013173	-1.429188190425
H	0.173396675973	3.779026108008	-2.657493368610
H	2.079660025364	2.515654492719	1.007098378014
H	2.164773099619	5.124420133469	-3.229720537976
H	4.067783109969	3.897458403109	0.443694790609
H	4.119490686148	5.198589105568	-1.683892655595
C	-1.618932514156	3.312537266282	0.308940404570
C	-1.178049885367	4.254096394561	1.252872857491
C	-2.978024788204	3.296562435862	-0.031741357283
C	-2.069373549038	5.153015552043	1.835243855234

C	-3.872939309104	4.193150494914	0.555984356372
C	-3.423205686222	5.122463389851	1.492786544571
H	-0.121371365072	4.288485159408	1.538648719968
H	-3.362202232783	2.577502082122	-0.759487457152
H	-1.704191481337	5.880461151752	2.565962237069
H	-4.930379227886	4.159346386811	0.278404601424
H	-4.124567085899	5.822892493109	1.954878367662
C	-2.086385206011	0.225601966524	-1.751524965638
H	-2.386914676047	-0.127128587481	-2.752448988659
H	-3.014952401008	0.508490467665	-1.225961537111
C	-1.147243837453	1.433527133489	-1.884273784764
H	-1.663193504173	2.250063484990	-2.417638392065
H	-0.266058537527	1.161696904978	-2.491567008332
Cl	1.924519226802	-1.163891155008	1.288841913921
C	-4.206929330475	1.125996690313	3.598537788350
O	-3.739137370251	1.339680839019	4.667288093980
O	-5.128262722582	1.122060919902	2.848398157139

XXVIII

Free Energy = -2905.11292837191

C	-0.906025146496	-0.521071296061	5.502711554099
C	-0.377749710433	-1.630941938633	6.213198108024
C	-1.864761575346	-0.780316831595	4.477387321539
H	0.361656360506	-1.459295730055	7.001940321300
C	-0.794336107634	-2.899408774104	5.897032155003
N	-2.262709003272	-2.051548748847	4.188272430440
H	-0.406400102034	-3.778112211631	6.417773774641
C	-1.750648138196	-3.050989591195	4.862439747843
H	-2.097872224523	-4.057183943474	4.593229999161
C	-1.035568671840	1.843783098067	5.035189531887
C	-0.499506711445	0.813064441390	5.767998770528
C	-1.986982369688	1.586320644560	4.019545328182
H	0.240535618905	0.999943250261	6.552082449852
H	-2.403840695787	2.425002098222	3.459765988855
C	-2.412928544366	0.307952785554	3.720970106088
H	-0.728807440659	2.876395373240	5.226968378503
C	-3.337013096822	0.034309564956	2.566482340138
H	-3.849608798251	-0.927536861167	2.732504468700
H	-2.710810751411	-0.123119074264	1.671540601821
Pd	0.039864656890	-0.176566344705	0.896028768268

P	-1.379036784447	-1.134029160210	-0.722371280460
C	-2.453247055402	-2.584893265912	-0.434749967459
C	-2.663843284222	-3.015449683871	0.880488314826
C	-3.088562987053	-3.255557917381	-1.489950499743
C	-3.511356500157	-4.094186586561	1.138867640228
C	-3.929302167933	-4.336292447741	-1.229404574369
C	-4.144105465206	-4.755344701938	0.086429940062
H	-2.180611070908	-2.507653504839	1.721014891216
H	-2.925187835312	-2.939182979582	-2.524960551047
H	-3.673950299049	-4.414450232557	2.172026743818
H	-4.420427325480	-4.853867966538	-2.058355136815
H	-4.806274865554	-5.602089120218	0.289195920832
C	-0.409495147829	-1.549000987045	-2.222245298509
C	0.825695238399	-2.187425842544	-2.034057591342
C	-0.820602933290	-1.238610833173	-3.524880752396
C	1.626698320991	-2.519710389090	-3.125071388481
C	-0.013997378897	-1.563791249059	-4.616897447982
C	1.208723044166	-2.205388219842	-4.419752807785
H	1.168181696476	-2.416068921069	-1.019284298617
H	-1.774572272222	-0.735980866743	-3.705843058381
H	2.586756603335	-3.017302766813	-2.962507814009
H	-0.345726342129	-1.312255091710	-5.628115949351
H	1.839980539925	-2.457646320728	-5.276546659132
P	-0.500234590804	1.835260262488	-0.148117428197
C	0.871646751899	2.610215333308	-1.082349645954
C	0.889543470471	3.972911899123	-1.407168615569
C	1.902755120927	1.780746072401	-1.544383954678
C	1.926441767667	4.497162369504	-2.178873666050
C	2.933881664146	2.305021362159	-2.323787454205
C	2.948559835731	3.664494722050	-2.639053064749
H	0.092013526564	4.633524805398	-1.054235193260
H	1.896470390072	0.713655648349	-1.294734027819
H	1.934625769194	5.563149457089	-2.423417938002
H	3.731940352023	1.647908610057	-2.680287859410
H	3.760461918350	4.077703598963	-3.244293636063
C	-1.170986873388	3.172203978694	0.894876956451
C	-0.288286246019	3.845651586498	1.754387652007
C	-2.535832186933	3.471288882052	0.942367587447
C	-0.761293361455	4.823290733363	2.624724895290
C	-3.007535939619	4.448417657013	1.821689584490

C	-2.125199802817	5.128238055273	2.658959971559
H	0.779877388692	3.603797886665	1.743544837235
H	-3.258975053066	2.909344448623	0.346792615985
H	-0.064232549967	5.344745011449	3.286622470713
H	-4.079523266968	4.656094694999	1.865453417893
H	-2.498514485491	5.889350620588	3.349971996295
C	-2.535004746998	0.211851787488	-1.236085177608
H	-3.114239742113	-0.078865637569	-2.129053746674
H	-3.262729624071	0.351994028624	-0.409932746963
C	-1.750151310490	1.501343026679	-1.489593765648
H	-2.422960467526	2.364779812405	-1.616357242804
H	-1.161182600968	1.418869447741	-2.419035835111
Cl	1.319198179954	-1.639740829323	2.329476048392
C	-4.420282568083	1.087646635273	2.223856763693
O	-4.916224452288	1.748647378518	3.154719995234
O	-4.740132162785	1.140676965745	1.008518669596

S3. Development of a Synthetic Route to β -Amino Acids via a CO₂-Coupled Electron Transfer Based on Theoretical Investigations of a Mechanistically Analogous Reaction

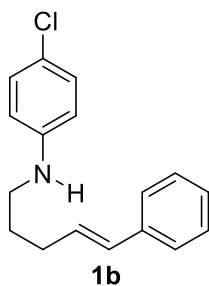
S3.1. General

All manipulations were carried out under an atmosphere of nitrogen unless otherwise noted. Infrared (IR) spectra were recorded on a JASCO FT/IR 4600 Fourier transform infrared spectrophotometer. NMR spectra were recorded on a JEOL ESZ-400S spectrometer, operating at 400 MHz (¹H) and 100 MHz (¹³C). Chemical shifts in CDCl₃ were reported in the scale relative to CHCl₃ (7.26 ppm) for ¹H NMR and to CDCl₃ (77.16 ppm) for ¹³C NMR as internal references. Data are reported as follows: chemical shift, multiplicity (s = singlet, brs = broad singlet, d = doublet, t = triplet, q = quartet, dd = doublet of doublets, td = doublet of triplets, m = multiplet), coupling constants (Hz), and integration. PR160L-440 nm (blue LED (440 nm), Kessil Lighting) was used as the light source under photochemical conditions. A cylinder of carbon dioxide (CO₂) was purchased from Hokkaido Air Water, Inc. ESI mass spectra were measured on a Thermo Scientific Exactive. High resolution mass spectra were recorded at the Instrumental Analysis Division, Global Facility Center in Hokkaido University.

S3.2. Synthesis of substrates

Substrate **1** was prepared according to the reported conditions.¹

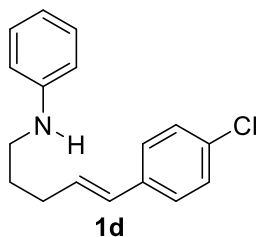
(*E*)-4-chloro-*N*-(5-phenylpent-4-en-1-yl)aniline (**1b**)



IR (ATR): 2929, 2861, 1596, 1495, 1479, 967, 818, 740, 694 cm⁻¹; ¹H NMR (400 MHz, CDCl₃) δ : 7.37-7.27 (m, 4H), 7.21 (tt, J = 7.1, 1.7 Hz), 7.14-7.08 (m, 2H), 6.55-6.49 (m, 2H), 6.42 (d, J = 16.0 Hz), 6.23 (dt, J = 16.0, 6.9 Hz), 3.66 (br), 3.15 (t, J = 7.1 Hz, 2H), 2.38-2.29 (m, 2H), 1.85-1.75 (m, 2H) ppm; ¹³C NMR (100 MHz, CDCl₃) δ : 147.0, 137.6, 130.8, 129.8, 129.2, 128.7, 127.2, 126.1, 121.8, 113.9, 43.7, 30.7, 29.1 ppm; HRMS (ESI) m/z calcd. for C₁₇H₁₉NCl⁺ [M+H]⁺: 272.12005, found:

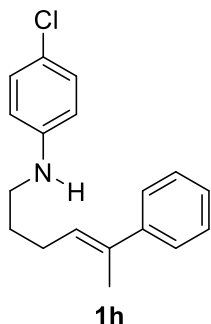
272.11969.

(*E*)-*N*-(5-(4-chlorophenyl)pent-4-en-1-yl)aniline (**1d**)



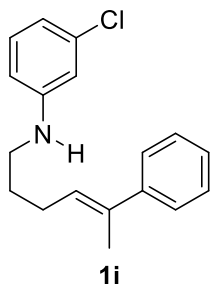
IR (ATR): 2928, 2857, 1600, 1503, 1487, 1313, 1177, 1007, 796 cm^{-1} ; ^1H NMR (400 MHz, C_6D_6) δ : 7.24-7.17 (m, 2H), 7.14-7.08 (m, 2H), 6.95-6.90 (m, 2H), 6.78 (tt, $J = 7.3, 1.0$ Hz), 6.52-6.45 (m, 2H), 6.09 (d, $J = 15.8$ Hz), 6.23 (dt, $J = 15.8, 7.0$ Hz), 3.04 (br), 2.86-2.74 (m, 2H), 1.98-1.89 (m, 2H), 1.41-1.31 (m, 2H) ppm; ^{13}C NMR (100 MHz, CDCl_3) δ : 148.4, 136.2, 132.7, 130.8, 129.5, 129.4, 128.8, 127.3, 117.4, 112.9, 43.5, 30.7, 29.2 ppm; HRMS (ESI) m/z calcd. for $\text{C}_{17}\text{H}_{19}\text{NCl}^+$ $[\text{M}+\text{H}]^+$: 272.12005, found: 272.11982.

(*E*)-4-chloro-*N*-(5-phenylpent-4-en-1-yl)aniline (**1b**)



IR (ATR): 2926, 2861, 1595, 1494, 1478, 1313, 1175, 1083, 813, 758 cm^{-1} ; ^1H NMR (400 MHz, CDCl_3) δ : 7.40-7.35 (m, 2H), 7.34-7.28 (m, 2H), 7.25-7.20 (m), 7.14-7.08 (m, 2H), 6.56-6.49 (m, 2H), 5.78 (tq, $J = 7.2, 1.2$ Hz), 3.66 (br), 2.32 (dt, $J = 7.2, 7.2$ Hz, 2H), 2.04 (d, $J = 1.2$ Hz, 3H), 1.78 (tt, $J = 7.2, 7.2$ Hz, 2H) ppm; ^{13}C NMR (100 MHz, CDCl_3) δ : 147.1, 143.8, 135.8, 129.2, 128.4, 127.4, 126.8, 125.7, 121.8, 113.9, 43.8, 29.4, 26.4, 16.0 ppm; HRMS (ESI) m/z calcd. for $\text{C}_{18}\text{H}_{21}\text{NCl}^+$ $[\text{M}+\text{H}]^+$: 286.13570, found: 286.13517.

(*E*)-4-chloro-*N*-(5-phenylpent-4-en-1-yl)aniline (**1i**)



IR (ATR): 2926, 2858, 1596, 1493, 1325, 1087, 987, 835, 754, 681 cm^{-1} ; ^1H NMR (400 MHz, CDCl_3) δ : 7.41-7.35 (m, 2H), 7.35-7.28 (m, 2H), 7.25-7.20 (m), 7.06 (t, $J = 8.1$ Hz), 6.65 (ddd, $J = 8.0, 2.1, 0.8$ Hz), 6.57 (t, $J = 2.1$ Hz), 6.46 (ddd, $J = 8.0, 2.1, 0.8$ Hz), 6.46 (tq, $J = 7.2, 1.2$ Hz), 3.74 (br), 3.16 (t, $J = 7.2$ Hz, 2H), 2.32 (dt, $J = 7.2, 7.2$ Hz, 2H), 2.04 (d, $J = 1.2$ Hz, 3H), 1.79 (tt, $J = 7.2, 7.2$ Hz, 2H) ppm; ^{13}C NMR (100 MHz, CDCl_3) δ : 149.6, 143.8, 135.8, 135.1, 130.3, 128.3, 127.4, 126.8,

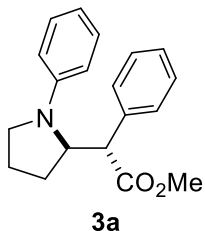
125.7, 117.1, 112.3, 111.2, 43.5, 29.3, 26.4, 16.0 ppm; HRMS (ESI) m/z calcd. for $C_{18}H_{21}NCl^+$ $[M+H]^+$: 286.13570, found: 286.13496.

S3.3. General procedures for the synthesis of β -amino acids

In an oven-dried 10 mL pressure-resistant glass tube were placed aminoalkene **1** (0.20 mmol, 1.0 equiv) and $[Ir(ppy)_2(dtbbpy)]PF_6$ (0.9 mg, 0.001 mmol, 0.5 mol%). After the addition of DMF (4.0 mL) under nitrogen, the tube was placed into an autoclave which consists of a polycarbonate cylinder, and CO_2 gas was pressurised to 10 atm. The resulting mixture was stirred at room temperature for 15 min under irradiation of blue LED light (PR160L-440 nm Kessil light). A fan was used for cooling, and the flask was positioned between at approximately 2 cm from the lamp. After the irradiation, the resulting mixture was diluted with Et_2O and extracted with saturated aq. $NaHCO_3$ (15 mL $\times$ 3), and then the combined aqueous layer was neutralized with 1 M HCl and extracted with $EtOAc$ (10 mL $\times$ 3). The combined organic layer was then dried over Na_2SO_4 , filtered, and evaporated to give the crude mixture.

For their isolation: the crude product was methyl esterified with CH_2N_2 as following procedure. To a 10 mL flask were added 40% aq. KOH (3 mL) and Et_2O (4 mL), which was then cooled down to 0 °C in an ice-water bath. 1-Methyl-3-nitrosoguanidine (wetted with ca. 50% water) (0.4 g, 1.4 mmol, 7.0 equiv) was then added portion wise. The resulting ethereal solution of CH_2N_2 (upper layer: 3 mL, calc. 5.0 equiv) was added to the solution of crude product in Et_2O (2 mL) (concentration of CH_2N_2 in diethyl ether: 0.2 M, 5 mL). After stirring for 10 min, (AcOH was added to quench the excess amount of CH_2N_2 until N_2 bubbling ceased.), the reaction mixture was directly concentrated under high vacuum to the crude methyl ester. It was then purified by silica-gel column chromatography isolation (eluent: hexane/ $EtOAc$), affording the corresponding pure methyl ester.

methyl 2-phenyl-2-(1-phenylpyrrolidin-2-yl)acetate (**3a**)

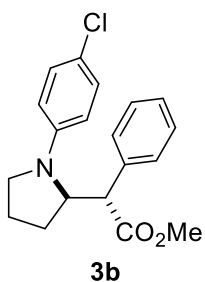


(*E*)-*N*-(5-phenylpent-4-en-1-yl)aniline (**1a**; 47.5 mg, 0.20 mmol, 1.0 equiv) was employed as a starting material. Purification of the crude product by silica-gel column chromatography (eluent: hexane/EtOAc, 50/1 to 20/1) afforded diastereomixture of **3a** (50.6 mg, 0.171 mmol, 86% yield). Colorless oil;

3a-anti: IR (ATR): 2950, 1730, 1597, 1503, 1362, 1202, 1154, 992, 744, 693 cm^{-1} ; ^1H NMR (400 MHz, CDCl_3) δ : 7.42-7.36 (m, 2H), 7.31-7.19 (m, 3H, overlapped with solvent peak), 7.10 (dd, J = 8.4, 7.3 Hz, 2H), 6.60 (t, J = 7.3 Hz), 6.47 (d, J = 8.4 Hz, 2H), 4.32 (t, J = 5.7 Hz), 4.01 (d, J = 6.0 Hz), 3.66 (s, 3H), 3.56-3.47 (m), 3.25-3.17 (m), 2.29-2.18 (m), 2.08-1.92 (m, 3H) ppm; ^{13}C NMR (100 MHz, CDCl_3) δ : 173.2, 147.3, 136.7, 129.0, 128.9, 128.5, 127.5, 116.0, 112.4, 62.0, 53.7, 52.0, 49.4, 29.4, 23.3 ppm; HRMS (ESI) m/z calcd. for $\text{C}_{19}\text{H}_{21}\text{NO}_2\text{Na}^+$ $[\text{M}+\text{Na}]^+$: 318.14645, found: 318.14723.

3a-syn: IR (ATR): 2950, 1731, 1597, 1503, 1363, 1342, 1151, 992, 744, 692 cm^{-1} ; ^1H NMR (400 MHz, CDCl_3) δ : 7.33-7.26 (m, 5H), 7.25-7.20 (m, 2H), 6.76-6.70 (m, 3H), 4.50-4.44 (m), 4.17 (d, J = 4.6 Hz), 3.66 (s, 3H), 3.15 (dt, J = 8.6, 2.2 Hz), 3.07-2.99 (m), 2.09-1.89 (m, 2H), 1.68-1.58 (m), 0.98-0.83 (m) ppm; ^{13}C NMR (100 MHz, CDCl_3) δ : 173.5, 146.8, 135.9, 129.5, 129.4, 128.4, 127.5, 116.2, 112.4, 60.3, 52.1, 51.7, 48.8, 28.1, 23.0 ppm.

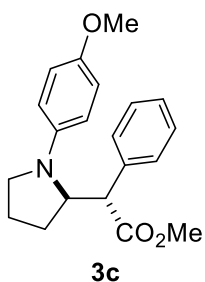
methyl 2-(1-(4-chlorophenyl)pyrrolidin-2-yl)-2-phenylacetate (**3b**)



(*E*)-4-chloro-*N*-(5-phenylpent-4-en-1-yl)aniline (**1b**; 54.4 mg, 0.20 mmol, 1.0 equiv) was employed as a starting material. Purification of the crude product by silica-gel column chromatography (eluent: hexane/EtOAc, 10/1 to 4/1) afforded diastereomixture of **3b** (50.5 mg, 0.153 mmol, 77% yield). Pale yellow solid; IR (ATR): 2920, 2850, 1725, 1595, 1495, 1481, 1145, 803, 742, 697 cm^{-1} ; ^1H NMR (400 MHz, CDCl_3) δ : 7.37-7.31 (m, 2H, *anti*), 7.30-7.18 (m, 7H, *syn*-), 7.25-7.18 (m, 3H, *anti*-), 6.98 (d, J = 8.7 Hz, 2H, *anti*), 6.63 (d, J = 8.7 Hz, 2H, *syn*), 6.31 (d, J = 8.7 Hz, 2H, *anti*), 4.47-4.40 (m, *syn*), 4.35-4.26 (m, *anti*), 4.09 (d, J = 5.0 Hz, *syn*), 3.91 (d, J = 6.9 Hz, *anti*), 3.68 (s, 3H, *anti*), 3.65 (s, 3H, *syn*), 3.54-3.44 (m, *anti*), 3.21-3.09 (m, *anti*-), 3.21-3.09 (m, *syn*-), 3.01 (q, J = 8.7 Hz, *syn*),

2.23-2.11 (m, *anti*), 2.11-1.88 (m, 3H, *anti*-), 2.11-1.88 (m, 2H, *syn*-), 1.71-1.62 (m, *syn*), 1.07-0.92 (m, *syn*) ppm; ^{13}C NMR (100 MHz, CDCl_3) δ : 173.3, 173.1, 146.0, 145.3, 136.3, 135.8, 129.3, 129.2, 128.9, 128.6, 128.4, 127.6, 127.6, 121.0, 120.7, 113.5, 113.4, 62.0, 60.5, 54.1, 52.2, 52.1, 51.8, 49.5, 48.9, 29.8, 28.2, 23.3, 23.0 ppm; HRMS (ESI) m/z calcd. for $\text{C}_{19}\text{H}_{20}\text{NO}_2\text{ClNa}^+$ $[\text{M}+\text{Na}]^+$: 352.10748, found: 352.10707.

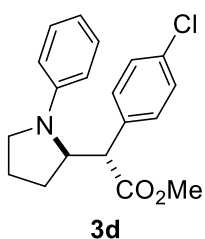
methyl 2-(1-(4-methoxyphenyl)pyrrolidin-2-yl)-2-phenylacetate (**3c**)



(*E*)-4-methoxy-*N*-(5-phenylpent-4-en-1-yl)aniline (**1c**; 53.5 mg, 0.20 mmol, 1.0 equiv) was employed as a starting material and the reaction time was extended for 6 h. Purification of the crude product by silica-gel column chromatography (eluent: hexane/EtOAc, 10/1 to 4/1) afforded diastereomixture of **3c** (20.1 mg, 0.062 mmol, 31% yield). Pale yellow oil; IR (ATR): 2949, 2835, 1732, 1717, 1509, 1272, 1239, 1204, 1163, 1144, 1038, 804, 742, 696 cm^{-1} ; ^1H NMR (400 MHz, CDCl_3) δ : 7.41-

7.35 (m, 2H, *anti*), 7.32-7.18 (m, 3H, *anti*), 7.32-7.18 (m, 5H, *syn*), 6.92-6.87 (m, 2H, *syn*), 6.75-6.66 (m, 2H, *anti*), 6.75-6.66 (m, 2H, *syn*), 6.46-6.38 (m, 2H, *anti*), 4.43-4.37 (m, *syn*), 4.26-4.20 (m, *anti*), 4.10 (d, $J = 5.0$ Hz, *syn*), 3.97 (d, $J = 6.0$ Hz, *anti*), 3.79 (s, 3H, *syn*), 3.72 (s, 3H, *anti*), 3.65 (s, 3H, *anti*), 3.65 (s, 3H, *syn*), 3.54-3.45 (m, *anti*), 3.21-3.09 (m, *anti*), 3.21-3.09 (m, *syn*), 2.99 (q, $J = 8.5$ Hz, *syn*), 2.27-2.18 (m, *anti*), 2.05-1.88 (m, 3H, *anti*), 2.05-1.88 (m, 2H, *syn*), 1.69-1.58 (m, *syn*), 1.02-0.84 (m, *syn*) ppm; ^{13}C NMR (100 MHz, CDCl_3) δ : 173.6, 173.3, 151.1, 151.0, 142.3, 141.7, 136.8, 136.1, 129.4, 128.9, 128.5, 128.3, 127.5, 127.4, 115.2, 114.7, 113.4, 113.3, 62.7, 60.8, 56.0, 55.9, 54.1, 52.2, 52.1, 52.0, 50.2, 49.4, 29.5, 28.2, 23.6, 23.2. ppm; HRMS (ESI) m/z calcd. for $\text{C}_{20}\text{H}_{24}\text{NO}_3^+$ $[\text{M}+\text{H}]^+$: 326.17507, found: 326.17474.

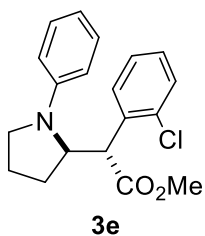
methyl 2-(4-chlorophenyl)-2-(1-phenylpyrrolidin-2-yl)acetate (**3d**)



(*E*)-*N*-(5-(4-chlorophenyl)pent-4-en-1-yl)aniline (**1d**; 54.4 mg, 0.20 mmol, 1.0 equiv) was employed as a starting material and the reaction time was extended for 3 h. Purification of the crude product by silica-gel column chromatography (eluent: hexane/EtOAc, 10/1 to 4/1) afforded diastereomixture of **3d** (36.2 mg, 0.110 mmol, 55% yield). Pale yellow solid; IR (ATR): 2950, 2849, 1730, 1597, 1503, 1491, 1363,

1155, 1091, 1013, 745, 691 cm^{-1} ; ^1H NMR (400 MHz, CDCl_3) δ : 7.35-7.27 (m, 2H, *anti*), 7.35-7.20 (m, 4H, *syn*), 7.25-7.20 (m, 2H, *anti*), 7.20-7.15 (m, 2H, *syn*), 7.15-7.08 (m, 2H, *anti*), 6.74 (t, $J = 7.3$ Hz, *syn*), 6.71 (d, $J = 7.8$ Hz, 2H, *syn*), 6.63 (t, $J = 7.1$ Hz, *anti*), 6.45 (d, $J = 8.2$ Hz, 2H, *anti*), 4.47-4.41 (m, *syn*), 4.34-4.27 (m, *anti*), 4.17 (d, $J = 4.1$ Hz, *syn*), 3.95 (d, $J = 6.0$ Hz, *anti*), 3.68 (s, 3H, *syn*), 3.67 (s, 3H, *anti*), 3.54-3.46 (m, *anti*), 3.24-3.16 (m, *anti*), 3.17-3.10 (m, *syn*), 3.08-3.00 (m, *syn*), 2.21-2.11 (m, *anti*), 2.06-1.90 (m, 3H, *anti*), 2.06-1.90 (m, 2H, *syn*), 1.71-1.61 (m, *syn*), 1.01-0.82 (m, *syn*) ppm; ^{13}C NMR (100 MHz, CDCl_3) δ : 173.1, 172.9, 147.2, 146.6, 135.1, 134.3, 133.5, 133.5, 130.8, 130.4, 129.6, 129.0, 128.6, 128.5, 116.5, 116.3, 112.5, 112.4, 61.9, 60.3, 53.4, 52.2, 52.2, 50.9, 49.5, 48.8, 29.5, 28.0, 23.3, 23.1 ppm; HRMS (ESI) m/z calcd. for $\text{C}_{19}\text{H}_{21}\text{NO}_2\text{Cl}^+ [\text{M}+\text{H}]^+$: 330.12553, found: 330.12484.

methyl 2-(2-chlorophenyl)-2-(1-phenylpyrrolidin-2-yl)acetate (**3e**)

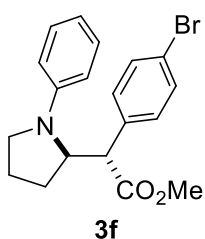


(*E*)-*N*-(5-(2-chlorophenyl)pent-4-en-1-yl)aniline (**1e**; 54.4 mg, 0.20 mmol, 1.0 equiv) was employed as a starting material and the reaction time was extended for 2 h. Purification of the crude product by silica-gel column chromatography (eluent: hexane/EtOAc, 10/1) afforded diastereomixture of **3e** (51.1 mg, 0.155 mmol, 77% yield). Yellow solid; IR (ATR): 2950, 2856, 1731, 1597, 1503, 1363, 1337, 1165,

1145, 741, 692 cm^{-1} ; ^1H NMR (400 MHz, CDCl_3) δ : 7.72-7.67 (m, *syn*), 7.67-7.61 (m, *anti*), 7.37 (dd, $J = 7.9, 1.5$ Hz, *syn*), 7.30 (td, $J = 7.5, 1.5$ Hz, *syn*), 7.27-7.24 (m, 2H, *syn*, overlapped with solvent peak), 7.24-7.18 (m, 2H, *anti*), 7.24-7.18 (m, *syn*), 7.14-7.08 (m, *anti*), 7.08-7.02 (m, 2H, *anti*), 6.77-6.72 (m, 2H, *syn*), 6.72-6.67 (m, *syn*), 6.58-6.52 (m, *anti*), 6.52-6.47 (m, 2H, *anti*), 4.66-4.60 (m, *syn*), 4.58 (d, $J = 7.0$ Hz, *anti*), 4.56-4.49 (m, *anti*), 4.51 (d, $J = 7.1$ Hz, *syn*), 3.67 (s, 3H, *anti*), 3.56-3.48 (m, *anti*), 3.47 (s, 3H, *syn*), 3.46-3.40 (m, *syn*), 3.23-3.11 (m, *anti*), 3.23-3.11 (m, *syn*), 2.21-1.92 (m, 4H, *anti*), 1.87-1.80

(m, 2H, *syn*), 1.69-1.58 (m, *syn*), 0.96-0.80 (m, *syn*) ppm; ^{13}C NMR (100 MHz, CDCl_3) δ : 173.2, 172.9, 147.2, 147.1, 134.9, 134.9, 134.7, 134.3, 130.8, 129.9, 129.8, 129.7, 128.8, 128.8, 128.7, 126.8, 116.3, 115.9, 112.4, 61.2, 60.1, 52.3, 52.2, 50.0, 49.6, 49.1, 48.6, 30.2, 29.0, 23.4, 23.2 ppm; HRMS (ESI) m/z calcd. for $\text{C}_{19}\text{H}_{21}\text{NO}_2\text{Cl}$ $[\text{M}+\text{H}]^+$: 330.12553, found: 330.12490.

methyl 2-(4-bromophenyl)-2-(1-phenylpyrrolidin-2-yl)acetate (**3f**)

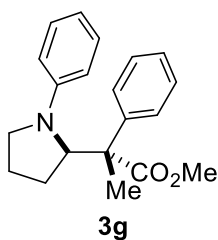


(*E*)-*N*-(5-(4-bromophenyl)pent-4-en-1-yl)aniline (**1f**; 63.2 mg, 0.20 mmol, 1.0 equiv) was employed as a starting material and the reaction time was extended for 3 h. Purification of the crude product by silica-gel column chromatography (eluent: hexane/EtOAc, 10/1 to 4/1) afforded diastereomixture of **3f** (36.3 mg, 0.097 mmol, 48% yield). Pale yellow oil;

3f-anti: IR (ATR): 2950, 1731, 1597, 1504, 1488, 1362, 1155, 1010, 745, 691 cm^{-1} ; ^1H NMR (400 MHz, CDCl_3) δ : 7.43-7.34 (m, 2H), 7.30-7.21 (m, 5H, overlapped with solvent peak), 7.17-7.07 (m, 2H), 6.68-6.58 (m), 6.50-6.41 (m, 2H), 4.35-4.26 (m), 3.94 (d, $J = 5.9$ Hz), 3.66 (s, 3H), 3.55-3.44 (m), 3.26-3.14 (m), 2.22-2.10 (m), 2.07-1.88 (m, 3H). ppm; ^{13}C NMR (100 MHz, CDCl_3) δ : 172.9, 147.2, 135.6, 131.6, 130.7, 129.1, 121.6, 116.4, 112.5, 61.9, 53.4, 52.2, 49.5, 29.5, 23.3 ppm; HRMS (ESI) m/z calcd. for $\text{C}_{19}\text{H}_{21}\text{NO}_2\text{Br}$ $[\text{M}+\text{H}]^+$: 374.07502, found: 374.07447.

3f-syn: IR (ATR): 2924, 1733, 1597, 1505, 1487, 1364, 1150, 1011, 746, 692 cm^{-1} ; ^1H NMR (400 MHz, CDCl_3) δ : 7.41-7.36 (m, 2H), 7.31-7.26 (m, 2H), 7.14-7.07 (m, 2H), 6.76-6.67 (m, 3H), 4.42 (ddd, $J = 7.2, 4.4, 2.4$ Hz), 4.14 (d, $J = 4.4$ Hz), 3.67 (s, 3H), 3.13 (td, $J = 8.8, 2.4$ Hz), 3.02 (d, $J = 8.8$ Hz), 2.06-1.89 (m, 2H), 1.71-1.59 (m), 1.01-0.89 (m). ppm; ^{13}C NMR (100 MHz, CDCl_3) δ : 173.0, 146.6, 134.9, 131.4, 131.2, 129.6, 121.7, 116.5, 112.4, 60.3, 52.2, 51.0, 48.8, 28.0, 23.1. ppm.

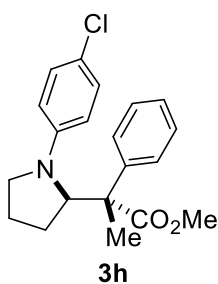
methyl 2-phenyl-2-(1-phenylpyrrolidin-2-yl)propanoate (**3g**)



(*E*)-*N*-(5-phenylhex-4-en-1-yl)aniline (**1g**; 50.3 mg, 0.20 mmol, 1.0 equiv) was employed as a starting material and the reaction time was extended for 20 min. Purification of the crude product by silica-gel column chromatography (eluent: hexane/EtOAc, 50/1) afforded diastereomixture of **3g** (44.6 mg, 0.144 mmol, 72% yield). Pale yellow solid; IR (ATR): 2952, 2864, 1719, 1595, 1503, 1361, 1325,

1230, 1118, 743 cm^{-1} ; ^1H NMR (400 MHz, CDCl_3) δ : 7.34-7.27 (m, 2H, *anti*), 7.34-7.27 (m, 5H, *syn*), 7.16-7.10 (m, 3H, *anti*), 6.91-6.83 (m, 2H, *anti*), 6.87-6.81 (m, 2H, *syn*), 6.71 (tt, $J = 7.4, 1.1$ Hz, *syn*), 6.47 (tt, $J = 7.3, 1.2$ Hz, *anti*), 4.86 (dd, $J = 8.4, 1.7$ Hz, *syn*), 4.73 (dd, $J = 8.6, 1.7$ Hz, *anti*), 4.01 (d, $J = 6.0$ Hz), 3.72 (s, 3H, *anti*), 3.68-3.61 (m, *anti*), 3.63 (s, 3H, *syn*), 3.31 (td, $J = 9.0, 3.0$ Hz, *syn*), 3.28-3.18 (m, *anti*), 3.07 (q, $J = 8.8$ Hz, *syn*), 2.21-2.09 (m, *anti*), 2.05-1.96 (m, *syn*), 1.95-1.82 (m, 3H *anti*), 1.82-1.76 (m, *syn*), 1.63 (s, 3H *anti*), 1.63 (s, 3H *syn*), 0.95-0.81 (m, *syn*), 0.75-0.63 (m, *syn*) ppm; ^{13}C NMR (100 MHz, CDCl_3) δ : 176.1, 149.6, 141.9, 128.9, 128.2, 128.1, 128.0, 127.9, 127.4, 127.1, 116.2, 114.3, 113.7, 64.6, 56.7, 52.9, 52.7, 52.1, 30.3, 29.5, 24.1, 23.1, 19.0 ppm; HRMS (ESI) m/z calcd. for $\text{C}_{20}\text{H}_{24}\text{NO}_2$ $[\text{M}+\text{H}]^+$: 310.18016, found: 310.17954.

methyl 2-(1-(4-chlorophenyl)pyrrolidin-2-yl)-2-phenylpropanoate (**3h**)

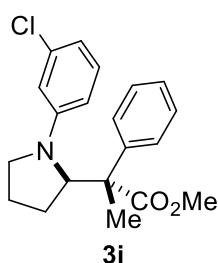


(*E*)-4-chloro-*N*-(5-phenylhex-4-en-1-yl)aniline (**1h**; 57.2 mg, 0.20 mmol, 1.0 equiv) was employed as a starting material and the reaction time was extended for 30 min. Purification of the crude product by silica-gel column chromatography (eluent: hexane/EtOAc, 50/1) afforded diastereomixture of **3h** (67.5 mg, 0.196 mmol, 98% yield). Yellow oil;

3h-anti: IR (ATR): 2924, 2852, 1724, 1596, 1496, 1362, 1244, 1098, 808, 697 cm^{-1} ; ^1H NMR (400 MHz, CDCl_3) δ : 7.30 – 7.22 (m, 3H, overlapped with solvent peak), 7.18 – 7.08 (m, 3H), 6.82 – 6.73 (m, 2H), 6.12 (dd, $J = 9.2, 3.2$ Hz, 2H), 4.65 (d, $J = 8.8$ Hz), 3.73 (q, $J = 2.3, 1.9$ Hz, 3H), 3.68 – 3.56 (m), 3.19 (q, $J = 8.8$ Hz), 2.28 – 2.06 (m), 2.01 – 1.81 (m, 3H), 1.61 (s, 3H) ppm; ^{13}C NMR (100 MHz, CDCl_3) δ : 176.0, 148.2, 141.7, 128.3, 127.9, 127.3, 127.3, 120.8, 114.7, 64.9, 56.7, 53.0, 52.2, 30.4, 24.1, 18.6 ppm; HRMS (ESI) m/z calcd. for $\text{C}_{20}\text{H}_{23}\text{NO}_2\text{Cl}$ $[\text{M}+\text{H}]^+$: 344.14118, found: 344.14070.

3h-syn: IR (ATR): 2923, 2852, 1727, 1596, 1496, 1238, 1093, 809, 699 cm^{-1} ; ^1H NMR (400 MHz, CDCl_3) δ : 7.33-7.27 (m, 5H), 7.17-7.11 (m, 2H), 6.77-6.71 (m, 2H), 4.81 (dd, $J = 8.5, 1.8$ Hz), 3.63 (s, 3H), 3.29 (td, $J = 9.1, 3.2$ Hz), 3.03 (q, $J = 8.6$ Hz), 1.99-1.88 (m), 1.79 (ddt, $J = 13.5, 8.1, 2.4$ Hz), 1.60 (s, 3H), 0.98-0.82 (m), 0.82-0.63 (m) ppm; ^{13}C NMR (100 MHz, CDCl_3) δ : 176.7, 148.6, 141.3, 128.6, 128.1, 127.8, 127.2, 121.5, 115.4, 63.3, 56.5, 52.8, 52.2, 29.5, 23.2, 21.7 ppm.

methyl 2-(1-(3-chlorophenyl)pyrrolidin-2-yl)-2-phenylpropanoate (**3i**)

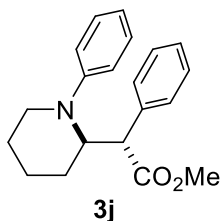


(*E*)-3-chloro-*N*-(5-phenylhex-4-en-1-yl)aniline (**1i**; 57.2 mg, 0.20 mmol, 1.0 equiv) was employed as a starting material. Purification of the crude product by silica-gel column chromatography (eluent: hexane/EtOAc, 50/1) afforded diastereomixture of **3i** (67.6 mg, 0.197 mmol, 98% yield). Pale yellow oil;

3i-anti: IR (ATR): 2950, 1721, 1592, 1481, 1241, 1095, 989, 836, 757, 696 cm^{-1} ; ^1H NMR (400 MHz, CDCl_3) δ : 7.30-7.26 (m, 2H, overlapped with solvent peak), 7.19-7.10 (m, 3H), 6.79-6.71 (m, 1H), 6.41 (ddd, $J = 7.8, 2.0, 0.9$ Hz, 1H), 6.15 (t, $J = 2.3$ Hz, 1H), 6.08 (ddd, $J = 8.4, 2.7, 0.9$ Hz, 1H), 4.67 (dd, $J = 8.6, 1.5$ Hz, 1H), 3.74 (s, 3H), 3.66-3.59 (m, 1H), 3.22 (dt, $J = 9.7, 8.1$ Hz, 1H), 2.32-2.08 (m, 1H), 2.01-1.83 (m, 3H), 1.62 (s, 3H) ppm; ^{13}C NMR (100 MHz, CDCl_3) δ : 175.9, 150.5, 141.5, 134.1, 129.0, 128.3, 127.4, 127.2, 116.1, 113.6, 111.8, 64.8, 56.7, 52.7, 52.2, 30.3, 24.0, 18.5 ppm; HRMS (ESI) m/z calcd. for $\text{C}_{20}\text{H}_{22}\text{NO}_2\text{ClNa}^+$ [$\text{M}+\text{Na}$] $^+$: 366.12313, found: 366.12249.

3i-syn: IR (ATR): 2924, 1725, 1592, 1503, 1478, 1362, 1237, 1092, 989, 760 cm^{-1} ; ^1H NMR (400 MHz, CDCl_3) δ : 7.35-7.27 (m, 5H), 7.10 (dd, $J = 8.4, 7.1$ Hz), 6.78 (t, $J = 2.2$ Hz), 6.71-6.33 (m, 2H), 4.82 (dd, $J = 8.3, 1.8$ Hz), 3.66 (s, 3H), 3.29 (td, $J = 9.1, 3.2$ Hz), 3.07 (q, $J = 8.7$ Hz), 2.00-1.89 (m), 1.85-1.76 (m), 1.61 (s, 3H), 1.54-1.48 (m), 0.84-0.66 (m) ppm; ^{13}C NMR (100 MHz, CDCl_3) δ : 176.6, 150.9, 141.3, 129.8, 128.2, 127.8, 127.3, 116.6, 114.1, 112.4, 63.2, 56.4, 52.6, 52.3, 29.5, 23.1, 21.7 ppm.

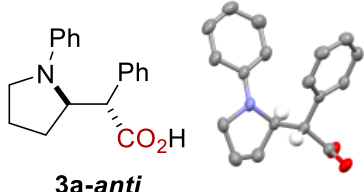
methyl 2-phenyl-2-(1-phenylpiperidin-2-yl)acetate (**3j**)



(*E*)-*N*-(6-phenylhex-5-en-1-yl)aniline (**1j**; 50.3 mg, 0.20 mmol, 1.0 equiv) was employed as a starting material. Purification of the crude product by silica-gel column chromatography (eluent: hexane/EtOAc, 50/1 to 20/1) afforded diastereomixture of **3j** (6.9 mg, 0.022 mmol, 11% yield), and the major diastereomer was isolated by GPC (5.4 mg, 0.017 mmol, 9% yield). Colorless oil;

IR (ATR): 2928, 2854, 1731, 1596, 1497, 1250, 1230, 1155, 749, 693 cm^{-1} ; ^1H NMR (400 MHz, CDCl_3) δ : 7.33-7.28 (m, 2H), 7.15-7.06 (m, 3H), 7.05-6.97 (m, 2H), 6.63-6.53 (m, 3H), 4.70-4.63 (m), 4.36 (d, $J = 11.0$ Hz), 3.40-3.32 (m), 3.17-3.07 (m), 1.94-1.80 (m, 2H), 1.77-1.59 (m, 4H) ppm; ^{13}C NMR (100 MHz, CDCl_3) δ : 173.6, 151.0, 136.1, 128.8, 128.7, 128.3, 127.5, 117.4, 115.8, 58.7, 52.3, 42.7, 26.9, 24.1, 19.9 ppm; HRMS (ESI) m/z calcd. for $\text{C}_{20}\text{H}_{24}\text{NO}_2^+$ $[\text{M}+\text{H}]^+$: 310.18016, found: 310.17971.

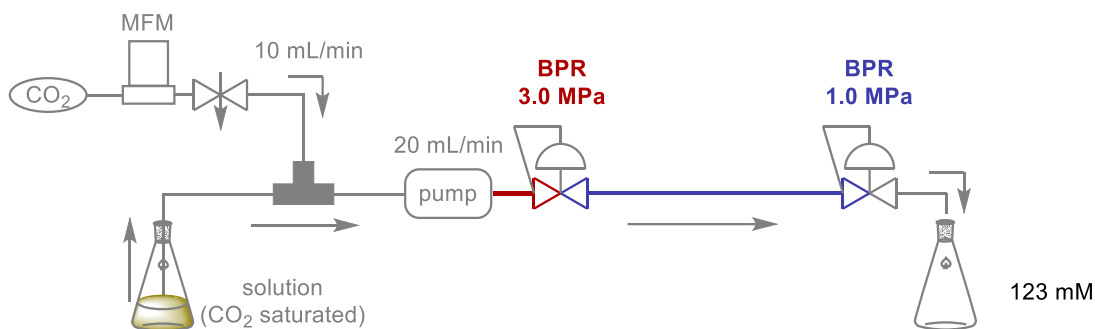
S3.4. Crystal structure

Compound	 3a-anti
CCDC Name	CCDC 2359995
Empirical Formula	C ₁₈ H ₁₉ NO ₂
Formula Weight	281.34
Crystal System	Monoclinic
Crystal Size / mm	0.05 × 0.05 × 0.2
<i>a</i> / Å	16.5231(3)
<i>b</i> / Å	5.5038(2)
<i>c</i> / Å	17.5105(3)
α / °	90
β / °	108.672(2)
γ / °	90
<i>V</i> / Å ³	1508.59(7)
Space Group	P 1 21/c 1
<i>Z</i> value	4
<i>D</i> _{calc} / g cm ⁻³	1.239
Temperature / K	123(2)
2 θ _{max} / °	74.767
μ (CuK α) / mm ⁻¹	0.639
No. of Reflections Measured	3007
No. of Observations (All reflections)	40099
Residuals: <i>R</i> ₁ (<i>I</i> > 2.00 σ (<i>I</i>))	0.0412
Residuals: <i>wR</i> ₂ (All reflections)	0.1152
Goodness of Fit Indicator (<i>GOF</i>)	1.025
Maximum peak in Final Diff. Map / Å ³	0.179
Minimum peak in Final Diff. Map / Å ³	-0.204

S3.5. CO₂ concentrations in flow reaction conditions

CO₂ concentrations under flow reaction conditions were measured with a Shimadzu GC-2010 Plus. To make the solution saturated with CO₂, DMF was circulated for 2 hours while flowing CO₂ in 10 mL/min flow rate. Afterwards, sample solution for measurement was obtained from exit. Measurements of CO₂ concentration performed three times for one condition.

(a) Fine Bubble Condition



(b) Control

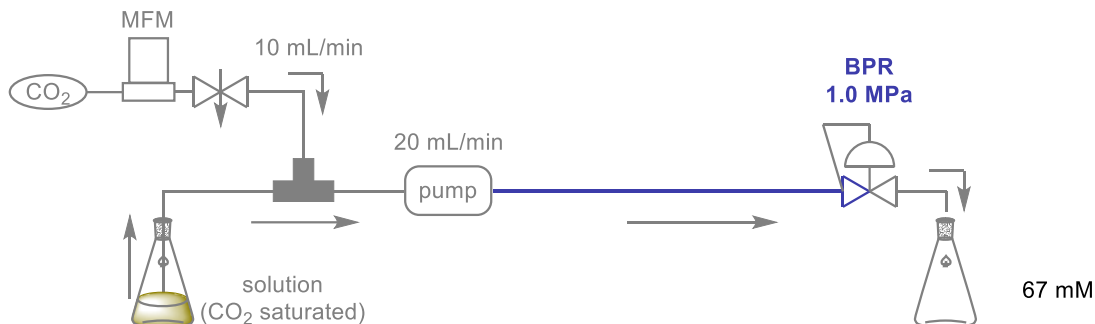


Figure S3.1. Measurement of CO₂ concentration.

S3.6. Details for quantum chemical calculations

For reaction pathway calculation in Figures 3.1-3.5, the artificial force induced reaction (AFIR) method implemented in the global reaction route mapping (GRRM) program² combined with the Gaussian 16 program³ was used. All calculations were performed at the U ω B97X-D/6-311+G(d,p)/SMD(acetonitrile) level of theory. The probable reaction pathways and approximate transition state (TS) structures were first obtained by the AFIR method, where the value of γ was set as 50, 100 or 200 kJ/mol for the artificial force between the reactive sites. Obtained approximate TSs were re-optimized and vibrational frequencies of all obtained structures were calculated at the same level of theory to confirm whether these structures corresponded first-order saddle points. For obtained TS structures, the intrinsic reaction coordinate (IRC) calculations were carried out to confirm the connections between the corresponding intermediates. In the calculations of electron transfer steps, the photoredox catalyst was represented by the energy shift approach using the experimental redox potential (the potential of *Ir(III) to Ir(II) of [Ir(ppy)₂(dtbbpy)]PF₆: 0.66 V vs SCE: 490.3 kJ/mol = 117.2 kcal/mol and the potential of Ir(II) to Ir(III) of [Ir(ppy)₂(dtbbpy)]PF₆: -1.51 V vs SCE: 281.0 kJ/mol = 67.2 kcal/mol). To optimize minimum energy seam of crossing (MESX) structures, energies of neutral (S₀ state) species were shifted by 490.3 kJ/mol for *Ir(III)/Ir(II) or 281.0 kJ/mol for Ir(III)/Ir(II). For obtained MESX structures, meta-IRC calculations in both S₀ and D₀ states were carried out to confirm the connections between the corresponding intermediates. To search for CO₂-coupled electron transfer paths, MESX geometries were firstly optimized on the force-modified (FM) potential energy surface by applying a weak attractive force (γ was set as 50 or 100 kJ/mol) between the carbon atoms forming the C-C bond, and then the mass-weighted steepest descent path (the meta-IRC path) on seam hypersurface⁴ starting from each obtained crossing point geometry was calculated. Finally, additional meta-IRC calculations from all the steps in the obtained meta-IRC path were performed, and the geometry with the lowest energy among the steps which were connected to the carboxylated intermediate VI with the corresponding meta-IRC paths in S₀ state was assigned as FM-SX. From obtained FM-SX structures, meta-IRC calculations in D₀ state were also performed to confirm the connections to the radical intermediate II. The Gibbs free energy values at 298.15 K and 1 atm were estimated by assuming ideal-gas, rigid-rotor, and harmonic-vibrational models,

where all the harmonic frequencies smaller than 50 cm^{-1} were set as 50 cm^{-1} as suggested in the literature.⁵

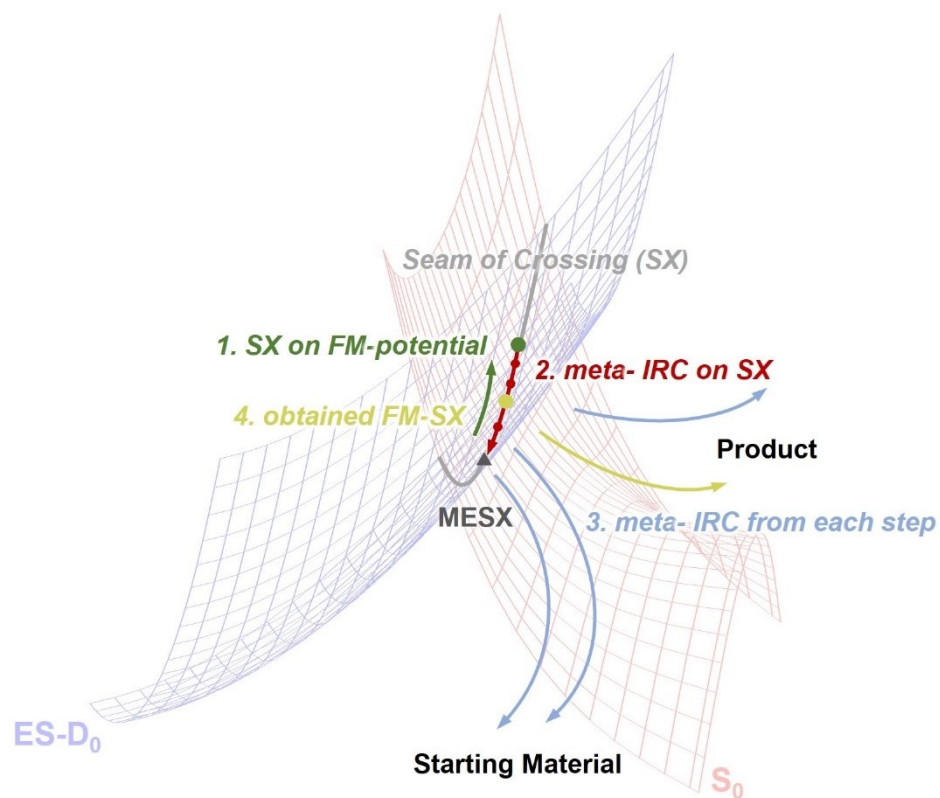


Figure S3.2. Schematic image of FM-SX search.

CO₂

free energy = -188.585932032060 Hartree

C	-0.000000000434	-0.000000000004	-0.000000000004
O	1.156188833619	0.000000000001	0.000000000001
O	-1.156188833293	0.000000000001	0.000000000001

1a

free energy = -713.674839797883 Hartree

N	1.989882118080	0.788959125535	-4.356916945645
H	1.811040266190	1.161269460479	-3.435846867570
C	1.440252135588	1.613045228232	-5.423778463270

H	1.667040676977	2.650043645746	-5.161109567770
H	1.980062256040	1.405228873849	-6.352770982572
C	-0.066210391191	1.475159171385	-5.672986966507
H	-0.299780878076	0.454594118208	-5.995700821451
H	-0.318151947824	2.132067125667	-6.511932930819
C	-0.951778204206	1.841206634142	-4.473172935113
H	-0.663366924590	2.821323331479	-4.076374394204
H	-1.982686938652	1.936095786451	-4.836889922381
C	-0.938162476065	0.817281971867	-3.377574181565
H	-1.140871585360	-0.204246428388	-3.696596918190
C	-0.687843136979	1.074880700863	-2.093089155366
H	-0.460597387290	2.100582746154	-1.805010601893
C	1.940034882834	-0.593828646706	-4.391835645599
C	1.857867090178	-1.318452236261	-5.591046864381
C	2.006449716684	-1.314713057315	-3.186224125714
C	1.851409518540	-2.709093800030	-5.573746536255
C	1.996164775107	-2.700211622734	-3.183337500031
C	1.918335673918	-3.414785986961	-4.377613190611
H	1.797078421228	-0.798390207524	-6.539737883167
H	2.056610946635	-0.768688074476	-2.248922859129
H	1.787176776671	-3.244969133306	-6.515350301526
H	2.041357353130	-3.226938127139	-2.235538471138
H	1.906801691291	-4.498665235357	-4.373572403904
C	-0.632011487053	0.093094036495	-0.994913423934
C	-0.173079643530	0.510624620461	0.259380036486
C	-0.991777519178	-1.252848033411	-1.150237629288
C	-0.063755453578	-0.382105559344	1.320056594557
C	-0.882371612845	-2.144521832704	-0.092798852246
C	-0.416074200417	-1.715402764461	1.148018233285
H	0.107143015623	1.550162936389	0.400279697213
H	-1.357457302845	-1.611724623429	-2.105904219006
H	0.298186333540	-0.033676988866	2.281388947500
H	-1.163432494175	-3.182314307504	-0.236791923701
H	-0.331578054403	-2.415387414463	1.971921554884

MESX 1a - I

free energy = -713.491022763425 Hartree

N	1.766785364479	0.674153331054	-4.439043502685
H	1.397189695290	-0.136839796748	-4.911287572668
C	1.602108031250	1.931920256206	-5.144169990359

H	1.651196700999	2.756544426744	-4.429909777838
H	2.427114853409	2.075322872673	-5.852158055291
C	0.272578938160	2.002257364448	-5.897079333719
H	0.123721149541	1.065637270383	-6.448158916610
H	0.343563921671	2.795896701620	-6.647216454532
C	-0.943951181402	2.285637857187	-5.003347189440
H	-0.837449125735	3.278174140381	-4.552068407787
H	-1.833071174361	2.318794011180	-5.645176625394
C	-1.154846237772	1.265716111424	-3.926854948808
H	-1.264428936366	0.236153626431	-4.264888983695
C	-1.175243549343	1.542795661171	-2.622294563432
H	-1.021270156668	2.574510541112	-2.308610595110
C	2.041968390703	0.509254975008	-3.107670685750
C	1.869599031781	-0.765143488390	-2.528239927446
C	2.490961761620	1.551378997995	-2.277406712676
C	2.123416910399	-0.978370689097	-1.185209578539
C	2.737697119623	1.320354536737	-0.928551895711
C	2.558574675961	0.062524709316	-0.364947134580
H	1.513464313488	-1.580179692175	-3.151472540346
H	2.657595556820	2.542297909482	-2.681104554601
H	1.967366943624	-1.968533143443	-0.769254742863
H	3.079196256949	2.145654482668	-0.311820397319
H	2.749149949229	-0.105630087685	0.688599932405
C	-1.312406663994	0.569850167454	-1.524099278255
C	-0.976265787148	0.966358251257	-0.225682572457
C	-1.735975594504	-0.751477600552	-1.721642656756
C	-1.034919581432	0.071983749420	0.837211973472
C	-1.795507767624	-1.644791866988	-0.661716317564
C	-1.440779579387	-1.239798640025	0.623423956042
H	-0.649047299396	1.987084695371	-0.053162102567
H	-2.023404899275	-1.085873543396	-2.712615830884
H	-0.758987661444	0.401344990590	1.833203904383
H	-2.123839225699	-2.663725747113	-0.837306870722
H	-1.487130393434	-1.940637615698	1.449650863129

I

free energy = -713.492754624722 Hartree

N	1.860422380532	0.778669234321	-4.258385123047
H	1.703369416205	-0.107383013792	-4.732511176541
C	1.488330860171	1.958870206339	-5.026119969526

H	1.435920269272	2.819835595780	-4.361951770440
H	2.287249052509	2.132752857321	-5.753703758656
C	0.159903700866	1.749142754110	-5.751912755765
H	0.189273933984	0.793366230485	-6.286950957844
H	0.077392740026	2.532047013251	-6.509478599928
C	-1.067468988673	1.805700269880	-4.828191208558
H	-1.147324626789	2.806639400592	-4.392336282637
H	-1.958905193292	1.642064030413	-5.443340728309
C	-0.993829320290	0.780201377263	-3.740291803556
H	-0.969506319288	-0.258030061446	-4.068778571649
C	-0.855034917602	1.076482702683	-2.446572625604
H	-0.848857293429	2.125714886618	-2.154495535837
C	2.393283296285	0.700027454699	-3.037423507720
C	2.622575528155	-0.600865765267	-2.496004470629
C	2.705358001665	1.850469624363	-2.258815937771
C	3.143062902135	-0.736011549464	-1.233544047900
C	3.228493054181	1.685426461717	-1.001074959116
C	3.448020156876	0.401790660469	-0.477718916019
H	2.370377925879	-1.467535334040	-3.096667756971
H	2.540588590102	2.842656847175	-2.655744291975
H	3.308730481505	-1.723009270662	-0.820545377737
H	3.470047892983	2.556250916705	-0.404274664818
H	3.854296426619	0.292320282251	0.520507899565
C	-0.583317291182	0.125481981563	-1.358276944624
C	-0.173803261881	0.625685895901	-0.117522543687
C	-0.656588541994	-1.265475623564	-1.520603869358
C	0.175848821043	-0.229265208802	0.920216891688
C	-0.313428177396	-2.119821990819	-0.482960492287
C	0.111614941396	-1.606821326848	0.740162025497
H	-0.112520867826	1.699992619159	0.025264447366
H	-0.985454724062	-1.684760341931	-2.464954319834
H	0.501506550328	0.180777522426	1.869960875574
H	-0.375305825816	-3.192744812024	-0.629030902658
H	0.384533368849	-2.276928349787	1.547792886350

TS I - II

free energy = -713.479863689520 Hartree

N	1.399562900585	0.920855446932	-4.243747081602
H	2.001955182770	1.319697408219	-3.532936385731
C	1.814566160246	1.268594041661	-5.608601528802

H	2.704310619628	1.891312699858	-5.513444103196
H	2.080627480310	0.360892261316	-6.152458122209
C	0.707643241086	2.048271403537	-6.319884258512
H	-0.084194291990	1.365369106013	-6.640810899218
H	1.109773721519	2.535701330751	-7.209511805874
C	0.140428700221	3.064737063733	-5.331636228042
H	0.874775502930	3.837329087352	-5.087153585697
H	-0.734559381895	3.556137396924	-5.772611808459
C	-0.299106115951	2.348119212391	-4.103081562824
H	-0.997940220067	1.533432970180	-4.270903689381
C	-0.143996602506	2.833482451638	-2.818443887873
H	0.476354520499	3.715698469737	-2.680544031586
C	0.914756010370	-0.341838526399	-3.879839016482
C	0.201240369505	-1.139292486064	-4.779891436266
C	1.096694367304	-0.764845898979	-2.559151922927
C	-0.313811946503	-2.353351557475	-4.352099096823
C	0.575844376212	-1.981674574059	-2.145370316298
C	-0.133002455873	-2.778776009657	-3.037577253933
H	0.044087255372	-0.813025310873	-5.800866203735
H	1.647527815425	-0.135438847809	-1.868166630601
H	-0.865815744521	-2.971407221753	-5.050864535501
H	0.722105920228	-2.304081352227	-1.121011941659
H	-0.542248011788	-3.728361578703	-2.712969842318
C	-0.656690147068	2.210098512649	-1.629183145849
C	-0.285422118511	2.743283553509	-0.377614193215
C	-1.491445110029	1.072466256546	-1.653465079077
C	-0.720234090842	2.159790166097	0.798592000077
C	-1.924764386673	0.495903109513	-0.472738818758
C	-1.540436921134	1.033002099901	0.754717001165
H	0.355107303043	3.618455819146	-0.348803881345
H	-1.799994933104	0.638546551028	-2.596979827455
H	-0.422446003029	2.578309327824	1.753017718876
H	-2.563448996243	-0.379172514334	-0.505193000631
H	-1.882037126544	0.575543140906	1.676341537871

II

free energy = -713.494629511831 Hartree

N	0.955135439160	0.828473481885	-4.231685833419
H	1.644816515166	1.306664535505	-3.648139690677
C	1.218960766862	1.273849291939	-5.663553632744

H	2.198520645108	1.747539380221	-5.662063709017
H	1.246881293307	0.395579003249	-6.301866263653
C	0.087363071042	2.244186963577	-6.004234901832
H	-0.693594436790	1.724745370828	-6.563638860734
H	0.451177733700	3.073502582860	-6.609863704881
C	-0.454772307753	2.694879011044	-4.649521302954
H	0.190399547046	3.453816867515	-4.195976813936
H	-1.469539566818	3.088336076424	-4.705662358193
C	-0.416444896121	1.423379869977	-3.816968670905
H	-1.149240575661	0.712177040331	-4.198663941592
C	-0.488874798088	1.591419762822	-2.346007456304
H	-0.030816554790	2.491677587366	-1.945273961748
C	1.069951256831	-0.602059366469	-3.947327619802
C	0.350039766907	-1.512522008352	-4.707845838539
C	1.833416820635	-1.000484930326	-2.862759914969
C	0.404307704453	-2.856832693708	-4.367445273541
C	1.877912665123	-2.349539643984	-2.529331208293
C	1.163291951103	-3.275805930750	-3.278229055032
H	-0.256441240489	-1.181448152338	-5.543353824700
H	2.378520153014	-0.266741114393	-2.278682391070
H	-0.154302516244	-3.577859790962	-4.952309382954
H	2.469588593113	-2.670450105373	-1.680336264611
H	1.196584703485	-4.326571546977	-3.014875174639
C	-1.033156763782	0.661282434336	-1.431237394218
C	-0.962307580445	0.946343988843	-0.041430571245
C	-1.636050401284	-0.564744286880	-1.817916278251
C	-1.448035156941	0.056606088941	0.896777565938
C	-2.116087198064	-1.447432486465	-0.868805571378
C	-2.025503129971	-1.148644784515	0.491919747930
H	-0.509335604571	1.879665725610	0.276925749361
H	-1.720686106895	-0.824656324545	-2.866072335750
H	-1.377806570000	0.295791329893	1.952161078373
H	-2.566555702794	-2.380815395154	-1.188000792144
H	-2.403065568150	-1.847657864878	1.229409237484

MESX II - 1a

free energy = -902.070444586542 Hartree

N	0.868057043117	0.616265319706	-4.201078794400
H	0.735330993821	-0.374224994341	-4.415884639853
C	1.393123857252	1.284400226586	-5.473452869368

H	2.133409031373	2.017603445107	-5.161369617325
H	1.865161622501	0.510814334325	-6.073689658487
C	0.173889095868	1.946564933173	-6.088133718065
H	-0.404480207832	1.228934587594	-6.674198994014
H	0.466156642737	2.774094378438	-6.732692180909
C	-0.611841868059	2.403665902003	-4.863170614168
H	-0.129124852725	3.264213059779	-4.391843528969
H	-1.651813043474	2.649766386321	-5.074332230073
C	-0.520453008573	1.186268380670	-3.955091025338
H	-1.224149663210	0.424803411375	-4.285730299404
C	-0.754347406356	1.474129338626	-2.492077519317
H	-0.659572866904	2.506853142583	-2.179273399726
C	1.795438209311	0.680306758175	-3.057195023654
C	2.264015109762	-0.507914566490	-2.524149804941
C	2.145581232930	1.915950408933	-2.531752065132
C	3.113245664247	-0.454825010718	-1.426269296107
C	2.979315461591	1.952129210357	-1.423116779568
C	3.467147723287	0.771273356627	-0.874272367892
H	1.974593963179	-1.459006235333	-2.956511946734
H	1.767639937202	2.834483926450	-2.968092455363
H	3.491494355993	-1.375497074898	-0.999706367747
H	3.252390869639	2.908048562357	-0.993339865953
H	4.122740854014	0.806620892055	-0.012245652050
C	-1.202554949914	0.532385537516	-1.506235823958
C	-1.557398697631	1.050239067519	-0.257215477541
C	-1.327913301662	-0.835228984788	-1.778670804149
C	-2.053134632654	0.199938702204	0.722089156587
C	-1.801955953889	-1.681531862133	-0.798405383970
C	-2.166037073281	-1.154671069355	0.442781374957
H	-1.445596940843	2.110415975453	-0.066901177364
H	-1.051133453914	-1.232071010433	-2.746751324528
H	-2.340995211515	0.586155962971	1.690505404839
H	-1.895795682298	-2.742184893694	-0.987952238811
H	-2.546540862666	-1.822663329532	1.206208651539
C	1.182704457111	-0.275959555005	1.318481449101
O	1.247806940729	0.834142909015	1.636087390801
O	1.118499515718	-1.389460461336	1.013147182934

SX II - VI-*anti*

free energy = -902.070072816222 Hartree

N	0.855377044650	0.873071018203	-4.185058885701
H	1.545744958747	1.436437964604	-3.678134007877
C	1.042948424824	1.204324259136	-5.640580720797
H	2.087689879651	1.047658124865	-5.899912442025
H	0.406238610742	0.526174543153	-6.207804781438
C	0.562892243951	2.643749435977	-5.706370228066
H	0.263282550304	2.907747840849	-6.719205888063
H	1.367223205715	3.316665413451	-5.402944429667
C	-0.611015232283	2.715665631738	-4.708374183500
H	-0.563468064268	3.615275993854	-4.094933288390
H	-1.570580815098	2.715658655020	-5.223286262780
C	-0.510614582952	1.434810148079	-3.840421001022
H	-1.225753655725	0.695436422440	-4.209473656865
C	-0.640577228605	1.588572614707	-2.365562191539
H	0.191206027030	1.271080606396	-1.744726027373
C	1.082782006232	-0.524202509938	-3.798477348854
C	0.290095609583	-1.529394054706	-4.332979980398
C	2.093823460171	-0.792914243356	-2.890044925543
C	0.526081253765	-2.840138494586	-3.941125029565
C	2.319932696816	-2.109892762498	-2.506600311416
C	1.537535575984	-3.131279709753	-3.030609942897
H	-0.498822221458	-1.302344737793	-5.040570102208
H	2.696481966664	0.013412360662	-2.485626907917
H	-0.084995796763	-3.635719012478	-4.350377574946
H	3.107951950379	-2.331737590933	-1.797063970133
H	1.714232141653	-4.157429708759	-2.729957818770
C	-1.791135403395	2.093491432747	-1.712501547707
C	-1.749756958234	2.272095544526	-0.309154902052
C	-2.979751581345	2.435078506605	-2.398698230403
C	-2.840700673526	2.779533351558	0.370820616572
C	-4.066651975325	2.937936972175	-1.707237170845
C	-4.002287932235	3.115810578928	-0.324720442898
H	-0.843039937354	2.011092412410	0.226141706560
H	-3.050344636660	2.293660819398	-3.470706727792
H	-2.792621564656	2.916623316832	1.444875005501
H	-4.973347418516	3.192909457238	-2.243648981348
H	-4.857578990256	3.513713332738	0.209259773305
C	1.205081776256	4.183716828184	-1.833983645919
O	0.548309157408	4.916254077458	-1.232251645509
O	1.873251800388	3.453365422352	-2.437724690776

SX II - VI-syn

free energy = -902.069570562158 Hartree

N	0.710523857548	0.892743376323	-4.523183425706
H	1.255246431465	1.725181981993	-4.276753270590
C	0.141173104777	1.164589760148	-5.891347027607
H	0.958410493868	1.440442761796	-6.554333797413
H	-0.328189472725	0.244391170254	-6.236656479177
C	-0.875739699017	2.255152665024	-5.616739353750
H	-1.622847951314	2.298736716960	-6.408188708347
H	-0.375320216867	3.224095206053	-5.563354360242
C	-1.483048907733	1.886218742873	-4.253388275549
H	-1.601375836206	2.767156340852	-3.622310464766
H	-2.457897425151	1.408741428515	-4.353635217911
C	-0.499061581569	0.879540071777	-3.600818935966
H	-0.897485762273	-0.134173992898	-3.657532175882
C	-0.150254933351	1.273202815249	-2.212401452371
H	0.739721103177	1.877547735688	-2.064323865411
C	1.626595741624	-0.255369631442	-4.432693433260
C	1.199497682422	-1.522630677031	-4.804545684062
C	2.912722233659	-0.030176652072	-3.966884016122
C	2.087467116949	-2.584521805117	-4.698982832263
C	3.791335291877	-1.103565611873	-3.860464696842
C	3.379702613649	-2.378926072129	-4.224976571392
H	0.188403346669	-1.688802992841	-5.156742718151
H	3.227544851285	0.968573129150	-3.684212283628
H	1.762954468124	-3.578326270817	-4.983296493783
H	4.795953474459	-0.935485443884	-3.491458106175
H	4.064888566216	-3.214477617836	-4.141279467255
C	-1.051204029435	1.123238381088	-1.124045270116
C	-0.722428545351	1.709011292231	0.120214530858
C	-2.283994852037	0.438543438613	-1.236469548648
C	-1.602015802597	1.648510998335	1.185579143549
C	-3.156327685839	0.384468237962	-0.163775108188
C	-2.826456278601	0.995421569251	1.046445484675
H	0.225564007969	2.225672616610	0.223189362840
H	-2.562091612674	-0.036943651214	-2.170224833793
H	-1.340334101405	2.116273766404	2.127754120074
H	-4.103417704607	-0.132283790810	-0.268324347215
H	-3.519387223099	0.957638104896	1.879573794945

C	1.298387063437	-0.843233158054	-1.143442217290
O	0.545881403885	-1.588808636078	-1.607858950792
O	2.050663556358	-0.105349943404	-0.666236775115

VI-anti

free energy = -902.237778525061 Hartree

N	0.985199380799	1.029569930536	-4.159177021848
H	1.665931703643	1.611536576694	-3.505602911267
C	1.248996849434	1.423373245865	-5.591763781185
H	2.180111023836	1.990806922823	-5.598187074574
H	1.375486631827	0.528661818408	-6.196561938118
C	0.054253350741	2.278959535333	-5.999558725536
H	-0.719161898177	1.654458507314	-6.454183518454
H	0.339594241984	3.049852294755	-6.715303083432
C	-0.446099689186	2.849448840624	-4.675267799192
H	0.197509199148	3.669072135106	-4.342083149486
H	-1.467062050810	3.22244922129	-4.736452501100
C	-0.326287260379	1.661438628157	-3.723861827094
H	-1.119453139197	0.938948114749	-3.927438895446
C	-0.235585387035	1.950677031032	-2.216494068350
H	0.070223296981	1.007878234620	-1.743329938980
C	1.105608501710	-0.387408083883	-3.857668518023
C	0.302734547499	-1.310138340420	-4.517468646706
C	2.023775182102	-0.789741046692	-2.898703798573
C	0.428073742084	-2.657895437348	-4.210678858992
C	2.141335884751	-2.142811872718	-2.596655932505
C	1.346383915696	-3.075631729036	-3.250697184296
H	-0.410067846847	-0.977395118789	-5.264203417484
H	2.633312234329	-0.050817149143	-2.391075878739
H	-0.193445822316	-3.383756366628	-4.722144481988
H	2.856557873555	-2.463387360191	-1.848153345670
H	1.440132109387	-4.129340393084	-3.013980380549
C	-1.548702074931	2.331177077632	-1.566806900616
C	-1.577338489828	2.488423309130	-0.175413492078
C	-2.747931623717	2.476542032529	-2.263485561068
C	-2.754768659988	2.793968945769	0.490410400211
C	-3.933621589088	2.785486532503	-1.597840424774
C	-3.943035248580	2.949074327281	-0.220480035211
H	-0.658407999934	2.372381019188	0.386657804440
H	-2.786831683064	2.342595139437	-3.337298939336

H	-2.747283947435	2.910125184228	1.569038442982
H	-4.851145731666	2.893498830872	-2.166331493731
H	-4.864883508592	3.189111175121	0.298024761223
C	0.954048711096	2.930183217498	-1.925645465466
O	0.806541380109	3.893579641518	-1.185177394937
O	2.041375764066	2.594223724066	-2.513168606060

VI-syn

free energy = -902.242161601798 Hartree

N	1.009979825927	1.026398293951	-4.440120992317
H	1.761299398505	1.563337244296	-3.834695062054
C	1.071632880616	1.571945976159	-5.847541868721
H	1.920512855412	2.255853573214	-5.884036350913
H	1.243250252544	0.755389469212	-6.544768842326
C	-0.249155532624	2.303817436105	-6.053963634308
H	-1.010451478991	1.612684700842	-6.425874565846
H	-0.145155383649	3.121124765129	-6.767735255898
C	-0.605885225216	2.773386425717	-4.647066841459
H	0.000007742970	3.640657778139	-4.366384090331
H	-1.657962933291	3.034644434600	-4.529795428710
C	-0.251304653340	1.569244277848	-3.783615584713
H	-1.025287923741	0.810304157850	-3.898146858086
C	0.004167030848	1.873737444480	-2.299332757188
H	-0.864796718884	2.442290100069	-1.957366726028
C	1.181391521656	-0.413317684848	-4.317029454752
C	0.285893872516	-1.274381313209	-4.938719239144
C	2.227009642811	-0.898188358588	-3.547273234878
C	0.437257306766	-2.644159176911	-4.772285534456
C	2.369623838901	-2.271616719745	-3.382766947825
C	1.474829164032	-3.144167164707	-3.990314548259
H	-0.525470075703	-0.879155565523	-5.540241698796
H	2.908129642722	-0.207460953596	-3.064547194787
H	-0.259982005661	-3.322136632928	-5.250735915928
H	3.179606790643	-2.655488902095	-2.773495765113
H	1.584909399189	-4.214198631301	-3.856094826149
C	0.107008181904	0.612102870769	-1.444271472144
C	1.181241180565	0.390828711037	-0.583021011195
C	-0.891182662648	-0.363481572849	-1.515599931437
C	1.272951515228	-0.781258328339	0.161267975825
C	-0.799321279568	-1.538529353496	-0.781075572411

C	0.289227214516	-1.756295778095	0.058142207250
H	1.968933496362	1.130536318722	-0.496276644587
H	-1.750462208603	-0.212966613501	-2.160950238107
H	2.123248412299	-0.932673828840	0.817483209453
H	-1.581470252695	-2.285489499598	-0.863906607636
H	0.365010121011	-2.675029265576	0.629189119751
C	1.244205461581	2.790155402582	-2.105392581458
O	1.188553576445	3.670750955510	-1.252273753127
O	2.250906541626	2.519481730528	-2.846977555184

3a-anti

free energy = -902.249388681679 Hartree

N	1.448877697172	1.073076682608	-4.207669294702
H	2.143947240843	2.023590577837	-2.905024895240
C	2.075682921438	1.622041064363	-5.438403931641
H	2.949926680821	2.226057644877	-5.176310117906
H	2.406842283337	0.810852391880	-6.088558948727
C	0.983594907165	2.474270407648	-6.077964484887
H	0.368753390722	1.856796800615	-6.738989972182
H	1.392474004720	3.300807776562	-6.660241784328
C	0.158082257482	2.935012545020	-4.881761188962
H	0.662860797359	3.762021511170	-4.371047689128
H	-0.845665627997	3.263795663405	-5.148955752764
C	0.124608388270	1.690626439311	-3.991802408973
H	-0.669539575106	1.025248405914	-4.350104054497
C	-0.148802645115	1.960463504492	-2.487689136036
H	0.017682888364	1.014554044808	-1.958780621926
C	1.645634348188	-0.292846115701	-3.920038054676
C	0.626745036447	-1.118628997689	-3.431280312496
C	2.923513359442	-0.843595446636	-4.098753173587
C	0.885118547180	-2.453851340781	-3.135812898822
C	3.166331593190	-2.177721969812	-3.809375458847
C	2.149605513136	-2.995430269019	-3.323241526500
H	-0.375989031792	-0.739298228401	-3.284018157142
H	3.732148502584	-0.216257852701	-4.455978679329
H	0.077833648451	-3.073699249261	-2.760574579108
H	4.163304772046	-2.578507105481	-3.957861294349
H	2.342929659148	-4.036797233625	-3.092926474039
C	-1.592811451597	2.349646890323	-2.272500758928
C	-2.508000441460	1.375366381434	-1.876361609881

C	-2.057058361202	3.641450595326	-2.527873939355
C	-3.858482555849	1.679940048872	-1.735094567537
C	-3.404566748125	3.948632268499	-2.387506488231
C	-4.310468762882	2.968882575364	-1.990626236485
H	-2.158614756321	0.367308189798	-1.674320850057
H	-1.359797486349	4.413980248322	-2.829642520047
H	-4.554765710057	0.909223300687	-1.422913741127
H	-3.748611590216	4.957820977191	-2.586655914796
H	-5.361751747916	3.211146943178	-1.879868688380
C	0.856671921100	2.917718562754	-1.843771708999
O	0.574451297024	3.759840335867	-1.031374317621
O	2.126428371386	2.714235456005	-2.196101394767

3a-syn

free energy = -902.246816652595 Hartree

N	1.040102803030	0.923496663953	-4.365642988983cd
H	1.873501483874	1.985068142183	-3.362601693404
C	1.209612818084	1.430721490029	-5.759895699349
H	1.998722355726	2.189011921693	-5.765849675753
H	1.515591645178	0.620248875379	-6.422250310669
C	-0.134827809965	2.044981822570	-6.142242541243
H	-0.798840449166	1.277502550270	-6.551323408001
H	-0.031709173120	2.841295655465	-6.880817784268
C	-0.666787514580	2.532087673202	-4.798157152549
H	-0.167417816697	3.463974393487	-4.510989039925
H	-1.743471936489	2.706626243684	-4.786617094989
C	-0.280895389280	1.393066627474	-3.855235066080
H	-1.021423419024	0.594442012372	-3.959417243483
C	-0.223635834064	1.792690569785	-2.364634304367
H	-1.197286556696	2.223222035580	-2.116954626943
C	1.273737249874	-0.489198511265	-4.210106711127
C	0.443514289631	-1.428114261018	-4.823426259587
C	2.338447871401	-0.921685355405	-3.428941300555
C	0.668864854860	-2.785615075322	-4.637868353276
C	2.562259905953	-2.282177617652	-3.241225491691
C	1.726257417545	-3.216501522731	-3.840981453320
H	-0.384634075256	-1.092285220680	-5.439449852102
H	2.980460269382	-0.188223356400	-2.954760242489
H	0.015939713586	-3.509239535391	-5.113440627496
H	3.389209430528	-2.609372089544	-2.620696635154

H	1.897202120759	-4.276583111730	-3.690190697815
C	0.008189549251	0.594012024236	-1.448608128675
C	1.109383607698	0.495058798285	-0.600539619174
C	-0.907021602334	-0.461429956782	-1.474226530784
C	1.305625503060	-0.637686311464	0.184194277966
C	-0.708372479274	-1.596819251102	-0.701125469711
C	0.404268702573	-1.692034538560	0.130306033166
H	1.841234967230	1.293613704832	-0.549688622170
H	-1.780684768135	-0.400573763342	-2.115010036043
H	2.173550277485	-0.694593098364	0.832000446181
H	-1.425759656875	-2.408998500273	-0.745981683871
H	0.562414398004	-2.579642599687	0.732727415322
C	0.798889479075	2.897288512168	-2.100421241200
O	0.591457597899	3.818563795830	-1.350315019513
O	1.960534550263	2.764601198243	-2.731657427879

TS II - V

free energy = -902.007808097151 Hartree

N	0.884869848384	0.945354311017	-4.243175050227
H	1.577737941531	1.703580268343	-3.442100142899
C	1.196111862864	1.339338101203	-5.658119092153
H	2.121052671342	1.919204706628	-5.645832113842
H	1.353197712209	0.449030840586	-6.264526467197
C	0.005663231526	2.177273535392	-6.116443694606
H	-0.734260639062	1.542168036926	-6.610434803260
H	0.303423636768	2.962912514613	-6.810757269199
C	-0.570100061762	2.725678849252	-4.813224531960
H	0.030463122858	3.564938976147	-4.449493675246
H	-1.598050570625	3.067921442174	-4.920908951233
C	-0.449490043276	1.528212938977	-3.870222225393
H	-1.236235688992	0.801069909321	-4.087423398017
C	-0.410320476891	1.810691559319	-2.358133229649
H	-0.116591897195	0.875928031656	-1.848628154944
C	1.034438263489	-0.462703113945	-3.938815570645
C	0.254209187513	-1.411580530183	-4.594534161939
C	1.963775717978	-0.852757658152	-2.983261854502
C	0.408626847967	-2.756261131070	-4.288361945994
C	2.112697493292	-2.202910062386	-2.679274091305
C	1.337369738723	-3.154109937297	-3.329612482631
H	-0.466100471061	-1.097013026571	-5.342241860156

H	2.567873237386	-0.106999276387	-2.479158181522
H	-0.196932226726	-3.496085470750	-4.799342170258
H	2.838236039391	-2.506704881131	-1.933515960557
H	1.455243075878	-4.205403419136	-3.092636794362
C	-1.673793031360	2.205115681798	-1.700066230240
C	-1.660364659874	2.288644154738	-0.254693999206
C	-2.881162351018	2.473362698035	-2.391012533033
C	-2.773076240616	2.674780300671	0.437723105652
C	-3.989249375349	2.856826798689	-1.693077557673
C	-3.944238872026	2.972011567600	-0.270800527096
H	-0.750404939043	2.024076041167	0.266777082308
H	-2.931954944098	2.377459908525	-3.465712275864
H	-2.759034581389	2.740287709071	1.517453135371
H	-4.916108275640	3.075056163186	-2.208302580392
H	-4.837985101271	3.276962686446	0.260587181927
C	0.770780541687	2.788860274207	-1.990668038754
O	0.636632045313	3.664313388558	-1.164320826864
O	1.851168639185	2.524030396732	-2.643445096437

V

free energy = -902.064359444490 Hartree

N	1.190287996452	0.875203448927	-4.487014707043
H	1.464750331054	3.288517468128	-0.400832456449
C	1.928753317951	1.664947182586	-5.481627962338
H	2.622559155448	2.320534548774	-4.949039363366
H	2.478649044901	1.003317375276	-6.147101877191
C	0.823502382857	2.453873704164	-6.169987397799
H	0.342378741629	1.828813136071	-6.926307089414
H	1.214322238142	3.348859234447	-6.652427232606
C	-0.142452079961	2.767136409505	-5.031442169780
H	0.204971315029	3.638258677355	-4.474574444418
H	-1.157498705284	2.961019390570	-5.374406311507
C	-0.099288785582	1.515762603805	-4.143192682856
H	-0.891552579756	0.823165757044	-4.440054509954
C	-0.261311175868	1.775981599658	-2.628347481095
H	-0.216486627031	0.820145834969	-2.099295384741
C	1.607307163505	-0.316690947488	-4.019192315979
C	0.703998081420	-1.216502061750	-3.383951966571
C	2.973324636305	-0.691607946848	-4.164487153956
C	1.162227426497	-2.423750058039	-2.913715768667

C	3.407636156756	-1.898437333726	-3.671625614488
C	2.511227996248	-2.771173156730	-3.045211270491
H	-0.350073556019	-0.982512646023	-3.318902117378
H	3.674890114048	-0.007597925029	-4.622327636926
H	0.468358071711	-3.114332524207	-2.450869052198
H	4.451867908792	-2.169757794302	-3.764708514123
H	2.861871881425	-3.723381613518	-2.665815222899
C	-1.634518198551	2.362934062693	-2.351218686981
C	-2.702215683967	1.494137818448	-2.129361422327
C	-1.869711617310	3.737581677034	-2.362060189799
C	-3.984684370699	1.988285795114	-1.922267649990
C	-3.151152979110	4.232838795223	-2.151976234032
C	-4.211809118374	3.360098501019	-1.932834559235
H	-2.524054066769	0.423346682402	-2.116287538203
H	-1.052436150816	4.430786717096	-2.533267590510
H	-4.804822067095	1.300801542115	-1.747718783106
H	-3.320303736536	5.303815969033	-2.159036861300
H	-5.210753733888	3.748259360917	-1.768145621539
C	0.884472696928	2.578424446400	-2.036769511014
O	1.873438447082	2.936961581817	-2.625013725587
O	0.696998924421	2.800716837061	-0.736121752141

MESX VI-*anti* - II

free energy = -902.217042948025 Hartree

N	1.088333606005	1.022371539252	-4.333495929982
H	1.867107665776	1.548809150604	-3.930727109090
C	1.058278618208	1.381766765716	-5.819786089899
H	1.971006569717	1.940992331070	-6.016119807306
H	1.067983294173	0.460830837502	-6.395249883384
C	-0.201688511353	2.219729928456	-6.007650643205
H	-1.030032897439	1.585705942422	-6.331426132881
H	-0.047541307425	2.996614151324	-6.755599706687
C	-0.486458142791	2.781000171109	-4.618679556328
H	0.184820110657	3.613349956807	-4.383691002585
H	-1.515656216470	3.114712383555	-4.497058623751
C	-0.189457397164	1.603127881974	-3.704562949573
H	-0.956379254989	0.838958155541	-3.821970523256
C	0.052704106700	1.931152418635	-2.246860614954
H	0.806098443598	2.712870919013	-2.147775539226
C	1.327795935362	-0.393622900898	-4.036713354969

C	0.440626845464	-1.347033745497	-4.514117174515
C	2.413140481723	-0.735530012631	-3.247808499555
C	0.645251384575	-2.677315955120	-4.177067612714
C	2.606289723024	-2.070813861573	-2.913581035551
C	1.722516888738	-3.039408038159	-3.373521968914
H	-0.404557506311	-1.057705500971	-5.128864165983
H	3.089803713487	0.030169125083	-2.884692796600
H	-0.042967312435	-3.431370913673	-4.539935396992
H	3.447331187208	-2.348835144693	-2.289703499300
H	1.873435606706	-4.079490215540	-3.108675041882
C	0.270758867281	0.830134254212	-1.298109833163
C	1.242852081983	0.977996417580	-0.294300907805
C	-0.468601620856	-0.365751636938	-1.352787057521
C	1.510479447313	-0.057149573315	0.586138884961
C	-0.196523279362	-1.397206079957	-0.472632090890
C	0.797150538439	-1.250347606520	0.495465059446
H	1.801424972506	1.905899283983	-0.233021422505
H	-1.248284877949	-0.487700624398	-2.094789918781
H	2.276920724470	0.061575458437	1.343453043795
H	-0.759989386870	-2.321041952262	-0.535546465235
H	1.009047673735	-2.062410222338	1.181832527742
C	-1.416838373233	2.715423097661	-1.661297251280
O	-2.402782963454	2.155951497879	-2.096522962521
O	-1.118334409787	3.639989135684	-0.938017779167

MESX VI-syn - II

free energy = -902.205681828245 Hartree

N	0.975191653795	1.031745924838	-4.659139686579
H	1.852164481961	1.464966948161	-4.355705718582
C	0.768960060467	1.465539538751	-6.111435371819
H	1.715893277889	1.886314989562	-6.442947044735
H	0.539781477634	0.580792886755	-6.698497620848
C	-0.363985674297	2.489692483336	-6.070194629771
H	-1.312222334356	2.008765658107	-6.317928411410
H	-0.188590466068	3.297239998604	-6.779636234099
C	-0.380782684000	2.972268160090	-4.621265701428
H	0.423436378665	3.690835342235	-4.447533742248
H	-1.327254364974	3.427074843989	-4.329665003709
C	-0.130653268280	1.687502533454	-3.850410348445
H	-0.998048364551	1.033928210379	-3.953261943170

C	0.246203470260	1.750794346071	-2.363372952535
H	0.478687012781	0.723655464714	-2.050802515354
C	1.121095927699	-0.414873453206	-4.457286067621
C	0.061589292371	-1.258073261465	-4.762019428553
C	2.322038512634	-0.898285542214	-3.966630119661
C	0.215576179718	-2.621851330566	-4.556285556837
C	2.463973937049	-2.267132161006	-3.765068709988
C	1.412696946417	-3.126703741480	-4.056297127676
H	-0.866538530424	-0.864078267013	-5.159844089229
H	3.136937527850	-0.218645362345	-3.744024133409
H	-0.603916617647	-3.291111257357	-4.789235556078
H	3.398941580148	-2.655502994755	-3.379347298241
H	1.524698782874	-4.192782901657	-3.896520524679
C	1.425383754924	2.631190307487	-2.009245549133
C	1.315339816377	4.025114227976	-1.996313591599
C	2.653025360931	2.046539460064	-1.697132719594
C	2.416617915524	4.814064380516	-1.690588764384
C	3.755780571198	2.836840437638	-1.393920035849
C	3.639714422600	4.222080375601	-1.392147799001
H	0.365477216127	4.498385248007	-2.219304793181
H	2.741889047197	0.965393217458	-1.685457692173
H	2.317051270370	5.893511252461	-1.682190064732
H	4.703001673280	2.368142073637	-1.152317594139
H	4.498519902760	4.839214897840	-1.153030093776
C	-0.980451654557	2.090627757934	-1.554668812836
O	-0.912655758862	2.707538103239	-0.456447481595
O	-2.138164637488	1.760017296153	-1.853224300258

VII-anti

free energy = -901.770216155390 Hartree

N	1.184848236681	0.882821019396	-4.446526489979
C	1.929385470019	1.737791637153	-5.359277982245
H	2.581823678829	2.433843473702	-4.815979397588
H	2.547200045181	1.140216067356	-6.033662644504
C	0.821100583029	2.482302583332	-6.096770408743
H	0.431792087708	1.847677642474	-6.899347616569
H	1.168629544258	3.418599683199	-6.538490553163
C	-0.231888143243	2.692855555372	-5.009416589943
H	0.029708588313	3.566154240346	-4.412120699738
H	-1.240123218458	2.814773798198	-5.409026567480

C	-0.124965415371	1.446034973356	-4.110873641189
H	-0.910597980832	0.727711576255	-4.384869595952
C	-0.269789333850	1.735364580831	-2.592945690239
H	-0.250327598966	0.772073104678	-2.080504803362
C	1.631817691184	-0.338998572011	-4.022428695606
C	0.763998571860	-1.283580688482	-3.431104925869
C	2.984464380133	-0.712355994772	-4.177586228590
C	1.230564956914	-2.527752862069	-3.033050149897
C	3.430706209700	-1.963693333690	-3.776725013099
C	2.564921163001	-2.888133143196	-3.200024151243
H	-0.283918557723	-1.048686014743	-3.295431365567
H	3.692436952591	-0.008449233903	-4.597416158083
H	0.531968820191	-3.228984179126	-2.587265664598
H	4.478902820849	-2.212542695968	-3.910360186261
H	2.921214666002	-3.861848720865	-2.884152249568
C	-1.627795187380	2.347198642027	-2.317671071664
C	-2.734683361911	1.503982031182	-2.173571743675
C	-1.836378674271	3.726633505392	-2.232073988166
C	-4.009064572908	2.016450903170	-1.957421980598
C	-3.109687152272	4.242583080178	-2.011558541909
C	-4.202274665146	3.392039403204	-1.875971669329
H	-2.590212611060	0.428503458059	-2.228838979157
H	-0.980533646521	4.384205923095	-2.334191944953
H	-4.850968501103	1.340701799747	-1.847572908607
H	-3.248577361560	5.316877902035	-1.944244773654
H	-5.194102131517	3.796470537107	-1.704500997568
C	0.936132991713	2.532343588062	-2.002368470282
O	1.211915212679	3.644457997434	-2.516755210589
O	1.520116696263	1.980474020479	-1.049509376769

VII-syn

free energy = -901.766765420997 Hartree

N	0.873376098970	0.693397245495	-4.389162740030
C	1.623806998992	1.633852257650	-5.210697662661
H	2.214290638832	2.303961156329	-4.578169180249
H	2.287823265130	1.108296857373	-5.898185832075
C	0.522095268765	2.390627762850	-5.950713194959
H	0.211439021127	1.808549610552	-6.823382072779
H	0.849478663083	3.373405795493	-6.296567587094
C	-0.616008179207	2.471192798050	-4.927511030011

H	-0.573715178311	3.409904300220	-4.371400512220
H	-1.598332340277	2.415082216452	-5.400310167740
C	-0.395216673472	1.279690874646	-3.962081758586
H	-1.194837814284	0.545330254598	-4.097489567566
C	-0.444522480373	1.740429403525	-2.472653659661
H	-1.475901233910	2.075923260434	-2.327204114020
C	1.220647005406	-0.626414080355	-4.249715425664
C	0.294571146363	-1.614118215634	-3.847684658640
C	2.543119307593	-1.054141338244	-4.497419125289
C	0.675065583434	-2.939446644974	-3.710897997365
C	2.905064355686	-2.387715852442	-4.361060066470
C	1.981753279394	-3.349673763961	-3.965994944549
H	-0.726441535641	-1.342149621942	-3.618626304396
H	3.301733261275	-0.330243042847	-4.768083354601
H	-0.068920727028	-3.664389153818	-3.395209654633
H	3.935008203891	-2.671291000484	-4.554711702764
H	2.272094799019	-4.387685574077	-3.851626309426
C	-0.208949257263	0.589930422307	-1.520051452469
C	1.073650283855	0.188686509301	-1.135716128904
C	-1.299107204596	-0.145466628967	-1.047140325646
C	1.258244023624	-0.926071116229	-0.326704043167
C	-1.118343271955	-1.263994342708	-0.240346872679
C	0.164943010570	-1.664111443195	0.118149907099
H	1.913291325917	0.771025402739	-1.494510060448
H	-2.304277663295	0.155010442725	-1.329982714315
H	2.263269124712	-1.226645067041	-0.047894970081
H	-1.980502622804	-1.823647986579	0.107773362780
H	0.311011617392	-2.538533537434	0.743432421115
C	0.444682149467	2.997436534844	-2.204496952844
O	-0.184712699805	4.050377896540	-1.966712389843
O	1.687796888736	2.860848174825	-2.269202875146

MESX VII-*anti* - VIII-*anti*

free energy = -901.769701078434 Hartree

N	0.991853185662	0.735446813791	-4.794861399353
C	1.896559808244	1.704188897140	-5.395130893816
H	2.494499483629	2.259669391463	-4.658465343784
H	2.580342538848	1.209722473645	-6.091873212068
C	0.924220851413	2.632240374799	-6.113587700673
H	0.629339847416	2.178657376225	-7.064959720741

H	1.357928991902	3.612380851033	-6.326798074035
C	-0.27222322420	2.713757490269	-5.154587571704
H	-0.153078509528	3.575156120512	-4.500427267282
H	-1.222564028122	2.797437519730	-5.686681609885
C	-0.209436813296	1.428938239775	-4.293974915689
H	-1.087328951056	0.804660630501	-4.500866297664
C	-0.215086872935	1.696963554795	-2.765399483664
H	-0.154197207903	0.722983534967	-2.276122606752
C	1.494858589633	-0.388085529680	-4.143245429183
C	0.627847223202	-1.348134566886	-3.592213329382
C	2.869442084632	-0.647463988180	-4.057205567433
C	1.115984655900	-2.506923712479	-3.002180175238
C	3.348231743847	-1.821386142305	-3.474435110077
C	2.483263225291	-2.763385795543	-2.937951249186
H	-0.443650149444	-1.187235862215	-3.632850649331
H	3.580411441499	0.071247450014	-4.446237710729
H	0.410302508608	-3.221609808369	-2.588800479753
H	4.421348678893	-1.984854466533	-3.435260945090
H	2.859599138519	-3.669690076050	-2.476980121122
C	-1.550703465410	2.290635672826	-2.363680265217
C	-2.642653379722	1.434973809965	-2.177705455631
C	-1.760688929440	3.662926997616	-2.200422671448
C	-3.900219829202	1.926926921790	-1.846954624168
C	-3.017508541994	4.159273958533	-1.865773774104
C	-4.094019739721	3.296150245220	-1.689930155482
H	-2.498267783624	0.364017999853	-2.291973558069
H	-0.918121151877	4.332172626495	-2.333770483437
H	-4.728408799512	1.239820725702	-1.706518838477
H	-3.155412178254	5.228610268748	-1.740512743850
H	-5.072565815685	3.684971816822	-1.428927026958
C	1.011851514413	2.493571933105	-2.220466290825
O	1.253401017780	3.618848830229	-2.725469676070
O	1.642609192818	1.938534710669	-1.298406698650

MESX VII-syn - VIII-syn

free energy = -901.765654726741 Hartree

N	0.536521130767	0.521620305448	-4.832374260865
C	1.416871323869	1.564765738294	-5.356582260956
H	2.189061821182	1.870816079958	-4.643983172162
H	1.910107683820	1.206100950546	-6.267397501501

C	0.468245014597	2.747536134077	-5.637597414957
H	0.395999805105	2.965578264186	-6.705938884722
H	0.825654830045	3.648086437191	-5.136138758582
C	-0.894028187779	2.317618249657	-5.059151239063
H	-1.402120854100	3.140028336197	-4.554655549661
H	-1.542393316853	1.939207126411	-5.854547401702
C	-0.563600529762	1.166532825407	-4.097857666818
H	-1.408364938893	0.471094787977	-4.056198664078
C	-0.359880092025	1.673835547543	-2.635380150537
H	-1.332866845519	2.112478935862	-2.391880489574
C	1.120563175713	-0.671640415507	-4.373492285887
C	0.316741733252	-1.744197071704	-3.954742712349
C	2.500344959670	-0.882734099303	-4.387624430824
C	0.869704306490	-2.942354550736	-3.531782331732
C	3.052620744451	-2.102372926507	-3.978865401361
C	2.251647607562	-3.139079247663	-3.535255362898
H	-0.760351600610	-1.623438776117	-3.928968118157
H	3.167729134624	-0.092634818655	-4.709308134308
H	0.209636079156	-3.737515607064	-3.197320386619
H	4.132050676804	-2.222020905357	-4.005448785386
H	2.681800751422	-4.078774140328	-3.207072257521
C	-0.173032179388	0.522717785570	-1.659782107257
C	1.072503376433	0.076635234247	-1.211900157388
C	-1.308085412101	-0.160129165092	-1.213352374561
C	1.177733237611	-1.023580504940	-0.368667563946
C	-1.208740755683	-1.268267248750	-0.377741647887
C	0.039611180583	-1.709990230482	0.046612501189
H	1.949264986655	0.615342999118	-1.546523455959
H	-2.289580260898	0.175659428797	-1.538221364801
H	2.158222948793	-1.355629387187	-0.041300908073
H	-2.108287987285	-1.783605587529	-0.056018205932
H	0.124353095050	-2.574407513103	0.696953704533
C	0.637471128809	2.867234845465	-2.493121275993
O	1.861154984443	2.622522492079	-2.375159365274
O	0.105843115992	3.999902375946	-2.525903850426

VIII-anti

free energy = -901.598479448646 Hartree

N	1.225999124502	0.936434076601	-4.394885497154
C	1.929093929257	1.656741212662	-5.463397518349

H	2.690700015189	2.289247830912	-5.003034830671
H	2.404815110917	0.943587142531	-6.135586913742
C	0.824696068120	2.478127100643	-6.118596859389
H	0.308402653503	1.873111123568	-6.868580635256
H	1.221713062910	3.369234185064	-6.604264816626
C	-0.107971843984	2.798416074697	-4.954356658335
H	0.287144613140	3.635957542062	-4.374818107798
H	-1.120433998208	3.045817225391	-5.271121835251
C	-0.089522240308	1.524441528504	-4.103760819185
H	-0.850337307647	0.824954643020	-4.470082049201
C	-0.286390193616	1.742152893610	-2.593551082170
H	-0.249982341106	0.764695879714	-2.102773421359
C	1.629643294352	-0.315704935736	-3.969117479799
C	0.707746818093	-1.244673687180	-3.458000693520
C	2.989187377904	-0.662246247180	-4.053818011440
C	1.146784339592	-2.491150150731	-3.044329020174
C	3.411052890919	-1.908650911448	-3.628398909371
C	2.495161744407	-2.828570060853	-3.121648677444
H	-0.347851849238	-1.011280347174	-3.415511336969
H	3.708706370616	0.056183599381	-4.424567605841
H	0.427597333851	-3.206988193463	-2.663976741858
H	4.462813789611	-2.163234554310	-3.686295859146
H	2.831006210297	-3.804533768135	-2.791247495789
C	-1.650324787764	2.326592417041	-2.311731301988
C	-2.728002922233	1.471396571775	-2.078089809858
C	-1.886321302871	3.702904432959	-2.335977429789
C	-4.010474627914	1.971708717940	-1.876197505360
C	-3.165547258984	4.207057536624	-2.135138479967
C	-4.233045701774	3.343545914591	-1.905451119888
H	-2.557788111181	0.398981280117	-2.052259177590
H	-1.058670743691	4.382452671241	-2.498276789575
H	-4.833576746553	1.289298484686	-1.693462580606
H	-3.329841450548	5.279187104828	-2.154417261061
H	-5.230386633304	3.738949632193	-1.746395244984
C	0.930962383026	2.514479342777	-2.001901261022
O	2.007748300629	2.332324035610	-2.637510241476
O	0.778375568091	3.168734567500	-0.967874525985

VIII-syn

free energy = -901.598242559169 Hartree

N	0.814473824788	0.734662149505	-4.524423420228
C	1.458902075280	1.651382321347	-5.468730644307
H	2.097206117886	2.322676761909	-4.888985730377
H	2.045722242357	1.092925736095	-6.194816956254
C	0.264773732455	2.385093538926	-6.068514374126
H	-0.186161669038	1.772291291663	-6.853095257016
H	0.559883421908	3.341441546881	-6.499750083559
C	-0.686956223323	2.535360724296	-4.881070622102
H	-0.451893184535	3.440345498920	-4.316483954683
H	-1.732645831588	2.590588405406	-5.182772692101
C	-0.435963362654	1.295474330149	-4.004077166939
H	-1.225778661924	0.554005808906	-4.147958092008
C	-0.377346376410	1.650654232582	-2.486911645816
H	-1.356266801271	2.097983342511	-2.294096678502
C	1.278734146716	-0.513016072231	-4.253844966305
C	0.408390356242	-1.540124816240	-3.814706883818
C	2.658735333569	-0.792683814145	-4.408344645907
C	0.912066724219	-2.789971453297	-3.523915206318
C	3.143531495980	-2.041763261915	-4.088808219794
C	2.277836216630	-3.045671373505	-3.645449123569
H	-0.654103140171	-1.358856609338	-3.741037694667
H	3.335097955003	-0.008342747929	-4.721655445261
H	0.237628120834	-3.574017843887	-3.201948788845
H	4.204596261231	-2.241545901776	-4.176917826610
H	2.668556190825	-4.026873670758	-3.403016866873
C	-0.239693205938	0.452063332301	-1.574109504880
C	0.996340579804	0.018019856132	-1.087020987415
C	-1.384259451071	-0.268632216271	-1.218415857650
C	1.084714349959	-1.110673757956	-0.279858601947
C	-1.297099796848	-1.401996846906	-0.420401561838
C	-0.058384718201	-1.829959105517	0.049965047852
H	1.887068969948	0.571096644790	-1.360843618174
H	-2.352781071717	0.060603426528	-1.583440390572
H	2.053748786121	-1.433867983875	0.085416419778
H	-2.196588657108	-1.950228475401	-0.161307765589
H	0.011973488682	-2.713765531646	0.674696621937
C	0.703626602306	2.744684861585	-2.218453495142
O	0.313492448109	3.761283904946	-1.622978605482
O	1.857289149911	2.476574533154	-2.631876432903

TS VIII-*anti* – IX

free energy = -901.584322671860 Hartree

N	1.297746162719	0.996775679663	-4.480067268621
C	2.278839197710	1.745808820459	-5.252934098014
H	2.980328309715	2.267390327433	-4.589794159913
H	2.844220863635	1.076935368686	-5.903567761899
C	1.412569022959	2.726031811119	-6.034081737848
H	1.016338763288	2.232712791823	-6.925572495306
H	1.964126502119	3.613931004843	-6.344913099590
C	0.282400224030	3.050881672283	-5.058561675064
H	0.574198683713	3.871042102139	-4.399307410394
H	-0.636577128226	3.344856022980	-5.564460865683
C	0.087591024622	1.748210913047	-4.253215112074
H	-0.770532605750	1.195394649825	-4.665738244856
C	-0.263702148593	1.880585951295	-2.761789949601
H	0.056705185740	0.997165111994	-2.213494980830
C	1.498240542723	-0.309238448925	-4.072912893725
C	0.427706599886	-1.133008201729	-3.677077778486
C	2.793452557314	-0.854783117020	-4.056118234546
C	0.653708114218	-2.446487041597	-3.293806577908
C	3.001265335263	-2.173279743327	-3.674062328470
C	1.938368825403	-2.982499781621	-3.288822939402
H	-0.587310785385	-0.755289205856	-3.677195584677
H	3.643398554388	-0.240957891656	-4.326678603782
H	-0.191680898092	-3.059361215687	-2.999380051176
H	4.012736547666	-2.565560697962	-3.669880582020
H	2.106607374217	-4.009732239057	-2.986971900811
C	-1.644292008557	2.236737476257	-2.382199865867
C	-2.248810866238	1.536336470412	-1.331035344058
C	-2.372390532617	3.249523561874	-3.021034892634
C	-3.550437297058	1.822144248606	-0.940100450002
C	-3.671929303316	3.533626405949	-2.631810478281
C	-4.265652477677	2.820855215605	-1.591449778387
H	-1.689858586371	0.756411085798	-0.823784400513
H	-1.919923532032	3.823818678029	-3.819353639792
H	-4.005650855556	1.265963347282	-0.128377601513
H	-4.225536129532	4.317464833975	-3.136546351242
H	-5.281983437023	3.047854454798	-1.289107556883
C	0.927800837483	3.055407271628	-2.107430968879
O	0.418952609692	4.084665643699	-1.742329887525

O	2.006728006507	2.507783950908	-2.186641575724
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TS VIII-syn – IX

free energy = -901.584258032365 Hartree

N	0.947742857753	0.749376631649	-4.446291639992
C	1.675869062316	1.674513570710	-5.313920274530
H	2.284643085093	2.365684223830	-4.721915016279
H	2.328829094308	1.126828063957	-5.994073384025
C	0.556665036146	2.407819906479	-6.048280343411
H	0.214188347984	1.797513670362	-6.888612258333
H	0.872960966225	3.379155465064	-6.431066630231
C	-0.538289624190	2.520271742851	-4.989163554767
H	-0.381525254723	3.415866877168	-4.385526461272
H	-1.541320190962	2.579126363179	-5.412109266296
C	-0.370949428873	1.243024748674	-4.138706063981
H	-1.125905895543	0.511516673948	-4.467163418405
C	-0.743853963856	1.425253760595	-2.660798232951
H	-1.796834397315	1.698754516837	-2.612604866500
C	1.328608484504	-0.573094647867	-4.293951696326
C	0.405366683860	-1.588131781015	-3.985227958860
C	2.683889403120	-0.930707077488	-4.411548892760
C	0.827051247063	-2.897171020834	-3.803517787984
C	3.089561431676	-2.245117797707	-4.231545093184
C	2.169240011501	-3.242104894580	-3.922769618631
H	-0.646735345313	-1.360840391025	-3.872020756812
H	3.426113385000	-0.168550258056	-4.615565093862
H	0.090058258675	-3.656348868084	-3.563671679150
H	4.143352111614	-2.487242064691	-4.321605157383
H	2.492176103050	-4.266174134389	-3.775407889575
C	-0.411010326585	0.425154339457	-1.630056063721
C	0.908870354708	0.043712397913	-1.333948686893
C	-1.459065711567	-0.169489085228	-0.910191813259
C	1.162451144475	-0.928806367141	-0.381147520347
C	-1.202339873345	-1.155707258168	0.030560242090
C	0.109274036220	-1.540399620795	0.294908528903
H	1.728757658923	0.523284449893	-1.850709780878
H	-2.480794416301	0.133390320541	-1.113689162849
H	2.185618846198	-1.215836450846	-0.166626266424
H	-2.024434507229	-1.621920916384	0.561709863159
H	0.310861344357	-2.307821467298	1.033979116080

C	0.091257486072	2.938819813848	-2.064168660827
O	1.261850027057	2.902649866533	-2.345587702286
O	-0.752071662804	3.606689381695	-1.521658756008

IX

free energy = -901.626866832498 Hartree

N	0.885122522870	0.750839937278	-4.409763960375
C	0.630007443092	1.681118801671	-5.519210395315
H	1.304357323042	2.542406337412	-5.469035029323
H	0.793721552754	1.188686094394	-6.482638808111
C	-0.830272157957	2.101222921544	-5.341545199434
H	-1.479566690686	1.441793104986	-5.924391502619
H	-1.006734208953	3.127750950278	-5.665845755164
C	-1.085710627386	1.893188329051	-3.852498627116
H	-0.678034625646	2.724730730581	-3.270612762687
H	-2.139858442725	1.776598990261	-3.597992977579
C	-0.287742923730	0.614809913960	-3.541450964049
H	-0.886821755567	-0.256477716336	-3.851445990071
C	0.074309227678	0.495419281846	-2.096896624045
H	1.054995839456	0.853754227473	-1.798696289642
C	1.790228783913	-0.283445048253	-4.565596711725
C	1.682044899133	-1.486990475615	-3.845267970057
C	2.873368768526	-0.145828604608	-5.454766745265
C	2.622369243634	-2.497019003541	-4.008677105654
C	3.799618454867	-1.166370003215	-5.610356228671
C	3.687669896295	-2.352690152958	-4.890259480672
H	0.862119328124	-1.640049520506	-3.155003985286
H	2.999481296876	0.775543547302	-6.010447509689
H	2.509789998096	-3.413852802408	-3.439020425362
H	4.624412971814	-1.026805091431	-6.301753103363
H	4.416068623495	-3.145888061303	-5.013551558661
C	-0.776942379672	-0.010733336207	-1.090590300738
C	-0.325434926788	-0.052852108200	0.256114322875
C	-2.087701263416	-0.490910858776	-1.353630539822
C	-1.129965784431	-0.542381608399	1.266628300267
C	-2.883083042388	-0.978785255375	-0.331660992735
C	-2.415881609814	-1.010246967436	0.983113746488
H	0.672962070600	0.308486817899	0.482105809168
H	-2.476394736438	-0.474416858463	-2.365430899166
H	-0.759548264956	-0.563539983546	2.285992408604

H	-3.881013524558	-1.339349220139	-0.557711354632
H	-3.045723472211	-1.393800969501	1.777759572010
C	2.738430646501	2.838955082024	-2.975730800178
O	3.547555407717	2.031969394338	-2.800904364191
O	1.952264431457	3.673391772941	-3.133693410139

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Acknowledgements

All the studies in this thesis were carried out under Professor Satoshi Maeda, Department of Chemistry, Faculty of Science, Hokkaido University. I am very grateful for his careful guidance, giving me a lot of advice and answering my questions until I understood.

All the studies about organic synthesis in my thesis have been conducted under Professor Tsuyoshi Mita, Institute for Chemical Reaction Design and Discovery (WPI-ICReDD), Hokkaido University. He took care of me, sometimes strictly, but carefully. I would like to thank him very much.

I appreciate the kind support of Prof. Harabuchi especially in the study of crossing points. I would not have been able to complete my research without him.

I would like to thank seniors, Dr. Hiroki Hayashi, Dr. Hideaki Takano, and Dr Kosaku Tanaka, III for kind instruction about experimental techniques and daily fruitful discussions.

I would also like to thank my co-workers in Mita group in WPI-ICReDD, Ms. Hitomi Katsuyama, Dr. Yong You, Dr. Saeesh R. Mangaonkar, Dr. Vishal Kumar Rawat, Dr. Chandu G. Krishnan, Dr. Suvankar Debbarma, Dr. Shun Zhou, Dr. Tavinder Singh, and Ms. Yan Song, and Dr. Simon Cooper for help in daily research life. I am thankful to people in WPI-ICReDD for kind advice and instruction of measuring instruments.

I would like to thank my coworkers in Theoretical Chemistry Laboratory (TCL), especially, Mr. Yamato Ueno, Mr. Kenta Miyauchi, who studied with me under Prof. Mita.

I am thankful to secretaries of TCL, Madoka Kurihara, Machiko Terashima, Takako Homma, Mami Aoki, Kazuhiro Namba, Yoko Iwatani, and Tomoko Namikawa for kind help of my academic life.