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COMPUTATIONAL MODELING OF ELECTRONICALLY EXCITED STATES IN COBALAMIN-
DEPENDENT REACTIONS

By

Brady D. Garabato

A Dissertation Submitted to the Faculty of the
College of Arts and Sciences of the University of Louisville in Partial Fulfillment of the Requirements
for the Degree of

Doctor of Philosophy in Chemistry

Department of Chemistry
University of Louisville
Louisville, Kentucky

May 2018

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DEPENDENT REACTIONS

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A Dissertation Approved on

April 12, 2018

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Dr. Lee M. Thompson

DEDICATION

This dissertation is dedicated to the blessings of my late grandfather

Davis Garabato and my grandmother Myrtle Jo Brady

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my mentor Prof. Pawel Kozlowski. It has been a pleasure knowing and working with him throughout my graduate studies, and I am truly grateful to have had the opportunity to be a part of his research family. His expertise, guidance, and patience throughout my studies have been critical to my development as a scientist and person. I am sincerely thankful to have worked with him and our collaborators in several diverse and interesting projects that challenged my skills and thinking.

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ABSTRACT

COMPUTATIONAL MODELLING OF ELECTRONICALLY EXCITED STATES IN COBALAMIN-DEPENDENT REACTIONS

Brady D. Garabato

April 12, 2018

The current understanding of the photolytic properties of Vitamin B₁₂ derivatives or cobalamins are summarized from a computational point of view. The focus is on two non-alkylcobalamins, cyanocobalamin (CNCbl) and hydroxocobalamin (HOCbl), two alkylcobalamins, methylcobalamin (MeCbl) and adenosylcobalamin (AdoCbl), as well as the stable cob(II)alamin radical. Photolysis of alkylcobalamins involves low-lying singlet excited states where photo-dissociation of the Co-C bond forms singlet-born alkyl/cob(II)alamin radical pairs (RPs). Potential energy surfaces (PESs) of low-lying excited states as functions of both axial bonds provide the most reliable tool for analysis of photochemical and photophysical properties. Due to the size limitations associated with the cobalamins, the primary method for calculating ground state properties is density functional theory (DFT), with time-dependent DFT (TD-DFT) mainly used for electronically excited states. The energy pathways on the lowest singlet surfaces of the alkylcobalamins, connect metal-to-ligand charge transfer (MLCT) and ligand field (LF) minima associated with photo-homolysis of the Co-C bond observed experimentally. Additionally, energy pathways between minima and seams associated with crossing of S₁/S₀ surfaces are the most efficient for internal conversion (IC) to the ground state. Depending on the specific cobalamin, such IC may involve simultaneous elongation of both axial bonds (CNCbl), or detachment of axial base coupled with corrin ring distortion (MeCbl). The possible involvement of triplet RPs is also discussed, and a mechanism of intersystem crossing based on Landau-Zener theory is presented.

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CHAPTER I INTRODUCTION

1.1 Scope of dissertation

This dissertation provides an in-depth description of the photochemical and photophysical properties of the cobalamins, known as Vitamin B₁₂ derivatives. Quantum computational methods were employed to elucidate photo-reaction mechanisms at the DFT, TD-DFT and multiconfigurational levels of theory. Energetic relationships and the character of excited states for photoreaction intermediates were determined by orbital analysis in accord with experimental data from ultra-fast transient absorption spectroscopy.

Chapter 1 introduces the cobalamins, their structural and chemical properties, as well as a brief synopsis from their discovery to their potential use as photocatalysts. General mechanisms of photostability and photolysis are discussed, as well as the conditions for generating alkyl and cob(II)alamin RPs. In Chapter 2, the electronic structures of cob(II)alamin are presented at the multiconfigurational and DFT levels. Enhanced reactivity associated with cob(II)alamin is associated with axial base detachment, and is attributed to increasing $d_{yz} + \pi \rightarrow d_z^{2*}$ character of the D₁ state with respect to dissociation that lowers the energy of the anti-bonding d_z^2 orbitals leading to near-degeneracy of the ground and D₁ states. Cob(II)alamin is stable and is regarded as an intermediate that acts as a conductor between the Co(I) and Co(III) oxidation states.

Chapter 3 highlights the theoretical and physical understanding of the photo-properties of two non-alkylcobalamins, cyanocobalamin (CNCbl) and hydroxocobalamin (HOCbl). Potential energy surfaces (PESs) of the low-lying excited states as functions of both axial bonds provide the most reliable analysis, and was also recently structurally validated by ultrafast polarized x-ray absorption near-edge structure (XANES). Energy pathways between minima and seams associated with crossing of S₁/S₀ surfaces are the most efficient path for internal conversion (IC) to the ground states, while depending on the specific cobalamin, IC that involves simultaneous elongation of both axial bonds may also, as in the case of HOCbl, compete with lower wavelength excitation in the controlled catalytic production of hydroxyl radicals.

In Chapter 4 a comprehensive theoretical analysis is presented for the influence of the axial base on the photolysis and electronic structures of the biologically active B₁₂ cofactors MeCbl, and AdoCbl. The axial nitrogenous base is sensitive with respect to environment, especially in strongly acidic conditions when replaced by water. Experiment has shown that absence of the axial base opens a channel for fast non-radiative decay to the ground state, and a decreased photolysis quantum yield from unity to 0.65 for MeCbl, and 0.13 for AdoCbl. To explain this, S₁ surfaces were determined by TD-DFT and characterized by two different regions of charge transfer (CT), MLCT, and ligand-field (LF). When the axial base is attached the barriers between these regions are significantly higher, resulting in initial MLCT dissociation by elongation of the Co-C bond. When the axial base is detached the energy of the LF region is lowered resulting in a near-barrierless transition by dissociation of the axial water to a stabilized LF state where photolysis only competes with internal conversion (IC) by corrin ring distortion. The axial base modulates photolysis by changing the topology of the S₁ surface; favoring initial MLCT when attached, and fast population of the photolytic LF state when detached. The involvement of triplet states is also discussed for the base-off forms, where the gradient of crossing the S₁ surface favors intersystem crossing (ISC) and possible triplet dissociation by an effective spin-orbit coupling (SOC).

1.2 Introduction

Vitamin B₁₂ cofactors appear as highly complex bioinorganic molecules considered among the most widely relevant catalytic systems in Nature.¹⁻¹¹ While B₁₂ is only fully synthesized in bacteria,¹²⁻¹⁴ B₁₂-coenzymes are required for several metabolic processes that depend on the binding and uptake of B₁₂ (cyanocobalamin, CNCbl), and the controlled delivery and transformation into the biologically active forms, MeCbl and AdoCbl.¹⁵⁻¹⁹ The biological reactivity of B₁₂ derivatives is enhanced due to a unique Co σ (d_z^2) bond, which enables oxidative control of the cobalt ion depending on the axial ligands involved, and the environment surrounding the cofactor.

Cobalamins contain a low-spin Co(III) ion ligated equatorially by four nitrogens of a non-planar corrin macrocycle, and di-axially by an upper cyano (CN), hydroxo (OH), adenosyl (Ado) or methyl (Me) group (Figure 1.1); and a lower 5,6 dimethylbenzimidazole (DBI) base attached to the ring via nucleotide loop. The cobalt center is coordinatively saturated in Co(III)-corrins, while Cob(II)alamin is a stable radical with an intermediate oxidation state capable of providing a reactive metal-center. Co(I)-corrins such as cob(I)alamin are highly nucleophilic, where reduction of Co(III)-corrins typically leads to loss of the upper ligand. Compared to the porphyrins, the non-planar non-aromatic corrin macrocycle of the cobalt corrinoids produces to an electron delocalization resulting in several low-lying near-degenerate excited states of mixed d- π character, in accord with experiment.

Figure 1.1. Molecular structure (upper), and truncated structural model of Vitamin B₁₂ derivatives (lower).

Cobalamins are classified into two groups based on their reactivities, non-alkyl forms with strongly coordinating upper ligands such as Cyanocobalamin (CNCbl, Vitamin B₁₂) and hydroxocobalamin (HOCbl), and the biologically active alkyl forms MeCbl, and AdoCbl. CNCbl and HOCbl are generally stable, while MeCbl and AdoCbl are cofactors in a series of enzymes that catalyze molecular transformations induced by cleavage of the organometallic Co-C bond. The Co-C bond is of moderate

strength ranging from 30 - 44 kcal/mol depending on the on the upper (alkyl) ligand and experimental conditions for measuring bond dissociation energies (BDEs).²⁰⁻²⁶ MeCbl-dependent enzymes are involved methyl transfer reactions by producing methyl cations, while AdoCbl dependent mutases are involved in intramolecular rearrangements that produce organic radicals.^{1, 3-5, 8-9, 27-29} The type of bond cleavage, heterolysis in the case of MeCbl and homolysis in the case of AdoCbl is thus controlled by the ligand, and the environment surrounding the Co(III) ion. The exact reason for the observed rate enhancement of thermal Co-C bond homolysis in AdoCbl-dependent enzymes by $\sim 10^{12}$ compared to solution, have significant implications for catalysis. The exact reasons for this observed enhancement remains an open issue and is currently the subject of active research.

1.3 Structural Models

Despite advances in computational methods cobalamins are still considered complex for theoretical studies, especially in regard to prediction of low-lying electronically excited states. This complexity is mainly due to the presence of a partially conjugated corrin macrocycle, which produces extensive mixing between the π orbitals of corrin and the d orbitals of cobalt. Depending on the upper axial ligand, B₁₂ cofactors range in size from 183 atoms (MeCbl) to 209 atoms (AdoCbl) and tractable calculations at multiscale levels (Figure 1.2, upper) or multiconfigurational levels (Figure 1.2, lower) require the use of truncated models with respect to side chains and the nucleotide loop.³⁰⁻³³ Structural models are typically derived directly from X-ray crystallographic data,³⁴⁻³⁸ where the ligands are modified accordingly. Side chains of the corrin ring are replaced by hydrogen atoms, and the nucleotide loop containing the negatively charged PO₄⁻ ion is omitted to afford a corrin model denoted B-[Co^{III}(corrin)]-R⁺ with a total charge of +1.

Figure 1.2. Solution and Protein-bound forms of MeCbl (upper) and corresponding truncated models adopted from coordinates and methods in Ref.³⁹

Truncation by partitioning the full cofactor to different levels of theory, as in multiscale models (Figure 1.2, upper), where quantum mechanics and molecular mechanics (QM/MM) or semi-empirical approaches are combined (ONIOM), to accurately account for the solvation environment surrounding the system where the effects of polarization and response may be treated accurately.^{30, 32, 40 33, 39} Truncation is also important for wavefunction methods to benchmark electronic structures, and where explicit analysis of couplings between different spin states strongly depends on the size of the active space.⁴⁰⁻⁴³ For example, the adenosyl group is fairly large and produces an active space that is computationally expensive for multiconfigurational methods, so the ring system may also be truncated to ribose (Figure 1.3, lower).

Figure 1.3. Solution and Protein-bound forms of AdoCbl and corresponding truncated models adopted from coordinates and methods in Ref.³³

There are two axial base conformations of cobalamin cofactors in enzymatic environments (Figures 1.3, Right). Eliminases and ribonucleotide reductases bind cobalamins in base-on forms,⁴³ while mutases and other proteins such as CarH bind cofactors by replacing DBI with a histidine residue, known as “base-off/His-on” conformations. Cob(III)alamin is a d_6 high-spin complex, and reduction of the Co(III) ion either chemically or as recently discovered, by photo-excitation, results in a stable cob(II)alamin radical relevant to several intermediates in catalysis.

Figure 1.4. Molecular structures of cob(II)alamin in solution and the cob(I)alamin/cob(II)alamin protein complex adopted from coordinates and methods in Ref.³⁰

The full cofactor-based cob(II)alamin model is shown in Figure 1.4.^{30, 32, 40} The enzyme-bound cob(I)alamin or “super-reduced” form is a d^8 high-spin complex that also produces the cob(II)alamin d^7 low-spin radical upon loss of an electron and attachment of the axial base.⁴⁰ Cob(I)alamin in its enzyme-bound conformation is a base-off cofactor, where oxidation of the cobalt ion leads to re-attachment of the axial base. Base-off cobalamins have been recently linked to enhanced reactivities in solution, where the dynamics of solvent-separated radicals are controlled by the stability of relevant alkyl anion, the solvent, or in the case photolysis, the wavelength applied.

1.4 History: from catalysis to photolysis

The famous discovery of the CNCbl crystal structure by Dorothy Hodgkin,⁴⁴ and the elucidation of the metabolic roles and structural diversity of the cobalamins by Barker et. al,¹⁶⁻¹⁸ the main functions of the cobalamins were mainly associated with thermally-driven enzymes. Although the photo-activities of the cobalamins were initially known their sensitivity to light was regarded mainly as side-reactions. Due to advances in experimental spectroscopy however, research interest has been gained in light-driven systems, where elucidation of relevant photo reaction mechanisms has led to implications of design as tunable photocatalysis. The axial base modulates reactivity in the cobalamins. Methyltransferases such as methionine synthase (MetH), produce methyl cations via S_N^2 reaction in the base-on form (favored), or by reductive elimination with homocysteine (Hcy) in the base-off/His-on conformation.³⁹

AdoCbl-dependent mutases on the other hand bind the cofactor in base-off/His-on conformations, and catalyze 1,2-intramolecular rearrangements initiated by binding of a substrate molecule followed by Co–C homolysis to form the respective RPs, and hydrogen abstraction.⁴⁵

Figure 1.5. Catalytic cycle of MeCbl-dependent methyltransferases.

A general scheme of MeCbl catalysis is shown in Figure 1.5, where Co–C bond heterolysis of a methyl cation leads to an effective transfer to the substrate (Sub_1) reducing Co(III) to Co(I) and completing the catalytic cycle after a second methyl transfer to cob(I)alamin from Sub_2 . Substrate bindings to AdoCbl dependent mutases and eliminases trigger Co–C bond homolysis affording cob(II)alamin and RPs (Figure 1.6). The alkyl radical then abstracts a hydrogen from the substrate resulting in a radical rearrangement and migration where the catalytic cycle is completed after re-abstraction of H by the substrate radical. Cob(II)alamin RPs may also be generated by light for MeCbl and AdoCbl.

Figure 1.6. Catalytic cycle of AdoCbl-dependent eliminases.

Although the photoactivity of the cobalamins has been known since their discovery, only recently has light-induced cleavage of the Co–C bond gained new interest due to advancements in ultrafast spectroscopy, in studies where photodissociation has been separated from the hydrogen abstraction step.^{46–49} Several reactions are known to be mediated by the cobalamins where the initial step is light-induced Co–C cleavage,^{50–67} Experimental has also shown that AdoCbl-dependent enzymes such as glutamate mutase (GLM)^{15–16} and ethanolamine ammonia-lyase (EAL)^{17–20} may also generate Ado and cob(II)alamin RPs without coupling to subsequent abstraction.

Recent attention has also been gained for the involvement of B₁₂ photochemistry in the regulation of carotenoid biosynthesis, specifically the newly discovered and structurally characterized CarH photoreceptor, which directly mediates transcription by light-induced large-scale structural change.^{68–69, 70} CarH is a tetramer that binds AdoCbl cofactors in a “dark-state” in base-off/His on forms, where photodissociation of the upper Ado ligands leads to a stable “light-state” with cofactors in bis-His conformations. The CarH mechanism is an unprecedented example of an AdoCbl-mediated reaction and was initially proposed to occur via carbanion intermediate,⁶⁹ in notable contrast to the known radical chemistry of AdoCbl.

On the other hand, among cobalamin-dependent aerobic transcriptional proteins the AerR activator binds HOCbl tightly^{71–72}, and was interestingly proposed to form a similar bis-His adduct during the aerobic conversion of AdoCbl or MeCbl- for which it has little to no affinity.⁷³ It has been suggested

that cobalamin RPs are stabilized in biological environments, implying from a theoretical point of view that spin-effects when favored, should be enhanced by proteins. Considering advances in experimental techniques involving free-electron lasers, it is currently possible to structurally resolve the intermediates involved in photo-excited processes on a femtosecond time scale in both biological environments and solution. A detailed theoretical picture of the electronic structures involved in alkylcobalamin photodissociation presented here are thus expected to provide necessary insights to current experimental groups towards further understanding cobalamin electron-transfer in both enzymatic and optogenetic processes.

1.5 Current Applications

The B₁₂ scaffold has gained interest in biological applications due to the controlled photolysis of different cobalamin upper ligands. For example, cob(II)alamin reacts with O₂ to form HOCbl, and under aerobic conditions with shorter wavelengths photo-catalytically generates hydroxyl radicals *in situ* (Figure 1.7). Currently this is the most effective method to probe DNA structure and binding, over the more common reduction of H₂O₂. Other B₁₂-derivatives known as “anti-vitamins” are synthetic cobalamins resistant to metabolic transformation to the biologically active forms. They have been used to study pathologies related to B₁₂ deficiency, and recently photoactive forms such as ethylphenylcob(III)alamin (EtPhCbl, Figure 1.7) represent a class of compounds which can selectively activate metabolism with light as *in vivo* precursors to AdoCbl and MeCbl.

Figure 1.7. Photoactive OH radical generation and B₁₂ antivitamins.

1.6 Computational Methods

Due to the size and the complexity of the cobalamins DFT is the most widely used computational method to calculate ground-state properties, while TD-DFT calculations are the only viable methodology employed to study the corresponding low-lying excited states. A common question with TD-DFT applied to complex conjugated systems containing transition metals is how appropriate the descriptions of the excited states are. It is important to recall that one of the key features of cobalamins is the dissociation energy of the Co-C bond (BDE), which has received considerable attention both experimentally and computationally. It has been shown that theoretical Co-C BDEs are very sensitive to the applied exchange-correlation functional. Hybrid DFT functionals with a substantial amount of the Hartree-Fock (HF) exchange, such as the popular B3LYP, considerably underestimate calculated Co-C BDEs, with

a magnitude of error proportional to the HF exchange in the functional. The M06-2X functional significantly underestimates the Co-C BDE at around 5 kcal/mol, while B3LYP, MPW1PW91, TPSSH, and even wB97X-D functionals all underestimate the Co-C BDE around ~23 kcal/mol, and generalized gradient approximation (GGA)-type functionals lead to significant improvement over B3LYP based calculations.⁷⁴ Dispersion corrections are important for accurate predictions of Co-C BDEs as well, where the best performing functionals for Co-C BDE are BP86 + D2, BP86 + D3, B97D, followed by BP86 and M06-L as benchmarked by Kornobis et. al.⁷⁴⁻⁷⁹ Of all DFT functionals examined, the most accurate description of Co-C bond breaking in the MeCbl cofactor were provided by B97-D, and BP86 with D3 correction functionals, respectively.

Figure 1.8 Ten lowest electronic transitions of Im-[Co^{III}(corrin)]-CN⁺ with corresponding Λ diagnostic values adopted from data in Ref.⁷⁹

Electronically excited states have also been the subject of benchmarks studies for low-lying excited state character, including the MeCbl and CNCbl (Figure 1.8, lower) systems.^{42, 74} Reported TD-DFT benchmarks with *ab initio* calculations target specific electronically excited states (MeCbl), or the low-lying electronically excited state manifold (CNCbl), in each case where the extent of predicted overlap is determined by the amount of MO mixing by the functional. Although TD-DFT describes electronic excitations very well using GGA-type as well as hybrid exchange-correlation functionals,⁸⁰⁻⁸¹ low energy

electronic transitions involving mixed charge-transfer (CT) or Rydberg states below the ionization potential should be carefully considered when these effects are underestimated or spurious due to correlation errors associated with self-interaction.⁸²⁻⁸⁷

The main obstacle with excited state calculations is thus benchmarking the extent of mixing between Co and π orbitals. Initial analysis of the S_1 state for MeCbl using B3LYP predicts a pure $\pi \rightarrow \pi^*$ character, while BP86 benchmarked with *ab initio* calculations correctly predicts a MLCT as a result of mixing Co d orbitals with corrin π .⁴² Excitations involving CT are often corrected using range-corrected functionals such the Coulomb-attenuated or long-range corrected methods, and low-lying excited states are effectively further corrected using the Λ diagnostic of Tozer et. al, where Λ corresponds to a value between 0 and 1, representing the extent of overlap between ground and excited state where a value of one would correspond to complete overlap, and Λ values $< .5$ are generally considered charge-separated. Although not observed for CNCbl or MeCbl, some special cases arise in highly conjugated dyes where the centers of the hole-electron pair states may be both well-separated, and have small overlap compared the overall excited state dispersed throughout the system. As benchmarked for CNCbl the CAM- correction does not capture the mixed character of the S_1 state, nor the correct excitation energies, while BP86 shows improved performance over both hybrid and coulomb-attenuated functionals, with d-orbital excited state character and energies in very good agreement with CD and MCD data.^{60, 88}

Multiconfigurational methods also offer a way to extend the range of cobalamin excited state PESs to dissociated axial bond distances past the TD-DFT limit, which is of particular interest for the base-off cobalamins. Although size limitations of the active space prevent the use of full structures, truncated models have generally been shown to correlate well with TD-DFT descriptions. Theoretical descriptions of cobalamins inside enzymatic environments using multi-scale approaches in many cases remain a challenge, due to the scalability of system size, and the sensitivity of available methods, and the effective diagnosis of CT as well as BDEs.

1.7 Benchmark Calculations: Axial bond lengths of cobalamins corresponding to S_0 and S_1 States

Cobalamins have been the subject of several structural investigations using DFT, and the

availability of structural data has been used to theoretically determine the effects axial bonding within the corrin system.¹⁰ The nature of the upper axial ligand determines the corresponding axial bond lengths, which are in fact the most sensitive parameters with respect to overall structural change. It has been shown that the BP86 functional reproduces experimental axial bond lengths very well, and based on this data, ground state properties of cobalamins were further rationalized by correlating axial bond distances in terms of *inverse vs. normal trans influence*. On the other hand the corrin structure is relatively insensitive to the nature of the upper axial ligand, and the bulkiness of the upper ligand changes only the planarity of corrin ring.

Figure 1.9 shows the comparison of experimental, and DFT/BP86-based Co-R, and Co-N_{im} bond lengths for ground states of the four cobalamins considered in this dissertation.^{34-36, 38, 89} As seen, the S₀ state reproduces Co-R bond lengths more accurately for Co-N_{axial} distances. The prediction of Co-N_{axial} distances are reasonable however, as their lengths are more sensitive with respect to structural simplifications, and local environments. Although predicted Co-N_{axial} bond lengths are generally more sensitive to the local environment, BP86 is considered to reproduce them very well.

Figure 1.9 Experimental, and optimized axial bond lengths at the DFT/BP86 level, for S₀ and TD-DFT/BP86 for S₁ excited states of the cobalamins under consideration (MeCbl,³⁴ AdoCbl,³⁶ CNCbl,³⁴ HOCbl³⁵). In all calculations the same basis sets, TZVPP for Co, C, N, and TZVP for H were used, employing the Conductor-like Screening Model (COSMO) solvent.

Because there is no structural data available for the excited states of cobalamins, we need to rely on computations. Figure 1.9 also shows the TD-DFT/BP86 optimized axial bond lengths corresponding to S₁ state. Predicted changes for alkylcobalamins indicate that Co-N_{im} distances of the optimized S₁ states are shorter, while Co-C bond lengths are longer for both MeCbl and AdoCbl in

comparison to the ground state. Changes in axial bonding in S_1 state for non-alkylcobalamins are less systematic. Significant lengthening of Co-CN and Co-N_{Im} bonds is observed in the case of CNCbl. Opposite changes are predicted for HOCbl, where both Co-OH and Co-N_{Im} are slightly shorter for S_1 in comparison to S_0 . The extent of lengthening for CNCbl however is much larger in comparison to the shortening predicted for HOCbl.

The photodissociation of the Co-C bond may also be used to follow a photoexcited electron along its reaction coordinate. Monitoring the formation of radical states as functions of Co-C dissociation is critical towards creating an accurate description of the relevant excited state mechanisms. Figure 1.10 shows spin separation as a function of bond dissociation, in this case for MeCbl. Around 2.6 Å RPs formation begins, spin is localized on Co and carbon atoms, and further bond dissociation leads to a cob(II)alamin and carbon RP.⁹⁰ Generating the correct ground state wavefunction is thus imperative for studying mechanisms of radical photochemistry.

Figure 1.10 Photolysis and intersystem crossing in MeCbl.⁹¹

This research is focused on photochemistry, specifically how light exposure generates a pair of radicals. Shown in Figure 1.11 for MeCbl, there are three possibilities from the singlet state upon excitation and generation of a RP; recombination, escape, and internal conversion (IC). Intersystem crossing (ISC) may also generate a triplet pair that may escape, but due will not recombine due to the Pauli exclusion principle which states that any two fermions cannot occupy the same quantum state simultaneously.⁹² If the spin density of cob(II)alamin is examined closely incorporating relativistic effects, we see one electron clearly in a d_z^2 orbital.⁹³ The ground state of cob(II)alamin was the target of initial research, to more closely understand how the ground state effects the excited state.

CHAPTER II COB(II)ALAMIN

2.1 Background

The reduced form of vitamin B₁₂ (cob(II)alamin or B_{12r}, Figure 1.4), where the cobalt metal has an oxidation state of +2, is typically generated after homolytic cleavage of the Co-C bond, and is found in many areas of B₁₂ chemistry and biochemistry.^{1, 3-9, 27-28, 37-38, 45, 89, 94} Cob(II)alamin is a five-coordinate radical Co^{II}(d⁷) ion. Due to the axially symmetric g-tensor of the paramagnetic Co^{II}(d⁷) center, electron paramagnetic resonance (EPR) spectroscopy has been a very sensitive probe of the local environment of cobalt.⁹⁵⁻¹⁰⁴

Analogues of cob(II)alamin can be found in solution, and in enzymatic environments at physiological pH. Under non-enzymatic conditions, cob(II)alamin may be generated by one-electron reduction of Co(III)-based cobalamins (such as aquacobalamin) electrochemically, or chemically with a reductant.^{30, 104-105} Upon reduction, the Co(II)-based species forms a stable five-coordinate low-spin radical complex, where the unpaired electron resides entirely on the Co d_{z²} orbital.³² Cob(II)alamin has been characterized by x-ray,^{89, 106} and the structural features of the Co(II)-corrin moiety are similar to the biologically active forms of vitamin B₁₂ (i.e., the Co(III)-corrins), with the exception of axial Co(II)-N_{DBI} distances are generally shorter.

Cob(II)alamin is a universal intermediate in enzymatic reactions catalyzed by derivatives of vitamin B₁₂. In the case of AdoCbl-dependent reactions substrate binding that initiates homolytic cleavage of the Co-C bond to produce cob(II)alamin.¹⁰⁷ The kinetics of Co-C cleavage in AdoCbl-dependent enzymes, have been studied using stopped-flow methods, and the detection of visible absorption changes associated with AdoCblCAS (I_{max} ~525 nm), and cob(II)alamin (I_{max} ~470 nm) transitions.¹⁰⁸ The formation of Co(II)-intermediates and their interactions with substrate radicals have also been extensively investigated by EPR spectroscopy to characterize radical centers inside enzymatic environments.¹⁰⁷

In the case of MeCbl-dependent methyltransferases, heterolytic cleavage of the Co(III)-C bond leads to the formation of cob(I)alamin intermediates.^{105, 109} The highly reactive enzymatic cob(I)alamin is occasionally oxidized to the inactive cob(II)alamin species, which then requires reactivation. It has been suggested that this step involves an axial ligand switch of the upper ligand to water, to form a

five-coordinate cob(II)alamin complex.^{105,110,111,112} Recent theoretical study predicted that the reactivation mechanism involves reorientation of the water ligand and formation of a Co(I)-H bond.³² The reduction of cob(II)alamin to the cob(I)alamin intermediate species also takes place in ATP corrinoid adenosyltransferases such as CobA, PduO, and EutT, in which reorientation of the water ligand may also occur.¹¹³⁻¹¹⁶

Cob(II)alamin may alternatively be generated by photolytic cleavage of the Co-C bond.^{50-63, 117-121} A number of factors affect Co-C bond photolysis- the nature of the upper axial ligand, the base-on or base-off conformation, and the excitation wavelength. The kinetic behavior observed in previous studies suggest that alkylcob(III)alamins, such as MeCbl or AdoCbl, initially undergo photodissociation to form metastable intermediates that each branch between two distinct photoproduct pathways.^{3, 5, 9, 45, 94, 122-123} The metastable photoproduct, [Co(III)-C]* either recovers to the ground state, or becomes a ligand field (LF) [Co(II)--*C]* diradical species. The Co(II)-based intermediate appears in time-resolved spectroscopy, and may be referred to as either an electronically excited state, or the ground state of cob(II)alamin.

Despite the importance of the Co(II)-based intermediates in B₁₂ chemistry, a detailed understanding of their electronic properties, and low-lying excited states remains limited. Analysis of low-lying electronically excited states of Co(II)-based corrins, is thus required to develop a detailed understanding of the photochemical reactions of the alkylcobalamins such as MeCbl or AdoCbl. Typically, TD-DFT calculations are the only viable method employed to study the excited states of these complex systems. However, the question that commonly arises with TD-DFT methods applied to large systems, is how appropriate the descriptions of the excited states are. One of the main objectives of this study therefore, is to provide insight regarding the low-lying excited state electronic properties of four- and five-coordinated cob(II)alamins at both the TD-DFT level, by employing wavefunction-based methods. This study may thus be summarized in three parts: (i) investigation of low-lying electronically excited states using CASSCF calculations followed by multiconfigurational second-order perturbation theory (XMCQDPT2) to establish a benchmark, (ii) analysis of Configuration State Functions (CSFs) to validate electronic excitations calculated at the TD-DFT level, and (iii) evaluation of the dependency of low-lying excited state manifolds on Co-N axial distance, where elongation of the cob(II)alamin axial bond leads to formation of the base-off form.

2.2 Computational Details

2.2.1. Structural Models

The full structure of cob(II)alamin (Figure 1.4) may either be obtained either from existing crystal structure,¹⁰⁶ or derived from other high resolution alkylcobalamin crystals, by removing the corresponding upper ligand.^{34, 124} It has been shown previously that electronic structures produced by both methods are not affected by the initial geometry, whereas their optimizations are sensitive to choice of functional. In this work the later strategy was used, and the full cob(II)alamin structural model was adopted from our EPR study.⁹³ The geometry was obtained by optimization of a modified MeCbl high resolution crystal structure at the BP86/TZ2P level of theory,^{80-81, 125} with relativistic corrections included in the optimization step using the scalar-relativistic zeroth-order-regular-approximation Hamiltonian (SC-ZORA),¹²⁶ implemented in the Amsterdam Density Functional (ADF) program.¹²⁷

To reduce computational costs, the full cob(II)alamin structure was truncated with respect to side-chains by replacing them with H-atoms, the DBI base was replaced with imidazole (Im), and the nucleotide loop was removed. The truncated model, denoted Im-[Co^{II}(corrin)]⁺, has an overall charge of +1 due to the lack of the nucleotide PO₄⁻ group. Additionally, a model with no axial ligand was constructed from the five-coordinate structure by removing its axial base, and is denoted [Co^{II}(corrin)]⁺.

2.2.2 DFT and TD-DFT

DFT and TD-DFT calculations performed in this study were carried out using either the TURBOMOLE¹²⁸ and Gaussian09¹²⁹ suites of programs for electronic structure calculations. In all calculations, the low-spin doublet state ($S = \frac{1}{2}$) of the Co(II) species was assumed. Vertical electronic excitations for the full structure of cob(II)alamin, and the truncated models, along with corresponding Natural Transition Orbitals (NTOs)¹³⁰ were obtained at the TD-DFT level using the BP86 functional, and the 6-311G(d,p),^{131,132} basis set, or Stuttgart-Dresden (SDD) pseudopotential basis sets using the Gaussian09 program.¹³³⁻¹⁴⁰ The Stuttgart-Dresden potentials used to include scalar relativistic effects were DF-relativistic 10-electron effective core potential (MDF10 ECP) for Co, quasi-relativistic 2-electron ECP (MWB2 ECP) for C, N, O and P, and the 1-electron ECP (D95 ECP)¹⁴¹ for H. Throughout this work, individual molecular orbitals (MOs) compose TD-DFT transitions, while NTOs, which may be composed of multiple donor or acceptor MOs, are referred to as NTO holes and particles, or an NTO hole-particle

pair, referring to the contribution to the transition. To obtain the PES of ground, and lowest excited states for the five-coordinate model, the Co-N_{Im} bond was systematically changed and fixed while all other coordinates were optimized at each point, using a step size of 0.05 Å, from 1.80-2.80 Å. TD-DFT vertical excitations along Co-N_{Im} coordinate were calculated at the UBP86/6-311G(d,p) level of theory. DFT geometry optimization of the truncated model of cob(II)alamin was also performed using the TURBOMOLE package at the UBP86/TZVPP level of theory. For the full structure, TD-DFT vertical states were calculated at the UBP86/SDD level of theory using the optimized geometry at the UBP86/6-311G(d,p) level of cob(II)alamin to extend the range of calculated excited states at reduced computational cost.

2.2.3. CASSCF/XMCQDPT2

The electronic properties and low-lying excited states of four-, and five-coordinate model complexes of cob(II)alamins were initially investigated by complete active space self-consistent field (CASSCF) calculations for benchmarking purposes, using the Firefly quantum chemistry package, version 8.0.0.¹⁴² However, CASSCF calculations alone are not sufficiently accurate, and need to be corrected by second order perturbation theory to account for dynamic correlation. Subsequently, a modified version of multiconfigurational quasi-degenerate second order perturbation theory, referred to as XMCQDPT2,¹⁴³ was applied to include the dynamic correlation effects in CASSCF calculations at the perturbation level. Note that, the XMCQDPT2 approach is a genuine multi-root (i.e., perturb-then-diagonalize) multi-reference perturbation theory technique using the CASSCF state-averaged (SA) electron density over the ground and excited states of interest, allowing a true mixing of the CASSCF zeroth-order states via the construction, and subsequent diagonalization of the effective Hamiltonian. To obtain accurate results, excited-states based on CASSCF/XMCQDPT2 calculations require the determination of a manifold of electronically excited states for analysis of low-lying states of interest, and they are particularly important for transition-metal systems like cobalt corrinoids, where several low-lying electronic states may interact one with another. Twenty electronic states were considered in state average (SA-CASSCF) calculations using 11 electrons and 12 orbitals in the active space. Details regarding the selection of active orbitals used in CASSCF/XMCQDPT2 calculations reported in this work are discussed in Sections 3.1. CASSCF/XMCQDPT2 calculations were performed using the 6-31G(d) basis set, at the optimized geometries of [Co^{II}(corrin)]⁺, and Im-[Co^{II}(corrin)]⁺ as previously mentioned.

2.3 Results and discussion

To begin, we discuss the electronic structure and low-lying excited states of the four-coordinate cob(II)alamin model, followed by analysis of the five-coordinate model for comparison. Electronically excited states of the truncated models produced by CASSCF/XMCQDPT2 are discussed first, followed by comparison of the corresponding TD-DFT states. The full cob(II)alamin structure at the TD-DFT level is then considered to analyze the influence of corrin side chains on the low-lying excited states, and to make further comparison with experimental spectra. Finally, the influence of Co-N_{lm} axial distance on the low-lying excited states is discussed to determine how the electronic properties of cob(II)alamins are modulated by lower axial ligands.

2.4 Four-coordinate model of cob(II)alamin

Analysis of the low-lying excited state manifold for the four-coordinated model begins by first considering excitation energies calculated by multiconfigurational SA-CASSCF calculations, followed by analysis of configuration state function (CSF) composition at the perturbation level. CASSCF and CASSCF-based multireference calculations such as the XMCQDPT2 approach however, are challenging when applied to large molecules containing transition metals coordinated by aromatic systems, and results obtained strongly depend on the choice of the active space. In the case of the CASSCF calculations for [Co^{II}(corrin)], the selection of active orbitals was guided by active spaces previously used for various derivatives of vitamin B₁₂.^{33, 40, 42, 79, 92, 144-145} The cob(II)alamin intermediate is among a class of Co^{II} square-planar complexes, where the local environment of cobalt in [Co^{II}(corrin)] causes splitting of d orbitals, with d⁷ as the dominant electronic configuration. Therefore, all five d orbitals are equally important for CASSCF calculations to investigate electronic properties. For such systems, the proper active space, therefore requires the inclusion of cobalt d orbitals, π orbitals of corrin as well as σ orbitals associated with axial bonding. Several other compositions have been previously tested, leading to the most appropriate choice of active space based on the distribution of 11 electrons between 12 active orbitals. Five d Co orbitals and one π occupied corrin MO were combined with their corresponding virtual orbitals, as shown in Figure 2.1. To account for the double shell effect in transition metal complexes, 4d correlating orbitals are added to the doubly occupied 3d. The occupied π corrin orbitals are correlated with the unoccupied π^* orbitals in the active space.

Figure 2.1. Active space corresponding to $[\text{Co}^{\text{II}}(\text{corrin})]^+$ used in the CASSCF(11,12) and subsequent XMCQDPT2 calculations.

SA-CASSCF was used to compute 20 electronic states, followed by second order perturbation theory calculations based on the quasi-degenerate approach by Nakano (QDPT2), and its modification by Gronovsky, (XMCQDPT2), which uses the CASSCF reference wavefunction to include dynamic correlation. Similar to previous studies of B_{12} derivatives, a large number of $[\text{Co}^{\text{II}}(\text{corrin})]^+$ excited states at the CASSCF level were considered to allow for intrinsic mixing at the correlated level (XMCQDPT2), and to improve the zeroth-order description of first five states of $[\text{Co}^{\text{II}}(\text{corrin})]^+$. The resulting excitation energies and their compositions in terms of CASSCF configurations are listed in Table 2.1.

Table 2.1. The lowest five states of $[\text{Co}^{\text{II}}(\text{corrin})]^+$ obtained from CASSCF/MCXQDPT2 calculations. CSF denotes the configuration state function.

State	eV	f	Weight (%) of CAS state in MCXQDPT2	CAS state	Weight of CSF [%]	Electronic configuration of CAS state	Character
D_0	0.00		75	1	94	$(d_z^2)^1$	$d_{yz} \rightarrow d_z^2$
			25	2	85	$(d_{yz})^1(d_z^2)^2$	
D_1	0.01	0.00000	25	1	94	$(d_{z^2})^1$	$d_{yz} \rightarrow d_z^2$
			75	2	85	$(d_{yz})^1(d_z^2)^2$	
D_2	1.35	0.00000	99	3	68	$(d_{x^2-y^2})^1(d_z^2)^2$	$d_{x^2-y^2} \rightarrow d_z^2$
						$(d_{xz})^\uparrow(d_{yz})^\downarrow$	
					15	$(d_{z^2})^2(d_{xy-n})^\uparrow$	$d_{xz}/d_{yz} \rightarrow d_z^2/d_{xy-n}$
D_3	2.05	0.00001	98	4	35	$(d_{x^2-y^2})^\uparrow(d_{xz})^\downarrow$	$d_{x^2-y^2}/d_{xz} \rightarrow d_z^2/d_{xy-n}$
						$(d_z^2)^2(d_{xy-n})^\uparrow$	
						$(d_{x^2-y^2})^\uparrow(d_{xz})^\uparrow$	
					26	$(d_z^2)^2(d_{xy-n})^\downarrow$	$d_{x^2-y^2}/d_{xz} \rightarrow d_z^2/d_{xy-n}$
					18	$(d_{xz})^\uparrow(d_z^2)^\downarrow(d_{xy-n})^\uparrow$	$d_{xz} \rightarrow d_{xy-n}$
D_4	2.18	0.00001	99	5		$(d_{xz})^\uparrow(d_z^2)^\uparrow(d_{xy-n})^\downarrow$	$d_{xz} \rightarrow d_{xy-n}$
						$(d_{xz})^\uparrow(d_{yz})^\downarrow$	
					62	$(d_z^2)^2(d_{xy-n})^\uparrow$	$d_{xz}/d_{yz} \rightarrow d_z^2/d_{xy-n}$
						$(d_{xz})^\uparrow(d_{yz})^\uparrow$	
					23	$(d_z^2)^2(d_{xy-n})^\downarrow$	$d_{xz}/d_{yz} \rightarrow d_z^2/d_{xy-n}$

Inclusion of dynamic correlation reveals that the D_0 and D_1 states corrected by XMCQDPT2 is a mixture of the first two CAS states. The first, and second CAS states have wavefunctions with one major CSF, with weight percentages of 94% and 85%, respectively. This CSF corresponds to two electronic configurations, that is $(d_z^2)^1$ and $(d_{yz})^1(d_z^2)^2$. The first has a larger weight contribution to D_0 state, while the second has a larger contribution to D_1 . Considering the compositions of the CAS states involved in the D_0 and D_1 XMCQDPT2 states, we may conclude that in D_0 , the unpaired electron is mainly localized on d_z^2 orbital, while in D_1 it is mainly localized on d_{yz} (with some admixture of $(d_{yz})^1$ occupation in D_0 , and $(d_z^2)^1$ in D_1). This can be considered an inversion of population, revealing that the D_1 excited state is almost degenerate with respect to D_0 ground state, with very low excitation energy (0.01 eV).

The next three electronically excited states of $[\text{Co}^{\text{II}}(\text{corrin})]^+$ model complex predicted at the XMCQDPT2 level do not mix CASSCF states. These excited states involve more than one dominant configuration in their wavefunction, and are mainly characterized as d-d type electronic transitions,

involving mainly excitations to the d_z^2 orbital. In particular, the D_2 has a dominant CSF of 68% $(d_x^2 - y^2)^1(d_z^2)^2$ with a 15% contribution from a $(d_{xz})^1(d_{yz})^1(d_z^2)^2(d_{xy-n})^1$ doubly excited configuration, and can be characterized as a $d_x^2 - y^2 \rightarrow d_z^2$ transition. D_3 is mainly composed of two $(d_x^2 - y^2)^1(d_{yz})^1(d_{z^2})^2(d_{xy-n})^1$ doubly excited configurations, having 35% and 26% weight contributions to the transition, while the remaining two $(d_{xz})^1(d_z^2)^2(d_{xy-n})^1$ configurations with 18% and 11% weight contributions are also symmetric, and characterized as $d_{xz} \rightarrow d_{xy-n}$ transitions. D_3 is thus characterized as a $d_x^2 - y^2/d_{xz} \rightarrow d_z^2/d_{xy-n}$ transition, with a small contribution, coming from a $d_{xz} \rightarrow d_{xy-n}$ excitation. The D_4 excited state has two dominant CSFs which are also composed of two $(d_{xz})^1(d_{yz})^1(d_z^2)^2(d_{xy-n})^1$ doubly excited configurations, with 62% and 26% weight contributions, similarly characterized as a $d_{xz}/d_{yz} \rightarrow d_z^2/d_{xy-n}$ transition. Due to the involvement of doubly excited configurations in the four-coordinate multiconfigurational model, D_3 and D_4 cannot be directly compared to TD-DFT.

TD-DFT calculations based on UBP86/6-311G(d,p) were then applied to analyze and compare excited states obtained from *ab initio* calculations. The Kohn-Sham frontier α and β orbitals for $[\text{Co}^{\text{II}}(\text{corrin})]^+$ model complex obtained from UDFT calculations, along with orbital energies were used in successive TD-DFT calculations, with frontier orbital subspaces relevant to low-lying excitations ranging from H-4 to L+3 for the α and β subspaces. DFT calculations indicate that the highest occupied molecular orbitals (HOMOs) are a mixture of Co d and π orbitals of the corrin macrocycle. One apparent difference between the orbitals for DFT and natural orbitals selected for SA-CASSCF, is mixing of DFT π MOs with the 3d MO. The unpaired electron of $[\text{Co}^{\text{II}}(\text{corrin})]^+$ is located on H-4(α ,91), and characterized as $d_z^2 + \pi$. The corresponding unoccupied β orbital, L(β ,95) is the lowest unoccupied MO (LUMO), and characterized as pure d_z^2 , as reported. The d composition of the $[\text{Co}^{\text{II}}(\text{corrin})]^+$ excited determined by TD-DFT, where further analyzed by NTO analysis, and NTOs of the four-coordinate $[\text{Co}^{\text{II}}(\text{corrin})]^+$ based on TD-DFT calculations, are presented in Figure 2.2.

NTO	eV	NTO Coeff	f	α hole	α particle	β hole	β particle
D ₁	0.45	0 (α) 100 (β)	0.0000	d_z^2	π^*	$d_{yz} + \pi$	d_z^2
D ₂	0.68	0 (α) 100 (β)	0.0000	π	π^*	$d_{xz} + \pi$	d_z^2
D ₃	1.38	0 (α) 99 (β)	0.0007	$d_{xz} + \pi$	π^*	$d_{x^2-y^2}$	d_z^2
D ₄	1.52	0 (α) 99 (β)	0.0003	π	π^*	π	d_z^2
D ₅	2.13	39 (α) 61 (β)	0.0005	$d_{yz} + \pi$	π^*	$d_{yz} + \pi$	π^*

Figure 2.2. Natural Transition Orbitals (NTOs) for $[\text{Co}^{\text{II}}(\text{corrin})]^+$ based on TD-DFT calculations at the uBP86/6-311G(d,p) level.

The lowest excited state determined by UBP86/6-311G(d,p) were characterized as an excitation from a mixed $d_{yz}+\pi$ orbital, where the involvement of π is small with the unoccupied d_z^2 orbital, and is mainly characterized d-d type transitions. The same character may be noticed in the D₂ state, but in this case the transition is $d_{xz} \rightarrow d_z^2$. These states are characterized by low excitation energies close to each other, equal to 0.45 eV and 0.68 eV, respectively. The D₃ state is also of d-d type from a $d_{x^2-y^2} \rightarrow d_z^2$ excitation with a transition energy of 1.38 eV. Consistent with SA-CASSCF, the lowest three excited states are d-d type with excitations to the d_z^2 orbital. The next two states, D₄ and D₅, can be characterized as mainly $\pi \rightarrow d_z^2$ excitations, with mixed $d + \pi \rightarrow \pi^*$ transitions.

The first excited states are of d-d type, similar to XMCQDPT2 calculations, and the ground state also is composed of a d_z^2 configuration. We note a difference in energy of the first excited state, that is 0.45 eV higher than S_0 by TD-DFT but nearly degenerate in XMCQDPT2 calculations. The main

difference between electronic structures determined by *ab initio* CASSCF/XMCQDPT2, and DFT calculations is in fact the lack of true degeneracy between the S_0 and S_1 DFT states, although the first transition is also described as $d_{yz} \rightarrow d_z^2$. We observe qualitative agreement in characters of the S_1 state, although there is some difference in energy. The energy and character of the D_2 state determined by CAS, and the D_3 state determined by TD-DFT are in a good agreement. The D_2 TD-DFT state in fact has no counterpart in XMCQDPT2 calculations, and is of $d_{xz} \rightarrow d_z^2$ character with some π orbital mixture. It is important to mention the involvement of such configurations relevant to transitions in the D_3 state obtained by XMCQDPT2 calculations (Table 2.1), but this state is much higher in energy (2.05 eV) and electronic transition involving also $d_{x^2-y^2}$ occupied and d_{xy} -n unoccupied molecular orbitals. We also note correlation between TD-DFT and CASSCF calculations, in that the lowest states are d-d type, and that the first excited state is very low in energy.

As shown in Figure 2.2, the lowest five TD-DFT excited states correspond almost exclusively to the β subspace, where the first four excited states are transitions on d_z^2 orbital. Furthermore, negligible α contributions to each TD-DFT excited state may also be attributed to π MO mixing. TD-DFT calculations also show near degeneracy between the first (0.45 eV) and second (0.68 eV) excited states. D_1 and D_2 states are very close to each other in energy, and are both transitions to the d_z^2 orbital from d-orbitals of cobalt. It may be noted that the D_1 state calculated by TD-DFT is composed an α d_z^2 orbital that does not participate to any significant extent in the transition (Figure 2.2), but may be interpreted as (TD-DFT) ground state character. The D_1 electronic state is thus characterized by an $(d_{yz})^1(d_z^2)^2$ configuration with some participation of the $(d_{zz})^1$ configuration of the D_0 ground state. Taking into account that the two first states from SA-CASSCF/XMCQDPT2 calculations are near degenerate with inverted weight contributions from $(d_z^2)^1$ and $(d_{yz})^1(d_z^2)^2$ electronic configurations, the D_1 electronic state from TD-DFT calculations correlates to the D_1 /XMCQDPT2 excited state. This characteristic of the ground state in the four-coordinate model, is also consistent with the five-coordinate LF state, as will be discussed further in the section regarding axial base dependence, and may be immediately observed in the five-coordinate minima as a significant contribution to D_1 from the α subspace. It should also be noted that the transition dipole moments of the lowest excited states of $[\text{Co}^{\text{II}}(\text{corrin})]^+$ calculated by both SA-CASSCF and TD-DFT are consistent with each other, and are both very low. As expected, the energy of the D_1 excited state calculated by TD-DFT is comparably greater than that by SA-CASSCF, by 0.44 eV.

In contrast, the energy of the D₂ excited state computed by TD-DFT is lower by 0.67 eV, than that determined by SA-CASSCF. Similarly, D₃ and D₄ by TD-DFT are 0.67 eV lower, and 0.66 eV lower, respectively, than by SA-CASSCF.

2.5 Five-coordinate model of cob(II)alamin

We now consider a more realistic model containing imidazole as the axial ligand, which is typically found in biological system. Similar to the four-coordinate model, in multiconfigurational SA-CASSCF calculations the active space of Im-[Co^{II}(corrin)]⁺ was comprised of 11 electrons distributed in 12 active orbitals, shown in Figure 2.3. Active orbitals were selected in SA-CASSCF in order to make comparison between the four-, and five-coordinate models, and to analyze the influence of the lower axial ligand.

The ground and four lowest excited states along with natural orbital compositions of Im-[Co^{II}(corrin)]⁺ obtained from the SA-CASSCF/ XMCQDPT2 calculations are collected in Table 2.2. It is important to mention that the XMCQDPT2 level of theory does not show mixing of CAS states, which is somehow different than the four-coordinate model. All five states observed at XMCQDPT2 retain the same order as that of their corresponding CASSCF states.

Table 2.2. The lowest five states of [Im-Co^{II}(corrin)]⁺ obtained from CASSCF/XMCQDPT2 calculations. CSF denotes the configuration state function.

State	eV	<i>f</i>	Weight (%) of CAS state in MC- XQDPT2	CAS state	Weight of CSF [%]	Electronic configuration of CAS state	Character
D ₀	0.00		100	1	92	(d _z ²) ¹	
D ₁	0.90	0.00009	96	2	55 31	(d _{yz}) ¹ (d _z ²) ² (d _{xz}) ¹ (d _z ²) ²	d _{yz} → d _z ² d _{xz} → d _z ²
D ₂	1.03	0.00012	96	3	55 31	(d _{xz}) ¹ (d _z ²) ² (d _{yz}) ¹ (d _z ²) ²	d _{xz} → d _z ² d _{yz} → d _z ²
D ₃	2.09	0.00001	95	4	67 16	(d _{x²-y²}) ¹ (d _z ²) ² (d _{xz}) ¹ (d _{yz}) ¹ (d _z ²) ² (d _{xy} -n) ¹	d _{x²-y²} → d _z ² d _{xz} /d _{yz} → d _z ² /d _{xy} -n
D ₄	2.87	0.00004	100	5	86	(d _z ²) ⁰ (d _{xy} -n) ¹	d _z ² → d _{xy} -n

As shown in Table 2.2, the ground state wavefunction obtained with CASSCF/XMCQDPT2 has one dominant CSF with a weight contribution of 92%. This indicates that the unpaired electron of the $\text{Im}[\text{Co}^{\text{II}}(\text{corrin})]^+$ model is mainly localized on the d_z^2 broadly in accord with the four-coordinate model. The most notable difference between the lower excited state manifolds of the four-, and five-coordinate models is a non-degeneracy of the D_0 and D_1 states, which is due to the presence of the imidazole ligand. The D_1 excited state of $\text{Im}[\text{Co}^{\text{II}}(\text{corrin})]^+$ is composed of two dominant CSFs, $(d_{yz})^1(d_z^2)^2$, and $(d_{xz})^1(d_z^2)^2$, that contribute 55% and 31% to the XMCQDPT2 electronic state, respectively. This excited state is near degenerate in terms of both energy and electron configuration with the D_2 excited state. D_2 has two dominant CSFs with inverted weight percentages, $(d_{xz})^1(d_z^2)^2$, and $(d_{yz})^1(d_z^2)^2$ configurations, contributing 55% and 35% to the electronic state respectively. D_1 and D_2 are thus characterized as near degenerate $d_{yz/xz} \rightarrow d_z^2$ type transitions. The remaining low-lying excited states are also composed of mixed d-d excitations, involving a d_z^2 acceptor orbital, with some minor d_z^2 contributions to each CSF. The D_3 excited state is characterized as mainly a $d_x^2-y^2 \rightarrow d_z^2$ transition, composed of a 67% $(d_x^2-y^2)^1(d_z^2)^2$ CSF, and a 16 % doubly excited $(d_{xz})^\uparrow (d_{yz})^\downarrow (d_z^2)^2(d_{xy-n})^\uparrow$ CSF. The 4th excited state has just one CSF, an 86% $(d_z^2)^0(d_{xy-n})^1$ configuration, characterized as $d_z^2 \rightarrow (d_{xy-n})$ transition.

Figure 2.3. Active orbitals of Im-[Co^{II}(corrin)]⁺ used in the CASSCF(11,12) and subsequent XMCQDPT2 calculations.

The low-lying excited state manifold of the five-coordinate model determined by CASSCF/XMCQDPT2 was then used as a benchmark for comparison with TD-DFT applied at the BP86/6-311G(d,p) level of theory. The frontier orbitals based on BP86/6-311G(d,p), contain a single occupied (SOMO) d_{z^2} type orbital, labeled H(α ,113) consistent with SA-CASSCF/XMCQDPT2 calculations of Im-[Co^{II}(corrin)]⁺. As observed in the four-coordinated model, π electron density is present to some extent in all DFT frontier MOs, including in this case, the α d_{z^2} MO, which has a small amount of π electron density from Imidazole.

To further understand similarities between the lower excited state manifold of Im-[Co^{II}(corrin)]⁺ determined by both CASSCF and TD-DFT approaches, analysis of TD-DFT electronic transitions was carried out in terms of NTOs. NTOs of the lowest five states of the five-coordinate model

are shown in Figure 2.4 (upper panel). The lowest excited states determined by both methods were composed of mixed d and π character, similar to the four-coordinated system, but were notably not exclusive to the β subspace. D_1 , D_3 and D_4 excited electronic states determined by TD-DFT are a d-d type transitions similar to lowest excited state determined by XMCQDPT. The D_2 state obtained in TD-DFT calculations comes from $d/\pi \rightarrow \pi^*$ excitation, and is not present in *ab initio* calculations. Transitions involving both occupied and unoccupied d_z^2 orbitals may be observed for the D_1 state calculated by TD-DFT, composed of both an $\alpha d_z^2 + \pi$ donor orbital, and a βd_z^2 acceptor orbital, and characterized as a 69% of $\beta d_{yz} + \pi \rightarrow d_z^2 + \pi^*$, and 31% of $\alpha d_z^2 + \pi_{lm} \rightarrow \pi^*$ transition. D_3 state also include d_z^2 orbital contributions and is characterized as a 17% of $\alpha d_z^2 + p_{lm} \rightarrow p^*$, and 83% of $\beta d_{xz} + p_{lm} \rightarrow d_z^2 + p^*$ transition, The D_1 and D_3 TD-DFT excited states are close in energy to each other, 1.40 and 1.59 eV respectively. This 0.2 eV difference in energy is relatively close to the difference in energy between D_1 and D_2 by SA-CASSCF/XMCQDPT2 (~ 0.1 eV). The D_4 TD-DFT excited state is very similar to D_3 but contains almost equal contributions from the $\alpha d_{z^2} + p_{lm} \rightarrow p^*$, and $\beta d_{yz} + p_{lm} \rightarrow d_z^2 + p^*$ transition, 52% and 48% , respectively. D_5 on the other hand, is a pure 92% $\beta d_{xz} + p_{lm} \rightarrow p^*$ transition.

NTO	eV	NTO Coeff	<i>f</i>	α hole	α particle	β hole	β particle
Im-[Co^{II}(corrin)]⁺							
D ₁	1.40	31 (α) 69 (β)	0.0001	$d_x^2 + \pi_{1m}$	π^*	$d_{yz} + \pi$	$d_x^2 + \pi_{1m}^*$
D ₂	1.50	36 (α) 64 (β)	0.0008	$d_{yz} + \pi$	π^*	$d_{yz} + \pi$	π^*
D ₃	1.59	16 (α) 83 (β)	0.0010	$d_x^2 + \pi_{1m}$	π^*	$d_{xz} + \pi$	$d_x^2 + \pi_{1m}^*$
D ₄	1.65	49 (α) 51 (β)	0.0026	$d_x^2 + \pi_{1m}$	π^*	$d_{yz} + \pi$	$d_x^2 + \pi_{1m}^*$
D ₅	1.81	8 (α) 92 (β)	0.0028	$d_{xz} + \pi_{1m}$	π^*	$d_{xz} + \pi_{1m}$	π^*
[Im--Co^{II}(corrin)]⁺ (2.80 Å)							
D ₁	0.72	0 (α) 100(β)	0.000	d_x^2	π^*	$d_{yz} + \pi$	d_x^2
D ₂	0.91	0 (α) 100(β)	0.0000	d_x^2	π^*	$d_{xz} + \pi$	d_x^2
D ₃	1.55	11 (α) 52 (β)	0.0017	π	π^*	$d_x^2 - y^2$	d_x^2
D ₄	1.66	25 (α) 50 (β)	0.0001	π	π^*	$d_x^2 - y^2$	d_x^2
D ₅	1.84	8 (α) 92 (β)	0.0015	π	π^*	π	d_x^2

Figure 2.4. NTOs for Im-[Co^{II}(corrin)]⁺ (upper) and [Im--Co^{II}(corrin)]⁺, Co-C = 2.80 Å, (lower) based on TD-DFT calculations at the uBP86/6-311G(d,p) level.

2.6 TD-DFT of the full structure of cob(II)alamin

Comparison of the low-lying excited states between both four-, and five-coordinate models reveals comparable agreement between *ab-initio* CASSCF/XMCQDPT2 and TD-DFT methods. This benchmark study provides further confidence that TD-DFT calculations can be extended to full cobalamin structural models to accurately predict electronically excited states. To evaluate the effects of truncation, TD-DFT was applied to cob(II)alamin to obtain the 10 lowest excited states at the BP86/6-311G(d,p) level. In addition, 160 states were obtained for cob(II)alamin at the BP86/SDD level to extend the range of states relevant to experiment at reduced computational cost. The experimental spectra of cob(II)alamin was taken from steady-state studies performed by the Sension group,⁵⁴ and is shown in Figure 2.5 with relevant TD-DFT states. Selected TD-DFT transitions of cob(II)alamin at the UBP86/SDD level, along with corresponding transitions for both minima and elongated Co-N truncated models at the UBP86/6-311G(d,p) level are collected in Table 2.3. NTOs for these transitions also correlate well with experiment and TD-DFT excited states of cob(II)alamin, and the truncated models as reported.

Table 2.3. Select TDDFT excited states of the full cob(II)alamin structure using BP86/SDD, and truncated models [Im-Co^{II}(corrin)]⁺_(min, 2.13 Å), and [Im- - Co^{II}(corrin)]⁺_(LF, 2.80 Å) using BP86/6-311G(d,p).

State	eV	λ (nm)	f	NTC Coeff.	major TDDFT MOs	Character
cob(II)alamin (min, 2.23 Å)						
D ₁₉	2.71	457.2	0.0276	46	251(α) $\rightarrow$ 255(α)	$d_{x^2-y^2} + \pi \rightarrow \pi^*$ $d_{x^2-y^2} + \pi \rightarrow$ $d_z^2 + \pi_{Im}^*$
				29	250(β) $\rightarrow$ 255(β)	$d_z^2 + \pi \rightarrow \pi^*$
				25	254(α) $\rightarrow$ 257(α)	$\pi_{Im} + p \rightarrow \pi^*$
D ₂₉	2.93	422.9	0.0377	63	247(α) $\rightarrow$ 255(α)	$\pi + d_z^2 \rightarrow \pi^*$
				19	246(α) $\rightarrow$ 255(α)	$\pi_{Im} \rightarrow \pi^*$
				19	247(β) $\rightarrow$ 254(β)	$d_{xz} + \pi \rightarrow \pi^*$
D ₆₁	3.39	366.2	0.0263	78	252(β) $\rightarrow$ 258(β)	$d_{xz} + \pi_{Im} \rightarrow \pi^*$
				22	252(α) $\rightarrow$ 258(α)	$d_{x^2-y^2} + \pi \rightarrow d_{xy-n}$
D ₁₄₄	3.95	313.7	0.0923	60	250(β) $\rightarrow$ 259(β)	$\pi_p \rightarrow \pi^*$
				40	242(α) $\rightarrow$ 257(α)	
[Im-Co ^{II} (corrin)] ⁺ _(min, 2.13 Å)						
D ₂₃	3.00	413.8	0.0610	32	109(α) $\rightarrow$ 114(α)	$\pi + d_z^2 \rightarrow \pi^*$
				17	113(α) $\rightarrow$ 117(α)	$d_z^2 + \pi \rightarrow \pi^*$
				30	110(β) $\rightarrow$ 115(β)	$d_{x^2-y^2} \rightarrow d_{xy-n}$
				21		$\pi \rightarrow d_{z2} + \pi^*$
D ₃₃	3.38	366.7	0.0500	75	111(β) $\rightarrow$ 117(β)	$d_{xz} + \pi \rightarrow \pi^*$
				25	110(α) $\rightarrow$ 115(α)	$d_{x^2-y^2} \rightarrow d_{xy-n}$ $d_{xz} + \pi +$
D ₄₅	3.80	326.1	0.0689	89	111(α) $\rightarrow$ 117(α)	$\pi_{Im} \rightarrow \pi^*$
					108(α) $\rightarrow$ 115(α)	
				11	112(β) $\rightarrow$ 114(β)	$d_{xz} + \pi \rightarrow \pi^*$
D ₅₆	4.09	303.0	0.2433	40	109(α) $\rightarrow$ 116(α)	$\pi + d_z^2 \rightarrow \pi^*$
				33	109(β) $\rightarrow$ 115(β)	$\pi + d_z^2 \rightarrow \pi^*$
				15	106(β) $\rightarrow$ 114(β)	$\pi \rightarrow d_{yz} + \pi^*$
				12		$\pi + d_{yz} \rightarrow \pi^*$
[Im- - Co ^{II} (corrin)] ⁺ _(LF, 2.80 Å)						
D ₁₇	2.73	455.0	0.0455	58	112(α) $\rightarrow$ 114(α)	$d_z^2 + \pi \rightarrow \pi^*$
					109(α) $\rightarrow$ 114(α)	
				42	109(β) $\rightarrow$ 114(β)	$d_z^2 + \pi \rightarrow \pi^*$
D ₂₆	3.09	401.2	0.0953	66	109(α) $\rightarrow$ 114(α)	$\pi + d_z^2 \rightarrow \pi^*$
				34	109(β) $\rightarrow$ 114(β)	$d_{x^2-y^2} \rightarrow \pi^*$ $\pi_{Im} + p \rightarrow$ $d_z^2 + \pi_{Im}^*$
D ₃₃	3.44	360.0	0.0520	74	105(β) $\rightarrow$ 113(β)	$\pi + d_z^2 \rightarrow d_{xy-n}$
				26	109(α) $\rightarrow$ 115(α)	$\pi + d_z^2 \rightarrow \pi^*$
D ₅₄	4.06	305.1	0.2472	40	109(α) $\rightarrow$ 116(α)	$\pi + d_z^2 \rightarrow \pi^*$
				33	109(β) $\rightarrow$ 115(β)	$\pi + d_{yz} \rightarrow \pi^*$
				15	107(α) $\rightarrow$ 114(α)	$\pi + d_{yz} \rightarrow \pi^*$
				12	107(β) $\rightarrow$ 114(β)	$\pi + d_{yz} \rightarrow \pi^*$

Calculated TD-DFT transitions of cob(II)alamin are consistent with the truncated models in energy with some subtle differences in electronic excited state character. NTOs of cob(II)alamin at the SDD level (Figure 2.6), the particle states are more delocalized than corresponding hole states due to the treatment of the TD-DFT electron density at the SDD level. and TD-DFT NTO character for these states was determined by significant MO composition. Differences in oscillator strengths between the full and truncated minima in the range of around 2.7 eV to 3.0 eV of the calculated spectrum may be attributed to higher weight contributions of LF-type transitions observed in the truncated TD-DFT states.

Figure 2.5. Experimental cob(II)alamin steady-state spectra (solid line), and TD-DFT transitions of cob(II)alamin at the BP86/SDD level (circles); and of the two truncated structural models with BP86/6-311g(d,p): Im-[Co^{II}(corrin)]⁺, min (filled triangles), and the [Im---Co^{II}(corrin)]⁺ LF state, Co-C = 2.80 Å, (empty triangles).

The experimental transition around 2.7 eV is not significantly resolved in the TD-DFT spectra of the truncated minima, but comparable oscillator strengths for this transition are observed in the full model and the LF state of the truncated model. This electronic transition was further explored and the D₁₉ state of the full structure at the UBP86/SDD level, and the D₁₇ state of the truncated model complex at

the BP86/6-311G(d,p) level both were around 2.7 eV, with comparable oscillator strengths. This transition, associated with $d_z^2 + \pi \rightarrow \pi^*$ character, appears in the D_{23} state of the truncated model with 17% contribution. This $d_z^2 + \pi \rightarrow \pi^*$ transition also occurs as a 25% weight contribution to D_{19} state for the full structure of cob(II)alamin, and essentially composes 100% of the LF excited state (D_{17}) as a partitioned β $d_z^2 + \pi \rightarrow \pi^*$ (58%), α $d_z^2 + \pi \rightarrow \pi^*$ (42%) transition.

NTO	eV	NTO Coeff	f	α hole	α particle	β hole	β particle
D_1	1.27	6 (α) 94 (β)	0.0001	$d_z^2 + \pi_{lm}$	π^*	$d_{yz} + \pi$	$d_z^2 + \pi$
D_2	1.42	0 (α) 100 (β)	0.0001	$d_z^2 + \pi_{lm}$	π^*	$d_{xz} + \pi$	$d_z^2 + \pi$
D_3	1.48	37 (α) 63 (β)	0.0005	$d_{yz} + \pi_{lm}$	π^*	$d_{yz} + \pi$	π^*
D_4	1.72	91 (α) 8 (β)	0.0074	$d_z^2 + \pi_{lm}$	π^*	$d_{yz} + \pi$	$d_z^2 + \pi^*$
D_5	1.78	14 (α) 85 (β)	0.0023	$d_{xz} + \pi$	π^*	$d_{xz} + \pi$	π^*

Figure 2.6. NTOs of the first 5 TDDFT excited states of the cob(II)alamin structure at the BP86/6-311G (d,p) level of theory.

NTOs of the lowest five TD-DFT excited states of cob(II)alamin at the UBP86/6-311G(d,p) level are shown in Figure 2.6. The most apparent difference at the TD-DFT level between the five lowest excited states of cob(II)alamin, and the truncated model is the reverse the order energy for D_2 and D_3 electronic states. In the case of the full structure of cob(II)alamin, there is a decrease in α d_z^2 character of

the lower two excited states. The D_1 state of cob(II)alamin occurs with less αd_z^2 character than Im- $[\text{Co}^{\text{II}}(\text{corrin})]^+$ model complex (6% vs. 31%, respectively), and the D_2 state occurs with a 100% βd_z^2 acceptor MO, and no α contribution. The remaining low-lying excited states of cob(II)alamin and the model complex are readily verified as consistent with each other in character, and are characterized as a 63% of $d_{yz} + \pi \rightarrow \pi^*$, 37% of $d_{yz} + \pi_{\text{Im}} \rightarrow \pi^*$ transition for the D_3 state, a 91% of $d_z^2 + \pi_{\text{Im}} \rightarrow \pi^*$, 8% of $d_{yz} + \pi \rightarrow \pi^*$ transition for the D_4 state, and a 85% of $d_{xz} + \pi \rightarrow \pi^*$, 14% of $d_{xz} + \pi \rightarrow \pi^*$, transition for the D_5 state. It may also be noted that the optimized Co- N_{Im} bond distance for cob(II)alamin is slightly longer than that of the truncated model, 2.23 Å vs 2.13 Å, respectively. This elongation of Co-N bond length could be attributed to the additional electron density of the full system where cobalt, corrin, and DBI are included, and may be attributed to larger a repulsive interaction of the DBI ligand with the equatorial coordination sphere in the full structure, when compared to the interaction of imidazole in the model complex. The LUMO and $L + 1$ β MOs at the UBP86/SDD level are consistent in character with UBP86/6-311G(d,p) although the d_z^2 character is higher in energy for SDD. It is important to mention that the D_1 state at the TD-DFT level is consistently a transition to the d_z^2 orbital, regardless of basis set, structural model, or whether the d_z^2 orbital is LUMO or $L + 1$. As discussed in section 3.5, an increase in Co- N_{Im} bond-length can be summarized as corresponding to lowering of energy of the d_z^2 orbital in both subspaces α and β , leading to a decrease in $\alpha d_z^2 \rightarrow \pi^*$ character, and an increase in $\beta d_{yz} + \pi \rightarrow d_z^2$ character of the D_1 excited states for the five-coordinate complex (Figure 2.7). At longer Co- N_{Im} distances two LF excited states are close in energy with small excitation energy, and correspond to the two low-lying LF states for four-coordinate complex.

Although subtle differences in electronic character of frontier orbitals may be noted between the full and truncated models, the energies of these transitions relative to their respective ground states are comparable, with oscillator strengths also comparable to experimental spectra, and as such these calculations should be considered reliable for the prediction of excited state properties.

2.7 Electronic structure of low-lying ligand field states: influence of axial base

Consistency between TD-DFT and *ab-initio* CASSCF/XMCQDPT2 methods for both four- and five-coordinated models, as well as consistency between the TD-DFT states of the full cob(II)alamin

structure, and the truncated models, further validates the accuracy of calculated TD-DFT excited states in the ligand-field range. To further understand the electronic structure, and the nature of low-lying excited cob(II)alamin states as a function of axial base, DFT/UBP86 was applied to the five-coordinated model to obtain a one-dimensional energy surface of frontier MOs (Figure 2.7).

Figure 2.7. Energies of frontier molecular orbitals for Im-[Co^{II}(corrin)]⁺ model complex as a function of Co-N_{Im} distance. Purple line – energies of alpha orbitals, black line – energies of beta orbitals, filled and dotted lines correspond to the occupied and unoccupied orbitals, respectively.

The most notable feature of Im-[Co^{II}(corrin)]⁺ with respect to elongation of the Co-N_{Im} distance is the lowering in energy of both α and $\beta d_z^2 + \pi$ orbitals in the LF. This is in agreement with a system approaching the four-coordinate structural model, where the $\beta d_z^2 + \pi$ is the LUMO, and much closer in energy to the occupied orbitals. In the Co-N_{Im} distances which the lowest electronic state has dominant LF character, the energy of the $d_z^2 + \pi_{Im}$ MO is also lower in the alpha subspace, and finally in

the distance about 2.80 Å corresponds to α H-4, while all other frontier orbitals remain essentially unchanged with respect to the Co-N coordinate. The band gap in the LF state of the five-coordinate model was also lower than at the minimum, 1.10 eV vs. 1.57 eV respectively, and was between β MOs $d_{yz} + \pi$ and $d_z^2 + \pi_{lm}^*$, rather than α MOs $d_z^2 + \pi_{lm}$ and π^* at the minima. Although the five-coordinate LF model, and the four-coordinate model have HOMOs and LUMOs consistent with each other, a lower band gap of 0.45 eV is observed for the four-coordinate model. The lowering of D_1 excitation energy with respect to Co- N_{lm} distance, is shown in Figure 2.8, and is associated with an increase in β $d_{yz} + \pi \rightarrow d_z^2$ excited state character.

Figure 2.8. Potential energy curves of the ground and nine lowest doublet TD-DFT excited states of the Im-[Co^{II}(corrin)]⁺ model complex as a function of Co- N_{lm} bond length.

Decreasing the Co- N_{lm} bond length to 1.85 Å lowers the D_1 energy, with an increase in α d_z^2 ground state that contributes to a 100% α $d_z^2 + \pi_{lm} \rightarrow \pi^*$ transition. NTOs of the lower excited state manifold of the LF state collected in Figure 2.4 (lower panel), and consist mainly of transitions to d_z^2

orbitals of the β subspace, with minor contributions from the $\alpha \pi^*$ acceptor. The D_1 and D_2 NTOs are exclusively comprised of the β subspace consistent with four-coordinated cob(II)alamin, and have very low excitation energies, 0.72 and 0.91 eV, respectively. The remaining three low-lying excited states can be described as having minor $\alpha \pi \rightarrow \pi^*$ character, with higher weight contributions from β transitions, to d_z^2 acceptor. This is also observed in D_4 and D_5 of the lower LF excited states shown in Figure 2.4 (lower panel). D_4 is composed of the same α and β MOs as D_3 , but higher in energy, 1.55 vs. 1.66 eV respectively, with a higher weight from the $\alpha \pi \rightarrow \pi^*$ transition. The D_5 electronic state, which has three π and π^* components, can be characterized as mainly a $\pi \rightarrow d_z^2$ (92%) transition.

2.8 Implications

It should be noted that both LF D_1 and D_2 transitions were below the experimental MCD detection limits for $[\text{Co}^{\text{II}}(\text{corrin})]^+$, and $\text{Im}-[\text{Co}^{\text{II}}(\text{corrin})]^+$ systems¹⁰³. Although the LF electronic state of the $\text{Im}-[\text{Co}^{\text{II}}(\text{corrin})]^+$ complex with $3d_{x^2-y^2}$ donor MO (~ 1.55 eV) may be considered close to the (four-coordinate) $[\text{Co}^{\text{II}}(\text{corrin})]^+$ MCD detection limit (~ 1.68 eV), this transition is also below reported MCD detection limits for $\text{Im}-[\text{Co}^{\text{II}}(\text{corrin})]^+$ (~ 2.19). As such, qualitative spin-orbit coupling descriptions of electronic transitions in this region based on experimental C/D values derived from low energy Abs and MCD data are difficult to assign. Improved resolution of experimental MCD spectra, would allow for further investigation into the properties of very low energy electronically excited states, such as possible charge-transfer character, and specific donor-acceptor composition.

2.9 Summary

TD-DFT calculations were carried out on the full structure and truncated structural models of cob(II)alamin, and were consistent with corresponding excited state descriptions at the CASSCF/XMCQDTP2 levels of theory. The distance of axial base from the cobalt center in the five-coordinate Co(II) corrin complex, modulates the character and energy of the low-lying excited state. The D_1 and D_2 TD-DFT electronic states of the five-coordinate Co(II) complex are close in energy, and can be characterized as LF $d \rightarrow d_{z^2}$ states for elongated Co-N distances. The increasing $d + \pi \rightarrow d_z^2$ character of these transitions at increasing Co- N_{ax} distances is directly associated with lowering the energy of the unoccupied d_z^2 orbitals. These LF states have nonbonding character in relation to bonding with the axial

base, and lowering their energy with increasing Co-N_{ax} distance, leads to partial or total disconnection of the axial base from the Co(II) corrin system. At larger Co-N_{ax} distances, the lowest D₁ and D₂ doublet states correspond to the appropriate lowest LF states of the four-coordinate Co(II) corrin complex, which are close in energy to ground state. On the other hand, SA-CASSCF/ XMCQDTP2 calculations for the four-coordinate complex shown that the D₀ ground state has a (d_{z²})¹ electronic configuration with small admixture of a (d_{yz})¹(d_{z²})² excited configuration. Simultaneously, the D₁ state corresponds mainly to the (d_{yz})¹(d_{z²})² configuration. The D₁ state has a very low excitation energy and from the point of view of *ab initio* calculations, is near degenerate with ground state. The detachment of axial base from Co(II) corrin complex should thus cause near degeneration of low-lying LF d → d_{z²} electronic states with the ground state.

TD-DFT states with simultaneous ground and excited state contributions from the d_{z²} MO may be noted throughout the lower excited state manifolds of the full structure and five-coordinate minima, and around 2.71 eV, and 3.00 eV at the UBP86/SDD, and UBP86/6-311G(d,p) levels, respectively. This α d_{z²} + π → π* component, may also be noted in the LF excited state (D₁₇) around 2.73 eV along with a symmetric 58% β d_{z²} + π → π* component, indicating that some LF character is inherent in the ground state at this energy.

CHAPTER III CYANOCOBALAMIN AND HYDROXOCOBALAMIN

3.1 Background

The electronic excited states, and internal conversion (IC) of CNCbl have been thoroughly investigated using ultrafast spectroscopy and TD-DFT.^{60, 64, 146-147} CNCbl is one of most well characterized cobalamins by high-quality transient IR, and UV-Vis, in the range of 266 to 590 nm. Most notably the CNCbl system is photostable, and the Co-CN bond does not photo-dissociate under simple photon excitation. HOCbl is also photostable, but is a special case where photolysis may also be induced by light, as will be addressed in 3.3.

Electronic excitation of CNCbl results in IC through a cascade of states involving the π/d orbitals of corrin and Co to the ground state through a short-lived LMCT intermediate. This S_1 state has decay rates, which are both temperature and solvent dependent, with increasing lifetimes in less polar solvents. In water at room temperature, the experimentally determined barrier to IC is 2.1 kcal/mol, and occurs on a 6.7 ± 0.2 ps time scale. The LMCT intermediate of CNCbl is a key photochemical state observed experimentally, and is characterized as $\pi \rightarrow \sigma^*(d_z^2)$ LMCT. The PESs calculated by TD-DFT are considered to describe the excited state dynamics of CNCbl very well in accord with experimental results.

The optimum energy path resulting in effective IC to the ground state lies on a diagonal cut bisecting the 3D PES. Analysis of the excited state manifold of CNCbl reveals that initial excitation results in Franck-Condon population of higher $\pi \rightarrow \pi^*$ states, followed by decay to an intermediate $\pi \rightarrow d$ LMCT state. Decay to this $\pi \rightarrow d$ LMCT intermediate results in only a slight elongation of both axial bond lengths, corresponding to 1.857 to 1.900 Å for Co-C, and 2.054 to 2.096 Å for Co-N_{Im} (labeled A and B in Figures below). This $\pi \rightarrow d$ LMCT state then relaxes along the S_1 surface to a very shallow $\pi \rightarrow \sigma^*(d_z^2)$ LMCT minimum with a more pronounced structural changes, corresponding to elongated bond lengths of 2.216 for Co-C, and

2.275 for Co-N_{Im}, (labeled C). Further axial bond elongation from this LMCT minimum does not lead to photodissociation, but rather a crossing of the S₀ state with S₁ at a Co-C distance of 2.650 Å, and Co-N distance of 2.55 Å, effectively leading to IC. The energy barrier between the S₁ minimum and the S₁/S₀ crossing point, was estimated to be around 5 kcal/mol, which can be compared directly with the experimental value of 2.1 ± 0.2 kcal/mol in water at room temperature, based on a dielectric constant of 80.

3.2 Cyanocobalamin

3.2.1 Potential energy surfaces and mechanism of photostability

While excited-state dynamics of CNCbl have been extensively studied experimentally, there until recently was a limited mechanistic understanding of its photostability. Previous theoretical investigations using DFT and TD-DFT examined the nature of the lowest electronic transitions, and their corresponding potential energy surfaces (PESs),²⁰⁻²¹ where the primary focus of these studies was on the electronic spectra of CNCbl, and the potential energy curves along the Co-C stretched bond. The S₁ PES as a functions of axial bond distances were computed for the lowest excited states as vertical excitations based on ground state geometries.²⁰

To obtain a more realistic description of the S₁ PES, and thus more reliable energetics of the intermediates associated with the internal conversion (IC) mechanism, in the present theoretical account the excited state structural properties of CNCbl were investigated using TD-DFT.²²⁻²⁶ The relaxed geometry of the S₁ state was constructed as a function of both axial Co-C and Co-N_{Im} distances, and a minimum energy crossing point with respect to the ground state was then located. These calculations were used to obtain a mechanism of S₁ state radiationless deactivation of vitamin B₁₂, that provide new insight at the molecular level into the excited state dynamics of CNCbl, in alignment with the latest experimental data.¹⁹

DFT and TD-DFT²⁶⁻²⁷ calculations were performed using an implicit COSMO solvent,²⁸ and the BP86 functional,²⁹⁻³⁰ with TZVPP basis set,³¹⁻³² as implemented in TURBOMOLE.³³ The structural model denoted Im-[Co^{III}(corrin)]-CN⁺ reproduces the structural and spectroscopic features of vitamin B₁₂ very well.^{20,47} The reliability of TD-DFT using the BP86 functional in the calculation of the lowest excited states for CNCbl was established in our previous studies.²⁰⁻²¹

The DFT-based optimized geometry of the ground state (S₀) was in good agreement with

x-ray crystallographic data. In the S_1 state the Co-C bond is much longer than in the S_0 state (2.216 versus 1.857 Å). A similar trend was observed for the Co-N_{Im} bond, which was equal to 2.275 Å in the S_1 state, while 2.054 Å in the S_0 state. A characteristic weakening of the axial bonds of these ligands in the S_1 state was in agreement with previous experimental observation. The cyanide ligand was also slightly bent in the S_1 state (bending angle 170°), in comparison with the linear arrangement in the ground state, while the geometry of the corrin ring remains essentially unchanged upon $S_0 \rightarrow S_1$ excitation. The NBO charge difference between the S_0 and S_1 electronic states calculated for the S_1 geometry also shows a significant positive charge increase on the corrin ligand, and a negative charge increase on cobalt, cyanide and imidazole.¹⁴⁶ Hence, the electron density is shifted from corrin to the axial ligands and cobalt. Similar conclusions can be drawn from the difference density between S_0 and S_1 isosurfaces confirming the fully optimized S_1 state as being LMCT-type.

Figure 3.1. Optimized energy of the S_1 state as function of the Co-C distance. Energy of the lowest vertical singlet excited state is denoted as A, and is based on the optimized geometry of the ground state. Point B corresponds to Co-C = 1.9 Å, while point C to the S_1 minimum.¹⁴⁵

Because the nature of the low-lying excited states of Im-[Co^{III}(corrin)]-CN⁺ have been analyzed previously, including their dependence on solvent, only a brief description will be given here. Analysis of the vertical electronic excitations revealed that the lowest transition is of $\pi \rightarrow$

π^* type. The second excited state (S_2) is of $\pi \rightarrow d$ character, while S_3 and S_4 are a mixture of $\pi \rightarrow \sigma^*$ and $\pi/d \rightarrow \pi^*$ excitations. The higher electronic transitions are of mixed $d \rightarrow \pi^*$, $\pi/d \rightarrow \sigma^*$ and $d \rightarrow d$ character. The optimized energy of the S_1 state as a function of Co-C distance is shown in Figure 3.1, where the energy of the vertical $\pi \rightarrow \pi^*$ excitation has been also included (denoted as A in Figure 3.1).

The minimum energy at 2.216 Å is labeled as C, while the vicinity of crossing between two states that corresponds to the distance of 1.9 Å, is labeled as B. Note that crossing of two states along the Co-C coordinate can only be approximately estimated, and previous studies have demonstrated that this crossing may involve more than two electronic states.²¹ It should be pointed out that the proposed mechanism is in accord with ultra-fast excited state dynamics, where an 80 fs decay of the initial excited state, a 190 fs decay of an intermediate electronic state, and a 6.7 ps decay of the S_1 excited state population to the ground state were reported.¹⁷ These experimental time constants are consistent with the nature of the potential energy curves. To further understand the electronic properties of the excited states shown in Fig. 3.1, frontier orbitals corresponding to three different geometries, S_0 minimum (A), the optimized S_1 geometry corresponding to a Co-C distance of 1.9 Å (B), and the S_1 minimum geometry (C), were obtained from TD-DFT calculations and collected in Figure 3.2.

The lowest singlet excited state for all three geometries comes from the HOMO $\rightarrow$ LUMO excitation. At the S_0 optimized geometry the lowest vertical S_1 excited state is of $\pi \rightarrow \pi^*$ character, and optimization at this point changes the character to $\pi \rightarrow d/\pi$. Around 1.9 Å the character of S_1 changes to $\pi \rightarrow \sigma^*$. The antibonding σ^* orbital contains a large contribution from the d_{z^2} cobalt MO, and the S_1 state at its optimal geometry can be described as a LMCT state with elongated and weakened axial bonds, consistent with experimental assignment based on transient absorption spectroscopy.¹⁹ These changes are nicely reflected by the change in nature of the LUMO orbital from A-C (Fig. 3.2).

Figure 3.2. Molecular orbital diagrams corresponding to the lowest singlet excited states of CNCbl representing; the optimized geometry of the S_0 state (A); the optimized geometry of the S_1 state with fixed Co-C bond distances at 1.9 Å (B); the optimized geometry of the S_1 state with fixed Co-C bond distances at 1.9 Å (B); the optimized geometry of the S_1 state (C).¹⁴⁵

Having discussed the properties of the low-lying electronic transitions along the Co-C stretched coordinate, the properties associated with the S_1 PES may now be discussed. The PES of the S_1 excited state of CNCbl was calculated based on the Im-[Co^{III}(corrin)]-CN⁺ structural model, and the energy of the excited state was optimized on a 0.05 Å grid, where Co-C and Co-N_{Im} distances were fixed and the remaining geometries were optimized at each point by TD-DFT. The resulting S_1 energy surface as a function of optimized Co-C and Co-N_{Im} distances is shown in Figure 3.3 along with the upper portion of the ground state surface, where the crossing with S_1 along the seam indicated by a black dashed line leads to IC.

Figure 3.3. Potential energy surface of the S_1 state, along with the upper portion of the ground state surface. Characteristic points on the S_1 PES correspond to: ground state S_0 geometry (A), S_1 with $\text{Co-C} = 1.9 \text{ \AA}$ (B); energy minimum of the S_1 state (C); minimum energy point of the S_1/S_0 crossing seam (D).¹⁴⁵

Note that the intersection seam was determined by extrapolation as will be described.

There is a shallow minimum on the S_1 energy surface at $\text{Co-C} = 2.216 \text{ \AA}$ and $\text{Co-N}_{\text{Im}} = 2.275 \text{ \AA}$ that corresponds to the optimized structure of S_1 . Starting from vertical excitation of the S_0 geometry (A), there is a valley leading to the S_1 minimum (C) (Figure 3.3). Characteristic points A, B, and C as well as the minimum energy crossing point to the ground state (D), are all on a diagonal cut bisecting the 3D PES. The corresponding energy curve along this minimum energy path between the S_0 and S_1 equilibrium geometries is presented in Figure 3.4. As noticed previously, even for Co-C distances in the range $1.8\text{-}1.9 \text{ \AA}$ the lowest excited state is not a $\pi \rightarrow \pi^*$ state, but a $\pi \rightarrow d$ transition, indicating that during geometry optimization of the S_1 state the first and second electronic transitions are very close in energy, and change their order. At Co-C distances slightly larger than $1.9 \text{ \AA}$, the crossing of two excited states occurs. This crossing is barrierless since it occurs before the minimum of the lowest singlet excited state, before changing its character to $\pi \rightarrow \sigma^*$. The changes in character of the S_1 state thus results in the crossing between the lowest excited states which are close in energy.

Figure 3.4. Schematic representation of the diagonal cut bisecting the 3D PES.¹⁴⁵

Radiationless deactivation (or vibrational relaxation known as IC) of an excited state occurs when the excited and ground states cross with a small energy barrier, or no barrier at all. Interestingly, if one takes into consideration the diagonal cut (Figure 3.4) through the 3D PES the resulting energy path in fact can be associated with the S_1 excited state IC in CNCbl.

Along seam where the crossing of two electronic states takes place the wavefunction should have a multiconfigurational character, and crossing surfaces cannot be appropriately described by a single-determinant-based TD-DFT wavefunction. As a consequence, problems with convergence of the SCF procedure appear at the intersection points.³⁴⁻³⁵ Due to the size of CNCbl (~160 atoms), the TD-DFT method is the only choice for determining excited state properties. Notably and as expected, the calculation encounters convergence problems when the energy difference between the S_0 and S_1 states becomes ~2 kcal/mol. To circumvent these problems inherent with TD-DFT, quadratic extrapolation was used to estimate the intersection point. The active coordinates in S_1/S_0 internal conversion were determined to be only Co-C and

Co-N_{lm} distances, because these coordinates differ mostly in the optimized structures of the S₀ and S₁ states. This can be deduced from the fact that when both distances were elongated, the S₁ and S₀ surfaces approach each other.

Other coordinates such as Co-C-N_{lm} bending angle and corrin distortion were also varied, but excitation energies remained mainly constant. The minimum energy point on the seam was taken as an intersection point (D), and the energy barrier between the S₁ minimum, and the minimum on the intersection seam was estimated to be ~5.0 kcal/mol. The energy of 5.0 kcal/mol can be directly compared to a 2.1 ± 0.2 kcal/mol experimental IC barrier based on the dielectric constant of 80 at room temperature for water.¹⁹ The estimated energy barrier of 5.0 kcal/mol has to be taken with caution, due to the method of searching for the S₀/S₁ crossing point.

Overestimation of barrier height is due to several possible sources of error: (1) the extrapolation procedure has an associated error which can be estimated to be around 2 kcal/mol, (2) only a limited number of parameters were taken into account in the search for the lowest energy crossing point. Although increasing the number of parameters (over three) could possibly lower the energy of the crossing, the calculations would not be feasible. (3) The accuracy of the computational method itself associated with TD-DFT also represents a limiting factor. (4) There may also be additional computational error associated with the solvent model, in accord with experiments that suggest the barrier is also sensitive to solvent polarity, though this may be the least significant source of error comparatively. By taking all of these factors into account, the calculated energy barrier can be viewed as quite satisfactory in comparison with experimental value.

Based on a diagonal cut through the 3D PES (Figure 3.4) showing the crossing of S₁ and S₀ energy surfaces the following mechanism of radiationless deactivation of the S₁ state in CNCbl can be proposed. After initial excitation to one of the higher-lying excited states, a fast reversion to the lowest $\pi \rightarrow \sigma^*$ excited state takes place. Next the system goes through an intermediate state of $\pi \rightarrow d$ character, and eventually reaches the S₁ minimum of $\pi \rightarrow \sigma^*$ character. This process is very fast and can be ascribed to the femtosecond time range of CNCbl photophysics.¹⁹ This process is also barrierless and crossing the intermediate state occurs before reaching the S₁ minimum. The lifetime of the lowest excited state of CNCbl can be estimated to be between 2 - 16 ps.¹⁹ By analyzing the minimum energy path leading from the vertically excited S₀ geometry

(A) to the minimum on the S_1 PES (C), and finally to the lowest energy point on the crossing seam between S_0 and S_1 (D), it can be seen that along this path both axial bonds are simultaneously elongated. The geometry of the crossing point has very long axial bond distances: 2.65 Å for Co-C and 2.55 Å for Co-N_{Im}. The cyanide ligand is practically linear, revealing that the Co-C bending angle has no impact on the energy of the intersection point. This is understandable since at long distances the cyanide ligand is weakly bound, and bending does not influence the total molecular energy.

3.2.2 Experimental outlook: Polarized XANES monitors structural evolution

Figure 3.5. Schematic representation of polarized XANES spectra monitoring structural evolution in cyanocobalamin.¹⁴⁶

Ultrafast, polarization-selective time-resolved X-ray absorption near-edge structure (XANES) was used to characterize the photochemistry of CNCbl in solution, with our collaborators from SLAC and the University of Michigan.¹⁴⁷ Polarized femtosecond XANES combined with UV-Vis spectroscopy reveals sequential structural evolution of CNCbl in the excited electronic state (Figure 3.5). Based on PESs calculated by TD-DFT, femtosecond

polarized XANES provides a critical structural dynamic link to optical transient absorption spectroscopy. Polarization selectivity may be used to uniquely identify electronic contributions and structural changes, even in isotropic samples when well-defined electronic transitions are excited. XANES measurements reveal structural changes upon photoexcitation occur mainly in the axial direction, where elongation of the axial Co–CN bond and Co–N Im bond on a 110-fs time scale is followed by corrin ring relaxation on a 260 fs time scale.

Simulations performed for the truncated cobalamin ground-state structure are in good agreement with measured ground-state XANES spectrum (Figure 3.6, left). The difference spectrum between ground- and excited-state structures is in good agreement with the isotropic difference spectrum measured at 1.5 ps (Figure 3.6a), providing direct experimental support for the theoretically predicted intermediates. The x and $y + z$ components of the difference spectrum are also compared with simulations (Figure 3.6b), and the relative magnitude of these signals at 1.5 ps are accurately predicted. In simulations the x - and y -polarized difference spectra are similar and both are small, indicating not much change occurs in corrin-cobalt coordination in the ground and excited states. The agreement between experimental and calculated x -polarized difference spectra further supports the assignment of the x direction defined by the methylene groups, where increased absorption at 7.74 keV is predicted for x and not y .

Figure 3.6. Comparison of experimental and simulated XANES spectra at 1.5 ps: (a) Isotropic XANES ground- and excited- state spectra and the difference spectrum between the ground and excited state. The ground state spectrum (blue) and the difference spectrum (green), are used to estimate the excited state spectrum (red) by adding appropriate percentage of ground state spectrum into the difference spectrum; (b) Components x , y , and z of the difference spectrum are compared. The $y+z$ difference (green) is plotted on the left-hand scale. The x difference (blue) is multiplied by four and offset for clarity. The $y+z$ simulation (yellow) is decomposed into the y and z contributions (violet dashed lines) with z making the largest contribution. The y contribution (violet dashed line) is also compared with the simulated x (pink) contribution.¹⁴⁶

From XANES data a picture emerges that begins with formation of the Franck-Condon state on a time scale not distinguished from the instrumental limit, followed by internal conversion to the $(\pi^1(\sigma^*d_z^2)^1)$ intermediate and rapid elongation of the axial bonds on a 110 fs time scale, followed relaxation of the corrin ring in the excited state on a 260 fs time scale, with IC to the ground state occurring on a 6.2 ps time scale. Although the same time range occurs in UV-Vis TAS data, only by polarized XANES is it possible to assign the associated time constants to specific structural changes. The results reported for time-resolved polarized XAS exploit the in-plane

polarization of the lowest absorption band of CNCbl, allowing separation of dynamics associated with the axial and equatorial coordination of the Co ion. Ultrafast polarized XANES is applicable to any system where a well defined molecular direction is identified, and these unprecedented results provide strong support for theoretical models derived from TD-DFT calculations.

3.3 Hydroxocobalamin

HOCbl has received special attention after it was demonstrated that it may be converted by light to cob(II)alamin and a hydroxyl radical, and as a result, may function as photocatalytic source of hydroxyl radicals to study the processes of DNA and RNA binding. Photochemically generated radicals may cleave supercoiled DNA into its relaxed form, for example. Electronically excited states of HOCbl have also been thoroughly investigated using ultrafast excited state dynamics. As a non-alkylcobalamin, HOCbl is generally photostable and radicals are only generated for shorter wavelengths (< 350 nm). The mechanism of hydroxyl radical formation involves competition between prompt Co-OH bond homolysis (Figure 3.7, red arrow) and internal conversion.

Figure 3.7. Potential energy surface of hydroxocobalamin shown with minimum energy paths leading to IC and possible dissociation. In all calculations the BP86 functional was used, with TZVPP for Co, C, N and TZVP for H basis sets, employing water as the COSMO solvent.

The results of femtosecond UV-Visible transient absorption spectroscopy reveal that there is no detectable long-lived photoproduct, and that the photostability of HOCbl can be explained assuming the model shown in Figure 3.8. Because the lowest PES consists of at least

three different electronic states (**1-3**), excitations using longer wavelengths leads effectively to population of the energy minimum corresponding to the S_2 state, which is primarily responsible for deactivation. On the other hand lower energy excitations (< 2.3 eV) populate a repulsive electronic state, which at longer Co-OH distances (> 2.1 Å), and slightly higher excitation energies (2.3-2.6 eV) becomes dissociative (**3**) with a dominant $p_{OH}/d \rightarrow \sigma^*$ or $d/p_{OH} \rightarrow \sigma^*$ character.

Figure 3.8. a) Potential energy curves of the ground and lowest singlet excited states of the Im-[CoIII(corrin)]-OH⁺ model complex along the Co-C coordinate computed at the ground state optimized geometry (green arrow – vertical excitation to the first electronic state with large oscillator strength, blue arrows – possible path of relaxation to the minimum S_1 state) . b) Scheme of radiationless deactivation for HOCbl.

3.2.1 Potential energy surfaces and wavelength dependent IC: comparison with cyanocobalamin

Figure 3.9. Photochemical paths leading to internal conversion for HOCbl and CNCbl. PESs of the optimized S_1 state are shown as function axial bond lengths for: a) $\text{Im}[\text{Co}^{\text{III}}(\text{corrin})]\text{-OH}^+$, characteristic points on the PES corresponds to: ground state S_0 geometry (A), energy minimum of the S_1 state (B); S_1 with $\text{Co-C} = 2.0 \text{ \AA}$ (C); b) $\text{Im}[\text{Co}^{\text{III}}(\text{corrin})]\text{-CN}^+$, characteristic points on the PES correspond to: ground state S_0 geometry (A), S_1 with $\text{Co-C} = 1.9 \text{ \AA}$ (B); energy minimum of the S_1 state (C).

Overall the low-lying states of HOCbl are similar to those of CNCbl (Figure 3.9).

For example, the proximity of the S_0 and S_1 states at longer axial bond distances and the shallowness of the minima towards longer Co-N_{Im} distances are both similar. Some features however are more in line with the alkylcobalamins such as two energy minima. The S_1 excited state PES HOCbl features three different electronic states. Two are associated with the energy minima, an MLCT state at short Co-OH and Co-N_{Im} axial distances (B), and an LF state at elongated Co-OH and Co-N_{Im} distances (C). The third region corresponds to elongated Co-OH distances ($> 2.7 \text{ \AA}$) and a Co-N_{Im} range near $1.9 - 2.2 \text{ \AA}$. This part of the S_1 surface has dissociative character. Orbital analysis associated with electronic excitations reveals that the minimum energy of the S_1 state has dominant $\text{p}_{\text{OH}}/\text{d} \rightarrow \pi^*$ character at short Co-OH distances (Table 3.1).

Table 3.1. The ten lowest, vertical singlet electronic transitions for Im-[Co^{III}(corrin)]-OH⁺ and Im-[Co^{III}(corrin)]-CN⁺ model complexes based on the TD-DFT/BP86/TZVPP calculations.

	E(eV)	λ (nm)	f	Coeff.	Character	Exp. ^a nm (eV)
Im-[Co ^{III} (corrin)]-OH ⁺						
S ₁	1.97	628.1	0.0011	96	117 → 118 H → L $n_{OH}/(d_{xz}-d_{yz}) \rightarrow \pi^*$	
S ₂	2.34	530.5	0.0001	90	117 → 119 H → L+1 $n_{OH}/(d_{xz}-d_{yz}) \rightarrow \sigma^*(d_z^2)$	
S ₃	2.55	485.9	0.0446	68	116 → 118 H-1 → L $\pi \rightarrow \pi^*$	
				24	116 → 119 H-1 → L+1 $\pi \rightarrow \sigma^*(d_z^2)$	
S ₄	2.56	484.7	0.0229	75	H-2 → L $(d_{xz}+d_{yz})/n_{OH} + \pi \rightarrow \pi^*$	
					H-2 → L+1 $(d_{xz}+d_{yz})/n_{OH} + \pi \rightarrow \sigma^*(d_z^2)$	
S ₅	2.61	475.1	0.0126	41	115 → 119 H-2 → L+1 $\pi \rightarrow \sigma^*(d_z^2)$	
				36	116 → 119 H-1 → L+1 $\pi \rightarrow \sigma^*(d_z^2)$	
S ₆	2.62	473.3	0.0131	46	115 → 119 H-2 → L+1 $(d_{xz}+d_{yz})/n_{OH} + \pi \rightarrow \sigma^*(d_z^2)$	
				33	116 → 119 H-1 → L+1 $\pi \rightarrow \sigma^*(d_z^2)$	
S ₇	2.71	456.9	0.0070	67	117 → 120 H → L+2 $p_{OH}/(d_{xz}-d_{yz}) \rightarrow d_{xy}-n$	
				13	114 → 118 H-3 → L $d_x^2-y^2 \rightarrow \pi^*$	
S ₈	2.84	436.4	0.0026	40	114 → 118 H-3 → L $d_x^2-y^2 \rightarrow \pi^*$	
				40	116 → 120 H-1 → L+2 $\pi \rightarrow d_{xy}-n$	
				11	117 → 121 H → L+3 $n_{OH}/(d_{xz}-d_{yz}) \rightarrow \pi^*$	
S ₉	2.86	433.1	0.0015	49	116 → 120 H-1 → L+2 $\pi \rightarrow d_{xy}-n$	
				36	114 → 118 H-3 → L $d_x^2-y^2 \rightarrow \pi^*$	
S ₁₀	2.90	427.6	0.0001	71	117 → 121 H → L+3 $n_{OH}/(d_{xz}-d_{yz}) \rightarrow \pi^*$	
Im-[Co ^{III} (corrin)]-CN ⁺						
S ₁	2.49	497.9	0.0471	87	119 → 120 H → L $\pi \rightarrow \pi^*$	550(2.25)
S ₂	2.59	478.6	0.0076	80	119 → 121 H → L+1 $\pi \rightarrow d_{xy}+n$	517(2.40)
S ₃	2.66	466.3	0.0168	47	119 → 122 H → L+2 $\pi \rightarrow \sigma^*(d_z^2) + n$	
				42	118 → 120 H-1 → L $\pi+d_{yz} \rightarrow \pi^*$	
S ₄	2.73	454.5	0.0183	50	119 → 122 H → L+2 $\pi \rightarrow \sigma^*(d_z^2) + n$	485(2.56)
				28	118 → 120 H-1 → L $\pi+d_{yz} \rightarrow \pi^*$	
S ₅	2.79	444.7	0.0036	75	118 → 121 H-1 → L+1 $\pi+d_{yz} \rightarrow d_{xy}+n$	
S ₆	2.87	431.5	0.0062	40	117 → 120 H-2 → L $d_{xz} \rightarrow \pi^*$	457(2.71)
				39	118 → 122 H-1 → L+2 $\pi+d_{yz} \rightarrow \sigma^*(d_z^2) + n$	
				44	117 → 120 H-2 → L $d_{xz} \rightarrow \pi^*$	
S ₇	2.91	426.6	0.0281	40	118 → 122 H-1 → L+2 $\pi+d_{yz} \rightarrow \sigma^*(d_z^2) + n$	
				96	116 → 120 H-3 → L $d_x^2-y^2 \rightarrow \pi^*$	
S ₈	3.05	406.7	0.0000	96	116 → 120 H-3 → L $d_x^2-y^2 \rightarrow \pi^*$	
S ₉	3.10	399.5	0.0069	92	115 → 120 H-4 → L $\pi_{Im} \rightarrow \pi^*$	
S ₁₀	3.26	379.7	0.0010	61	117 → 121 H-2 → L+1 $d_{xz} \rightarrow d_{xy}+n$	
				25	117 → 122 H-2 → L+2 $d_{xz} \rightarrow \sigma^*(d_z^2) + n$	

Upon Co-OH bond elongation the S₁ state crosses with higher excited states with dominant σ^* contributions, changing the character of the MOs shown in Figure 3.10 from $p_{OH}/d \rightarrow \pi^*$ (A) to $p_{OH}/d \rightarrow \sigma^*$ (C). For long Co-OH distances, the S₁ surface has mainly $p_{OH} \rightarrow \sigma^*$ character

with a small contribution from the d orbital of cobalt (E).

Figure 3.10. Molecular orbital MO diagrams of the Im-[Co^{III}(corrin)]-OH⁺ model complex representing: the optimized geometry of the S₀ state (A); the optimized geometry of the S₁ MLCT state (B); the optimized geometry of the S₁ state with fixed Co-C bond distances at 2.00 Å and 2.76 Å (C and D, respectively); the optimized geometry of the S₁ LF state (E).

The proximity of S_1 and S_0 surfaces of HOCbl to the ground state is generally lower than CNCbl leads to deactivation through two possible channels (Figure 3.11). The first involves simultaneous elongation of both axial bonds, path denoted as $B(S_{1min}) \rightarrow C(S_1) \rightarrow D(S_1)$, a mechanism similar to that observed in CNCbl. The second involves elongation and detachment of the axial base followed by corrin ring distortion denoted $B(S_{1min}) \rightarrow C(S_1) \rightarrow E(S_{1min})$, a mechanism similar to MeCbl, and AdoCbl. The dissociative pathway cannot be reached from $B(S_{1min})$ for energetic reasons, and it is inferred that low-energy excitations populate the energy minimum corresponding to the $p_{OH}/d \rightarrow \pi^*$ state primarily responsible for deactivation. High-energy excitations thus also populate a repulsive electronic state with dominant $p_{OH}/d \rightarrow \sigma^*$ or $d/p_{OH} \rightarrow \sigma^*$ character, that at longer Co-OH distances becomes dissociative (Figures 3.7, 3.10 (E)).

Figure 3.11. Scheme of the radiationless deactivation for non-alkylcobalamins: HOCbl and CNCbl.

3.4 Summary

The photo-homolysis of the Co-C bond in alkylcobalamins, such as MeCbl or AdoCbl has been known for some time and the ability to generate radicals via light has become the subject of intense experimental research. It is now accepted that the photolysis of the alkylcobalamins results in the formation of cob(II)alamin and alkyl RPs, similar to the intermediates observed in enzymes. While non-alkylcobalamins are photostable, HOCbl generates hydroxyl radicals using short wavelength excitations, representing a promising scaffold for controlled or tuned OH delivery in the study of DNA.

Cobalamin photolysis and photostability depends upon a number of factors; the nature of both axial ligands, the leaving environment, and the excitation wavelengths applied. Photolytic mechanisms at the molecular level represent complex problems, and only recently has it become possible to use computational methods to understand the properties of the cobalamins, to provide a detailed connection with experiment. There are a number of open issues from a theoretical perspective, the most important being related to AdoCbl which still requires better connection with experiment. Although it is argued that the most important mechanistic description requires PESs as functions of axial bonds, consideration of different internal coordinates may also be needed. This is particularly important in the base-off forms of the alkylcobalamins when considering mechanisms of internal conversion that compete with photolysis. Furthermore, although the majority of discussion presented has been of singlet states, triplets cannot be precluded in mechanistic descriptions of base-off alkylcobalamin photolysis.

CHAPTER IV METHYLCOBALAMIN AND ADENOSYLCOBALAMIN

4.1 Background

The purpose of this chapter is to describe the excited states, and influence of the axial base on the electronic structures of MeCbl and AdoCbl. Although results were previously published for the base-on alkylcobalamins, and for base-off MeCbl, here a comprehensive summary is presented including results for base-off AdoCbl to emphasize a few points. The photo reactivities of both base-on and base-off cobalamins are similar but some differences should be noted.⁵⁰⁻⁶⁷ In the base-on forms, photolysis occurs from a ligand-field (LF) state that is wavelength dependent for MeCbl and wavelength independent for AdoCbl. The upper ligand of AdoCbl is also easier to photolyze, and initial excitation occurs by MLCT followed by Co-C elongation. Photo- excitation of base-on MeCbl results in Co-C elongation by initial MLCT at lower energies, and direct population of the photolytic LF state at higher energies.

When the axial base is detached, photolysis occurs from a LF state that is wavelength independent for both MeCbl and AdoCbl. Photolysis in the base-off forms only competes with internal conversion by corrin ring distortion, while deactivation of the photoproducts of base-on cobalamins are associated with geminate recombination. In principle, the topologies of singlet and triplet surfaces of base-off cobalamins favor the involvement of triplet states, and although not to a significant extent for the base-on forms, the crossing of singlet and triplet surfaces favors an effective intersystem crossing (ISC) by spin-orbit coupling (SOC) when the axial base is detached, and dissociation from triplet states cannot be ruled out.

4.2. Computational details

Calculations were carried out at the DFT, and TD-DFT levels using the GGA BP86 exchange-correlation functional, with the TZVPP basis set for Co, C, N, and O, and the TZVP basis set for H as implemented in Turbomole.¹²⁸ DFT has been shown to successfully predict the geometries of

corrinoid systems, and the Co–C bond dissociation energies (BDEs) for isolated cofactors, as well as the B₁₂ derivatives, and cofactors in enzymatic environments.^{74, 76, 148-151} Dispersion corrections were not included in TD-DFT calculations for consistency with previous study, where it was demonstrated that such corrections only quantitatively effect the low-lying TD-DFT excited states,^{91, 152} while only producing larger ground-state bond dissociation energies (BDEs) for MeCbl,⁷⁶ and AdoCbl in solution.¹⁵⁰ The Resolution of the Identity (RI) approximation for computing the electronic coulomb interaction (RI-J) was applied in all calculations using the corresponding basis sets for RI-DFT. Solvation effects on the geometries, as well as on the electronic structures of the ground and excited states were accounted for using the Conductor-like Screening Model (COSMO) with water as the solvent.

The AdoCbl structural model was derived from high-resolution X-ray crystallographic data,³⁶ and truncated with respect to side chains and the axial base consistent with previous studies. The geometry corresponding to the base-on configuration is denoted Im-[Co^{III}(corrin)]-Ado⁺, where imidazole (Im) replaces dimethylbenzimidazole (DBI) as the axial base, and removal of the PO₄⁻ group results in a positive charge. The base-off models are denoted H₂O-[Co^{III}(corrin)]-Ado⁺, and H₂O-[Co^{III}(corrin)]-Me⁺. Omission of side chains for cobalamin structures at the TD-DFT level reduces computational costs significantly, where similar models at the multiconfigurational level may be readily used as benchmarks to validate DFT calculations and develop models for larger multiscale calculations involving proteins.

DFT and TD-DFT calculations were performed to construct potential energy surfaces as functions of Co–C, and Co–O distances. Structures of the ground state and relaxed S₁ excited state were optimized with respect to constrained Co–C, and Co–O coordinates, and the resulting geometries were used to calculate vertical singlet and triplet excitations by TD-DFT. Potential energy curves of the lowest triplet states as functions of Co–C bond lengths were calculated using the spin unrestricted Kohn-Sham wave functions resulting in UDFT curves with proper asymptotic behavior at the dissociation limit, compared to TD-DFT curves that drop faster in energy for elongated Co–C distances due to the instability associated with the single determinant-based wave function. Initially, low-lying singlet and triplet states along the Co–C coordinate were obtained by elongating and constraining the Co–C bond with a step size of 0.05 Å, where the ground state geometry (S₀) was optimized at each point. Excited states were calculated up to ~3.6 eV to cover the relevant spectral range from either the S₀ or the optimized S₁

surfaces.

Long-range charge-transfer (CT) does not occur in solution for the alkylcobalamins according to previous study by the Tozer diagnostic,⁸⁶ which has been shown to provide an efficient index (Λ , between 0 and 1) to quantify the spatial overlap between S_0 and S_1 excited state orbital contributions using single-reference based methods. To recall, excitations are considered effective when states have overlap corresponding to $\Lambda > .5$. Small overlap values according to Λ correspond to more charge separated states, which in the case of some highly-conjugated charge transfer systems where the centroids associated with the hole and particle may be separated by longer distances. In the case of base-off AdoCbl this condition is not met, and by the Tozer diagnostic ghost states are characterized as having small overlap as well as large CT distances ($\pi_{\text{Ado}} \rightarrow \pi^*$, $\pi_{\text{Ado}} \rightarrow \sigma^*(d_z^2)$) well outside the range defined by Hirao and co-workers as the far nucleus asymptotic regime ($\sim 5 \text{ \AA}$),⁸⁵ or according to the recent diagnostic of Ciofini et. al, D_{CT} distances above $6.0 \text{ \AA}$.¹⁵³⁻¹⁵⁴

Points were located on the base-off AdoCbl S_1 PES that correlate to intermediates involved in photolysis, represented as $\text{H}_2\text{O}-[\text{Co}^{\text{III}}(\text{corrin})]-\text{Ado}^+$, $\text{H}_2\text{O} + [\text{Co}^{\text{III}}(\text{corrin})]-\text{Ado}^+$ and $\text{H}_2\text{O} + [\text{Co}^{\text{III}}(\text{corrin})]^+ + \text{Ado}$, where the axial water is either partially or fully detached. Alkylcobalamin structures were optimized as fragments assuming a six-, five- or four-coordinate model, represented as $\text{H}_2\text{O}-[\text{Co}^{\text{III}}(\text{corrin})]-\text{Ado}^+$, $[\text{Co}^{\text{III}}(\text{corrin})]-\text{Ado}^+$, and $[\text{Co}^{\text{II}}(\text{corrin})]^+$. MeCbl fragments with weakly associated or completely dissociated axial water molecules are represented as $\text{H}_2\text{O}-[\text{Co}^{\text{III}}(\text{corrin})]-\text{Me}^+$, and $[\text{Co}^{\text{III}}(\text{corrin})]-\text{Me}^+$ in Tables 4.1 and 4.2.¹⁵² Low-lying excited states were determined by orbital analysis, and vertical excitations with respect to the ground state minima are collected in Tables 4.3, and 4.4 for $\text{H}_2\text{O}-[\text{Co}^{\text{III}}(\text{corrin})]-\text{Ado}^+$, and $[\text{Co}^{\text{III}}(\text{corrin})]-\text{Ado}^+$ consistent with previous analysis for $\text{H}_2\text{O}-[\text{Co}^{\text{III}}(\text{corrin})]-\text{Me}^+$ and $[\text{Co}^{\text{III}}(\text{corrin})]-\text{Me}^+$ collected in Tables 4.1 and 4.2 for convenience. Triplet states of MeCbl and AdoCbl and NBO charges as previously reported, are also listed for convenience in Tables 4.6, 4.6, 4.7, and 4.8.

Table 4.1. Ten lowest vertical singlet electronic transitions and value of $S_1 \rightarrow S_0$ adiabatic transition for $H_2O-[Co^{III}(\text{corrin})]-Me^+$ model complex based on TDDFT.¹⁵²

	E(eV)	$\lambda(\text{nm})$	f	%	character			Exp. λ (eV) ^a
S ₁	2.35	526.6	0.0036	88	103 $\rightarrow$ 105	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$	501(2.47)
S ₂	2.40	516.1	0.0286	79	104 $\rightarrow$ 105	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$	
S ₃	2.57	482.4	0.0023	69	101 $\rightarrow$ 105	H-3 $\rightarrow$ L	$d_{x^2-y^2} \rightarrow \pi^*$	
				18	102 $\rightarrow$ 105	H-2 $\rightarrow$ L	$\pi+d_{xz} \rightarrow \pi^*$	461(2.69)
				12	104 $\rightarrow$ 106	H $\rightarrow$ L+1	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$	
S ₄	2.66	466.5	0.0041	55	104 $\rightarrow$ 106	H $\rightarrow$ L+1	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$	
				25	101 $\rightarrow$ 105	H-3 $\rightarrow$ L	$d_{x^2-y^2} \rightarrow \pi^*$	
				15	102 $\rightarrow$ 105	H-2 $\rightarrow$ L	$\pi+d_{xz} \rightarrow \pi^*$	
S ₅	2.83	438.9	0.0857	56	102 $\rightarrow$ 105	H-2 $\rightarrow$ L	$\pi+d_{xz} \rightarrow \pi^*$	
				23	104 $\rightarrow$ 106	H $\rightarrow$ L+1	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$	
S ₆	2.97	417.5	0.0061	45	103 $\rightarrow$ 106	H-1 $\rightarrow$ L+1	$d_{xz}+\pi \rightarrow \sigma^*(d_z^2)$	
				36	104 $\rightarrow$ 107	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow d_{xy}+n$	
				10	103 $\rightarrow$ 107	H-1 $\rightarrow$ L+2	$d_{xz}+\pi \rightarrow d_{xy}+n$	
S ₇	3.04	407.7	0.0266	43	104 $\rightarrow$ 108	H $\rightarrow$ L+3	$d_{yz}+\pi \rightarrow \pi^*+d_{xy}$	
				28	104 $\rightarrow$ 107	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow d_{xy}+n$	
				13	103 $\rightarrow$ 106	H-1 $\rightarrow$ L+1	$d_{xz}+\pi \rightarrow \sigma^*(d_z^2)$	
S ₈	3.13	396.3	0.0100	71	102 $\rightarrow$ 106	H-2 $\rightarrow$ L+1	$\pi+d_{xz} \rightarrow \sigma^*(d_z^2)$	
S ₉	3.18	390.1	0.0040	31	104 $\rightarrow$ 108	H $\rightarrow$ L+3	$d_{yz}+\pi \rightarrow \pi^*+d_{xy}$	
				19	101 $\rightarrow$ 106	H-3 $\rightarrow$ L+1	$d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$	
				13	103 $\rightarrow$ 106	H-1 $\rightarrow$ L+1	$d_{xz}+\pi \rightarrow \sigma^*(d_z^2)$	
				12	104 $\rightarrow$ 107	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow d_{xy}+n$	
S ₁₀	3.31	374.9	0.0007	43	100 $\rightarrow$ 105	H-4 $\rightarrow$ L	$\pi+d_{yz} \rightarrow \pi^*$	
				42	102 $\rightarrow$ 107	H-2 $\rightarrow$ L+2	$\pi+d_{xz} \rightarrow d_{xy}+n$	
S ₁	1.87	661.9		49	103 $\rightarrow$ 105	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$ (MLCT)	
				48	103 $\rightarrow$ 105	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$	

^a C. Giannotti, Electronic Spectra of B12 and Related Systems, in *B12*, Volume 1: Chemistry, edited by D. Dolphin, John Wiley & Sons, New York 1982, Chap. 11, pp. 393–430.

Table 4.2. Ten lowest vertical singlet electronic transitions and value of $S_1 \rightarrow S_0$ adiabatic transition for $[\text{Co}^{\text{III}}(\text{corrin})]\text{-Me}^+$ model complex based on TDDFT.¹⁵²

	E(eV)	$\lambda(\text{nm})$	f	%	character		
S_1	2.28	544.2	0.0027	10	98 $\rightarrow$ 100	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$
				85	99 $\rightarrow$ 101	H $\rightarrow$ L+1	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$
S_2	2.34	530.5	0.0288	32	98 $\rightarrow$ 100	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$
				56	99 $\rightarrow$ 100	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$
S_3	2.39	517.8	0.0307	53	98 $\rightarrow$ 100	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$
				31	99 $\rightarrow$ 100	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$
S_4	2.58	481.2	0.0034	35	97 $\rightarrow$ 100	H-2 $\rightarrow$ L	$d_{x^2-y^2} \rightarrow \pi^*$
				60	98 $\rightarrow$ 101	H-1 $\rightarrow$ L+1	$d_{xz}+\pi \rightarrow \sigma^*(d_z^2)$
S_5	2.62	472.9	0.0013	58	97 $\rightarrow$ 100	H-2 $\rightarrow$ L	$d_{x^2-y^2} \rightarrow \pi^*$
				31	98 $\rightarrow$ 101	H-1 $\rightarrow$ L+1	$d_{xz}+\pi \rightarrow \sigma^*(d_z^2)$
S_6	2.96	419.3	0.0154	31	96 $\rightarrow$ 100	H-3 $\rightarrow$ L	$\pi \rightarrow \pi^*$
				50	99 $\rightarrow$ 102	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow \pi^*+d_{xy}+n$
S_7	3.03	409.1	0.0908	36	96 $\rightarrow$ 100	H-3 $\rightarrow$ L	$\pi \rightarrow \pi^*$
				32	96 $\rightarrow$ 101	H-3 $\rightarrow$ L+1	$\pi \rightarrow \sigma^*(d_z^2)$
				12	99 $\rightarrow$ 102	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow \pi^*+d_{xy}+n$
S_8	3.06	405.6	0.0358	31	96 $\rightarrow$ 101	H-3 $\rightarrow$ L+1	$\pi \rightarrow \sigma^*(d_z^2)$
				26	97 $\rightarrow$ 101	H-2 $\rightarrow$ L+1	$d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$
				10	99 $\rightarrow$ 102	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow \pi^*+d_{xy}+n$
S_9	3.06	405.1	0.0349	12	96 $\rightarrow$ 101	H-3 $\rightarrow$ L+1	$\pi \rightarrow \sigma^*(d_z^2)$
				36	97 $\rightarrow$ 101	H-2 $\rightarrow$ L+1	$d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$
				11	99 $\rightarrow$ 102	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow \pi^*+d_{xy}+n$
				14	99 $\rightarrow$ 103	H $\rightarrow$ L+3	$d_{yz}+\pi \rightarrow d_{xy}+n+\pi^*$
S_1 0	3.22	385.4	0.0236	20	97 $\rightarrow$ 101	H-2 $\rightarrow$ L+1	$d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$
				48	99 $\rightarrow$ 103	H $\rightarrow$ L+3	$d_{yz}+\pi \rightarrow d_{xy}+n+\pi^*$
S_1	1.60	775.4		98	99 $\rightarrow$ 100	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \sigma^*(d_{z2})$ (LF)

Table 4.3. Ten lowest vertical singlet electronic transitions and the value of the $S_1 \rightarrow S_0$ adiabatic transition for the $H_2O-[Co^{III}(\text{corrin})]-\text{Ado}^+$ model complex based on TDDFT.

	E(eV)	$\lambda(\text{nm})$	<i>f</i>	%	character	Exp. λ (eV) ^a
S ₁	2.38	522.0	0.0053	84	164 → 166 H-1 → L	$d_{xz}+\pi \rightarrow \pi^*$
				10	165 → 166 H → L	
S ₂	2.39	518.3	0.0238	77	165 → 166 H → L	$d_{yz}+\pi \rightarrow \pi^*$
				11	164 → 166 H-1 → L	$d_{xz}+\pi \rightarrow \pi^*$
S ₃	2.54	488.1	0.0006	60	165 → 167 H → L+1	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$
				21	163 → 166 H-2 → L	$\pi \rightarrow \pi^*$
				17	162 → 166 H-3 → L	$d_{x^2-y^2} \rightarrow \pi^*$
S ₄	2.62	473.0	0.0009	73	162 → 166 H-3 → L	$d_{x^2-y^2} \rightarrow \pi^*$
				21	165 → 167 H → L+1	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$
S ₅	2.66	465.8	0.0003	99	161 → 166 H-4 → L	$\pi_{\text{Ado}} \rightarrow \pi^*$
S ₆	2.78	446.2	0.0668	61	163 → 166 H-2 → L	$\pi \rightarrow \pi^*$
						465 (2.67)
S ₇	2.86	433.9	0.0044	65	164 → 167 H-1 → L+1	$d_{xz}+\pi \rightarrow \sigma^*(d_z^2)$
				21	165 → 168 H → L+2	$d_{yz}+\pi \rightarrow (d_{xy}-n) + \pi^*$
S ₈	3.00	413.9	0.0051	47	165 → 168 H → L+2	$d_{yz}+\pi \rightarrow (d_{xy}-n) + \pi^*$
				25	160 → 166 H-5 → L	$n_{\text{Ado}} \rightarrow \pi^*$
				15	165 → 169 H → L+3	$d_{yz}+\pi \rightarrow (d_{xy}-n) - \pi^*$
S ₉	3.03	409.9	0.0165	42	163 → 167 H-2 → L+1	$\pi \rightarrow \sigma^*(d_z^2)$
				31	160 → 166 H-5 → L	$n_{\text{Ado}} \rightarrow \pi^*$
S ₁₀	3.04	407.6	0.0237	36	160 → 166 H-5 → L	$n_{\text{Ado}} \rightarrow \pi^*$
				34	163 → 167 H-2 → L+1	$\pi \rightarrow \sigma^*(d_z^2)$
						$d_{yz}+\pi \rightarrow \pi^*$
S₁	1.80	661.9	0.0009	79	165 → 166 H → L	(MLCT)
				18	164 → 166 H-1 → L	$d_{xz}+\pi \rightarrow \pi^*$

Table 4.4. Ten lowest, vertical singlet electronic transitions and the value of the $S_1 \rightarrow S_0$ adiabatic transition for the $[\text{Co}^{\text{III}}(\text{corrin})]\text{-Ado}^+$ model complex based on TDDFT.

	E(eV)	$\lambda(\text{nm})$	f	%	character		
S_1	2.18	568.7	0.0042	90	160 $\rightarrow$ 162	H $\rightarrow$ L+1	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$
S_2	2.34	529.1	0.0175	57	160 $\rightarrow$ 161	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$
				30	159 $\rightarrow$ 161	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$
S_3	2.39	517.9	0.0156	63	159 $\rightarrow$ 161	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$
				23	160 $\rightarrow$ 161	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$
S_4	2.47	501.9	0.0033	92	159 $\rightarrow$ 162	H-1 $\rightarrow$ L+1	$d_{xz}+\pi \rightarrow \sigma^*(d_z^2)$
S_5	2.56	483.9	0.0000	100	157 $\rightarrow$ 161	H-3 $\rightarrow$ L	$\pi_{\text{Ado}} \rightarrow \pi^*$
S_6	2.62	473.7	0.0021	85	158 $\rightarrow$ 161	H-2 $\rightarrow$ L	$d_{x^2-y^2} \rightarrow \pi^*$
S_7	2.65	467.8	0.0002	100	157 $\rightarrow$ 162	H-3 $\rightarrow$ L+1	$\pi_{\text{Ado}} \rightarrow \sigma^*(d_z^2)$
S_8	2.93	423.9	0.0028	43	160 $\rightarrow$ 163	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow (d_{xy}\text{-n}) + \pi^*$
				28	158 $\rightarrow$ 162	H-2 $\rightarrow$ L+1	$d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$
				12	156 $\rightarrow$ 161	H-4 $\rightarrow$ L	$\pi+d_{x^2-y^2} \rightarrow \pi^*$
				26	155 $\rightarrow$ 161	H-5 $\rightarrow$ L	$n_{\text{Ado}}+d_{z^2} \rightarrow \pi^*$
				22	158 $\rightarrow$ 162	H-2 $\rightarrow$ L+1	$d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$
				22	160 $\rightarrow$ 163	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow (d_{xy}\text{-n}) + \pi^*$
S_9	2.95	420.5	0.0081	12	156 $\rightarrow$ 162	H-4 $\rightarrow$ L+1	$\pi+d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$
				11	160 $\rightarrow$ 164	H $\rightarrow$ L+3	$d_{yz}+\pi \rightarrow (d_{xy}\text{-n}) - \pi^*$
				66	155 $\rightarrow$ 161	H-5 $\rightarrow$ L	$n_{\text{Ado}}+d_{z^2} \rightarrow \pi^*$
				15	158 $\rightarrow$ 162	H-2 $\rightarrow$ L+1	$d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$
S_{10}	2.97	417.2	0.0050				
S_1	1.43	864.5	0.0034	99	160 $\rightarrow$ 161	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$ (LF)

Table 4.5. Fifteen lowest vertical triplet electronic transitions for the $[\text{Co}^{\text{III}}(\text{corrin})]\text{-Ado}^+$ model complex based on TDDFT.

	E(eV)	$\lambda(\text{nm})$	%	character		
T ₁	1.69	734.7	87	160 $\rightarrow$ 161	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$
T ₂	1.72	720.1	85	160 $\rightarrow$ 162	H $\rightarrow$ L+1	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$
			11	160 $\rightarrow$ 161	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$
T ₃	1.92	646.3	92	159 $\rightarrow$ 162	H-1 $\rightarrow$ L+1	$d_{xz}+\pi \rightarrow \sigma^*(d_z^2)$
T ₄	2.15	577.9	90	159 $\rightarrow$ 161	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$
T ₅	2.24	553.4	85	158 $\rightarrow$ 162	H-2 $\rightarrow$ L+1	$d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$
T ₆	2.36	525.1	49	160 $\rightarrow$ 163	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow (d_{xy}-n) + \pi^*$
			44	160 $\rightarrow$ 164	H $\rightarrow$ L+3	$d_{yz}+\pi \rightarrow (d_{xy}-n) - \pi^*$
T ₇	2.43	510.8	78	158 $\rightarrow$ 161	H-2 $\rightarrow$ L	$d_{x^2-y^2} \rightarrow \pi^*$
			14	156 $\rightarrow$ 161	H-4 $\rightarrow$ L	$\pi + d_{x^2-y^2} \rightarrow \pi^*$
T ₈	2.49	497.0	48	156 $\rightarrow$ 162	H-4 $\rightarrow$ L+1	$\pi + d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$
			12	156 $\rightarrow$ 161	H-4 $\rightarrow$ L	$\pi + d_{x^2-y^2} \rightarrow \pi^*$
			12	155 $\rightarrow$ 162	H-5 $\rightarrow$ L+1	$n_{\text{Ado}} + d_{z2} \rightarrow \sigma^*(d_z^2)$
			37	159 $\rightarrow$ 163	H-1 $\rightarrow$ L+2	$d_{xz}+\pi \rightarrow (d_{xy}-n) + \pi^*$
T ₉	2.53	490.2	35	159 $\rightarrow$ 164	H-1 $\rightarrow$ L+3	$d_{xz}+\pi \rightarrow (d_{xy}-n) - \pi^*$
			14	156 $\rightarrow$ 161	H-4 $\rightarrow$ L	$\pi + d_{x^2-y^2} \rightarrow \pi^*$
			100	157 $\rightarrow$ 161	H-3 $\rightarrow$ L	$\pi_{\text{Ado}} \rightarrow \pi^*$
T ₁₁	2.58	480.6	52	156 $\rightarrow$ 161	H-4 $\rightarrow$ L	$\pi + d_{x^2-y^2} \rightarrow \pi^*$
			14	159 $\rightarrow$ 163	H-1 $\rightarrow$ L+2	$d_{xz}+\pi \rightarrow (d_{xy}-n) + \pi^*$
			13	158 $\rightarrow$ 161	H-2 $\rightarrow$ L	$d_{x^2-y^2} \rightarrow \pi^*$
T ₁₂	2.65	468.0	97	157 $\rightarrow$ 162	H-3 $\rightarrow$ L+1	$\pi_{\text{Ado}} \rightarrow \sigma^*(d_{z2})$
T ₁₃	2.66	466.0	44	158 $\rightarrow$ 164	H-2 $\rightarrow$ L+3	$d_{x^2-y^2} \rightarrow (d_{xy}-n) - \pi^*$
			38	158 $\rightarrow$ 163	H-2 $\rightarrow$ L+2	$d_{x^2-y^2} \rightarrow (d_{xy}-n) + \pi^*$
T ₁₄	2.73	455.0	47	160 $\rightarrow$ 164	H $\rightarrow$ L+3	$d_{yz}+\pi \rightarrow (d_{xy}-n) - \pi^*$
			43	160 $\rightarrow$ 163	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow (d_{xy}-n) + \pi^*$
T ₁₅	2.79	445.1	30	155 $\rightarrow$ 162	H-5 $\rightarrow$ L+1	$n_{\text{Ado}} + d_{z2} \rightarrow \sigma^*(d_z^2)$
			21	156 $\rightarrow$ 162	H-4 $\rightarrow$ L+1	$\pi + d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$
			14	159 $\rightarrow$ 164	H-1 $\rightarrow$ L+3	$d_{xz}+\pi \rightarrow (d_{xy}-n) - \pi^*$

Table 4.6. Ten lowest, vertical triplet electronic transitions for $[\text{Co}^{\text{III}}(\text{corrin})]\text{-Me}^+$ model complex based on TDDFT.¹⁵²

	E(eV)	$\lambda(\text{nm})$	%	character		
T ₁	1.70	730.4	70	99 → 100	H → L	$d_{yz} + \pi \rightarrow \pi^*$
T ₂	1.83	678.2	69	99 → 101	H → L+1	$d_{yz} + \pi \rightarrow \sigma^*(d_z^2)$
T ₃	2.04	608.8	68	98 → 101	H-1 → L+1	$d_{xz} + \pi \rightarrow \sigma^*(d_z^2)$
T ₄	2.15	577.7	68	98 → 100	H-1 → L	$d_{xz} + \pi \rightarrow \pi^*$
T ₅	2.36	526.1	65	97 → 101	H-2 → L+1	$d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$
T ₆	2.41	514.0	46	99 → 102	H → L+2	$d_{yz} + \pi \rightarrow \pi^* + d_{xy} + n$
			49	99 → 103	H → L+3	$d_{yz} + \pi \rightarrow d_{xy} + n + \pi^*$
T ₇	2.45	506.6	43	96 → 100	H-3 → L	$\pi \rightarrow \pi^*$
			53	97 → 100	H-2 → L	$d_{x^2-y^2} \rightarrow \pi^*$
T ₈	2.51	494.5	53	96 → 100	H-3 → L	$\pi \rightarrow \pi^*$
			-40	97 → 100	H-2 → L	$d_{x^2-y^2} \rightarrow \pi^*$
T ₉	2.60	477.6	46	98 → 102	H-1 → L+2	$d_{xz} + \pi \rightarrow \pi^* + d_{xy} + n$
			47	98 → 103	H-1 → L+3	$d_{xz} + \pi \rightarrow d_{xy} + n + \pi^*$
T ₁₀	2.63	471.5	64	96 → 101	H-3 → L+1	$\pi \rightarrow \sigma^*(d_z^2)$

Table 4.7. Selected geometrical parameters and NBO charges for H₂O-[Co^{III}(corrin)]-Me⁺ model complex and other species involved in the photoreaction process.¹⁵²

H ₂ O- [Co ^{III} (corrin)]-Me ⁺	Geometry		NBO charges				
	I (S _{0min})	I (S _{1min})		q _{S0}	q _{S0} ^{a)}	q _{S1}	Δq ^{b)}
	Bond distances [Å]			(S _{0min})	(S _{1min})		
Co-C	1.969	1.962	Co	0.765	0.778	0.967	0.189
C-O	2.359	2.217	C	-0.658	-0.673	-0.637	0.036
Co-N ₂₁	1.876	1.879	O	-0.925	-0.913	-0.895	0.018
Co-N ₂₂	1.929	1.966	Me	-0.067	-0.083	-0.001	0.082
Co-N ₂₃	1.928	1.976	H ₂ O	0.075	0.096	0.125	0.029
Co-N ₂₄	1.871	1.881	Corr	0.227	0.208	-0.092	-0.300
	Bond angles [deg]						
C _{CN} -Co-O	175.6	164.5					
N ₂₁ -Co-N ₂₃	171.2	170.8					
N ₂₂ -Co-N ₂₄	173.4	172.7					
[Co ^{III} (corrin)]-Me ⁺	IIIB (S _{0min})	IIIB (S _{1min})		q _{S0}	q _{S0}	q _{S1}	Δq ^{a)}
	Bond distances [Å]			(S _{0min})	(S _{1min})		
Co-C	1.968	2.229	Co	0.738	0.777	0.876	0.099
Co-N ₂₁	1.866	1.857	C	-0.620	-0.617	-0.823	-0.206
Co-N ₂₂	1.920	1.927	Me	-0.016	-0.013	-0.238	-0.225
Co-N ₂₃	1.919	1.939	Corr	0.278	0.235	0.362	0.126
Co-N ₂₄	1.862	1.856					
	Bond angles [deg]						
N ₂₁ -Co-N ₂₃	167.4	160.4					
N ₂₂ -Co-N ₂₄	172.7	173.5					
[Co ^{II} (corrin)] ⁺	VIB (S _{0min})	VIB (S _{1min})		q _{S0}	q _{S0}	q _{S1}	Δq ^{a)}
	Bond distances [Å]			(S _{0min})	(S _{1min})		
Co-N ₂₁	1.875	1.842	Co	0.989	0.983	0.841	-0.142
Co-N ₂₂	1.926	1.915	Corr	0.011	0.017	0.159	0.142
Co-N ₂₃	1.926	1.915					
Co-N ₂₄	1.875	1.843					
	Bond angles [deg]						
N ₂₁ -Co-N ₂₃	172.0	170.2					
N ₂₂ -Co-N ₂₄	172.0	170.2					

^{a)} q_{S0} – charges in ground state in geometry of excited state

^{b)} Δq – difference between charge in excited state and ground state in geometry excited state

Table 4.8. Selected geometrical parameters and NBO charges for the H₂O-[Co^{III}(corrin)]-Ado⁺ model complex and other species involved in the photoreaction process.

H ₂ O- [Co ^{III} (corrin)]-Ado ⁺	Geometry		NBO charges				
	I (S _{0min})	I (S _{1min})		q _{S0}	q _{S0} ^{a)}	q _{S1}	Δq ^{b)}
	Bond distances [Å]			(S _{0min})	(S _{1min})		
Co-C	1.994	1.995	Co	0.779	0.786	0.963	0.177
C-O	2.435	2.219	C	-0.420	-0.447	-0.406	0.041
Co-N ₂₁	1.875	1.885	O	-0.949	-0.915	-0.880	0.035
Co-N ₂₂	1.929	1.968	Ado	-0.050	-0.069	0.045	0.114
Co-N ₂₃	1.923	1.972	H ₂ O	0.050	0.093	0.141	0.048
Co-N ₂₄	1.872	1.885	Corr	0.222	0.190	-0.149	-0.339
	Bond angles [deg]						
C-Co-O	178.1	166.4					
N ₂₁ -Co-N ₂₃	169.5	169.6					
N ₂₂ -Co-N ₂₄	172.9	172.3					
[Co ^{III} (corrin)]-Ado ⁺	IIIB	IIIB		q _{S0}	q _{S0}	q _{S1}	Δq ^{a)}
	(S _{0min})	(S _{1min})					
	Bond distances [Å]			(S _{0min})	(S _{1min})		
Co-C	1.996	2.335	Co	0.742	0.781	0.857	0.076
Co-N ₂₁	1.868	1.852	C	-0.393	-0.371	-0.542	-0.171
Co-N ₂₂	1.921	1.929	Ado	-0.006	0.025	-0.206	-0.231
Co-N ₂₃	1.917	1.925	Corr	0.264	0.195	0.349	0.154
Co-N ₂₄	1.864	1.858					
	Bond angles [deg]						
N ₂₁ -Co-N ₂₃	165.4	162.2					
N ₂₂ -Co-N ₂₄	171.8	173.4					
[Co ^{II} (corrin)] ⁺	VIB	VIB		q _{S0}	q _{S0}	q _{S1}	Δq ^{a)}
	(S _{0min})	(S _{1min})					
	Bond distances [Å]			(S _{0min})	(S _{1min})		
Co-N ₂₁	1.875	1.842	Co	0.989	0.983	0.841	-0.142
Co-N ₂₂	1.926	1.915	Corr	0.011	0.017	0.159	0.142
Co-N ₂₃	1.926	1.915					
Co-N ₂₄	1.875	1.843					
	Bond angles [deg]						
N ₂₁ -Co-N ₂₃	172.0	170.2					
N ₂₂ -Co-N ₂₄	172.0	170.2					

^{a)} q_{S0} – charges in ground state in geometry of excited state

^{b)} Δq – difference between charge in excited state and ground state in geometry excited state

4.3 Results and discussion

Due to the absence of X-ray structures for the base-off cobalamins, excited state geometries were determined by optimizing the ground states (S_0), and the low-lying excited states as functions of Co-O coordinate. However, one axial coordinate is not sufficient to describe the mechanism of photodissociation, and potential energy surfaces (PESs) were also constructed as functions of Co-C and Co-O bonds. We have good confidence that the geometries calculated for the base-off forms are valid by comparing the optimized base-on geometries to high-quality X-ray data. As seen in Figure 4.1., the largest structural changes upon excitation occur with respect to axial bonding, and the ground state (S_0) calculated for base-on MeCbl and AdoCbl are in very good agreement with experiment. Co-C and Co-N bonds at the DFT level were 1.986 Å and 2.175 Å for MeCbl respectively, compared to experimental values of 1.979 Å and 2.163 Å. Co-C and Co-N bonds of AdoCbl S_0 were calculated at 2.014 Å and 2.193 Å respectively, compared to experimental values of 2.032 Å and 2.240 Å. Co-C and Co-N bonds at the DFT level were 1.986 Å and 2.175 Å for MeCbl respectively, compared to experimental values of 1.979 Å and 2.163 Å. Co-C and Co-N bonds of AdoCbl S_0 were calculated at 2.014 Å and 2.193 Å respectively, compared to experimental values of 2.032 Å and 2.240 Å.

Figure 4.1. Experimental, and optimized axial bond lengths at the DFT/BP86 level, for S_0 and TDDFT/BP86 for S_1 excited states of the cobalamins under consideration (Im-MeCbl, HO-MeCbl, and Im-AdoCbl, HO-AdoCbl). In all calculations the same basis sets, TZVPP for Co, C, N, and TZVP for H were used, employing the Conductor-like Screening Model (COSMO) solvent.

No significant changes occur in Co-C bond lengths between S_0 and S_1 for both the base-on and base-off alkylcobalamins. In regard to the lower axial ligand, contraction of the Co-N or Co-OH₂

bond in the S_1 excited state is noted for the both base-on and base-off forms. The Co-N bond shortens for base-on MeCbl from 2.175 Å (S_0) to 2.055 Å (S_1), and for base-on AdoCbl from 2.193 Å (S_0) to 2.046 Å (S_1). The same is observed for the Co-OH₂ bond to a slightly greater extent, shortening from 2.359 Å (S_0) to 2.217 Å (S_1) for base-off MeCbl, and 2.435 Å (S_0) to 2.219 Å (S_1) for base-off AdoCbl in the excited state.

The photolytic properties of the alkylcobalamins are thus readily explained by analyses of low-lying electronically excited states,¹⁴⁷ and the corresponding photoreactions that occur along their potential energy surfaces (PESs) as functions of the axial coordinate.¹⁰ For MeCbl and AdoCbl, two possible photodissociation pathways were identified,^{91, 152, 155} and are distinguished by which bond is favored to elongate first; Co-C (Path A) or Co-N_{axial} / Co-OH₂ (Path B). Although the final state of each path is the same, a photolytic LF state with a partially or fully detached axial base, the properties of base-off alkylcobalamins are noticeably different. First, the barriers between the initial MLCT state, and the LF region responsible for photolysis are lowered in the base-off forms, and the LF minima are stabilized with respect to MLCT. This results in initial photodissociation by MLCT for base-on cobalamins primarily associated with elongation of the Co-C bond (Path A). Initial excitation of base-off cobalamins is also characterized as MLCT, but upon relaxation readily populates the lower LF minima responsible for Co-C photolysis by facile detachment of the axial water (Path B). Second, the resulting topology of the S_1 surface of the base-off cobalamins becomes shallow with respect to low-lying triplet states as a function of axial water dissociation.

The involvement of triplets is unlikely for base-on cobalamins according to semi-classical Landau-Zener theory. Two conditions must be satisfied for coupling to occur between singlet and triplet states near their minimum energy crossing points (MECPs) leading to lead to an effective ISC by SOC: 1) the gradient of crossing between singlet and triplet surfaces should be nearly orthogonal, and 2) a 90° rotation of d-orbitals should occur with favorable overlap according to El-Sayed rules, i.e. the SOC operator should have non-vanishing terms with rotation, and the magnitude of the SOC matrix element should be significant. SOC is difficult to determine explicitly as calculations require the use of a multiconfigurational wavefunction, and the large system size of the cobalamins make such calculations particularly expensive. However, we have shown that conditions for ISC are satisfied for base-off MeCbl

at both the multiconfigurational and DFT levels,^{156,157} and by analogy the involvement of SOC leading to dissociation from triplet states should be similar for AdoCbl.

Deactivation along Path A is controlled by the axial base and the formation of RPs, while deactivation along Path B is controlled by one coordinate, geminate recombination for the base-on forms, or rapid internal conversion by torsional angle distortion for the base-off forms. IC does not compete with homolysis when the axial base is attached (except for MeCbl along Path B), due to a high barrier to the stable LF state by axial base dissociation, where elongation of the Co-C bond along Path A by initial MLCT leads to an LF photolysis that competes with RP recombination. Geminate recombination is not observed for the base-off cobalamins (unless on a ns timescale), and initial MLCT leads to fast population of the stable LF state along Path B.

The long-lived S_1 LF state was identified as cob(II)alamin for both base-off and base-on alkylcobalamins, and homolysis involving the cob(II)alamin radical has been linked to enhanced reactivity associated with axial base detachment.^{43, 90, 93, 102, 104} The unique reactivity of cob(II)alamin is a result of an increasing $d_{yz} + \pi \rightarrow d_z^{2*}$ character of the D_1 state with respect to axial base dissociation, lowering the energy of the anti-bonding d_z^2 orbitals, and leading to a near-degeneracy between the ground and D_1 states. The axial base thus modulates deactivation, as well as ISC for the base-on and base-off cobalamins by formation of cob(II)alamin.

The channel for fast non-radiative decay to the ground state along Path B in the base-off cobalamins results in a reduced singlet-born quantum yield, from unity in the base-on forms, to 0.65 for base-off MeCbl, and 0.13 for base-off AdoCbl. Although magnetic field effect (MFE) studies suggest that the majority of base-off photo-products are singlet radicals, and the observed quantum yields may be explained by the cage-effect discussed in Section 3.4, the involvement of triplet states cannot be entirely ruled out when repulsive triplets may act as channels between surfaces, and the energetics of the S_1 and T_1 surfaces favor ISC in the base-off forms. To explain these effects in detail TD-DFT potential energy surfaces are summarized here to connect the intermediates involved in MeCbl and AdoCbl photolysis as controlled by the axial base.

4.3.1. Low-lying excited states with respect to Co-C dissociation

Vertical excited state energies as functions of Co–C coordinate are shown in Figure 3 for base-on MeCbl (a) and AdoCbl (b) (upper panel), along with excited state energies for the optimized five-coordinate base-off model structures of MeCbl (c) and AdoCbl (d) (lower panel).^{91, 152, 155} The base-on excited state manifolds were calculated from S_0 , and the base-off excited states were optimized from the S_1 state due to the LF surface becoming very flat, as seen by a smooth elongation of the Co–C bond in Figure 4.2. Although vertical S_1 excitation of the base-off alkylcobalamins with coordinated axial water occurs from a metal-to-ligand charge-transfer (MLCT) state, that is both more localized about the minima (Figure 4.4 c, d) and has a notable inversion of HOMO (H), and H-1 contributions upon relaxation, (Table 4.1, for $\text{H}_2\text{O}-[\text{Co}^{\text{III}}(\text{corrin})]-\text{Ado}^+$), adiabatic curves corresponding to cobalamins with completely detached axial waters provide the most realistic description of the S_1 LF state character, which increases upon relaxation from 90% to 99% (S_1 min Table 4.1)

Figure 4.2. Potential energy curves of the ground and lowest vertically excited states of (a) Im-CoIII(corrin)-Me⁺, (b) Im-CoIII(corrin)-Ado⁺, and lowest optimized states of the (c) H₂O-CoIII(corrin)-Me⁺ and (d) H₂O-CoIII(corrin)-Ado⁺ complexes along the Co-C bond computed at the ground-state optimized geometry (a, b) and at the S₁ state optimized geometry (d, c). The dotted line corresponds to the approximate course of the triplet excited state.^{151,152,157}

Two important features should be noted regarding the Co–C ground state bond dissociation energies (BDEs) of MeCbl and AdoCbl. First, although the base-on forms of MeCbl and AdoCbl have similar BDEs, 44.1 kcal/mol for MeCbl (Path A), and 38.0 kcal/mol for AdoCbl (Path B), the absence of axial base effectively does not change the ground state dissociation, corresponding to 43.7 kcal/mol for base-off MeCbl (Path B), and 37.6 kcal/mol for base-off AdoCbl (Path B), consistent with experimental studies where replacement of the axial base had minor change on the ground state BDEs.¹⁵⁸ Second, although the approximate difference of ~6 kcal/mol in ground state BDEs between base-on MeCbl and AdoCbl seems small, this results in an excited state manifold for base-on AdoCbl that is closer to the ground state with respect to Co–C photolysis, and an (LF) minimum is not accessed by higher energy excitation, or by axial-base dissociation. The wavelength-dependent photolysis observed for base-on MeCbl is a result of a higher barrier to the LF state by axial base dissociation, and a higher energetic proximity of the LF minimum relative to MLCT (Figure 4.4 a)).

The repulsive triplet state, $T_{(\text{TDDFT})}^3(\sigma \rightarrow \sigma^*)$ is common to the cobalamins, and lower in energy with respect to Co–C dissociation due to the instability associated with the single determinant-based wavefunction as seen in Figure 4.2. The character of the repulsive triplet was independently validated using an unrestricted DFT (UDFT) framework ($T_{(\text{UDFT})}$, Figure 4.2) where the $T_{(\text{UDFT})}^3(\sigma \rightarrow \sigma^*)$ wave function has proper asymptotic behavior and correctly levels off. This state becomes the lowest energy state at 2.3 Å for the base-on forms, and 2.6 Å for the base-off forms, where the lower triplet manifolds are closer to the ground state, and dissociation from triplet states in the base-off form, as discussed, cannot be ruled out.

The S_1 states of base-on cobalamins occur as MLCT for MeCbl at 2.26 eV as a 72% $\pi + d_{xz}/d_z^2 \rightarrow \pi^*$, 27% $d_{xz} + \pi \rightarrow \pi^*$ state, and for AdoCbl at 2.30 eV as a 44% $\pi + d_{xz}/d_z^2 \rightarrow \pi^*$, 28% $d_{xz} \rightarrow \pi^*$, 25% $d_{yz} + \pi \rightarrow \pi^*$ state, in excellent agreement with experimental values of 2.35 eV, and 2.35 eV respectively. The S_1 states of base-off cobalamins are also of MLCT character but occur higher in energy, for MeCbl at 2.35 eV as a 88% $d_{xz} + \pi \rightarrow \pi^*$ state, and for AdoCbl at 2.38 eV (Table 1) as an 84% $d_{xz} + \pi \rightarrow \pi^*$, 10% $d_{yz} + \pi \rightarrow \pi^*$ state, also in good agreement with experiment corresponding to 2.47 eV, and 2.41 eV respectively. When the axial base is replaced by water, the d_z^2 ground state contribution to

S_1 is removed, appearing first as anti-bonding character in the S_3 state of AdoCbl as a 60% $d_{yz} + \pi \rightarrow \sigma^*(d_z^2)$ contribution. The S_1 MLCT state is close in energy to S_2 which may be more closely associated with the experimental value, and to recall is more localized above S_0 .

The S_1 states of the four-coordinate base-off forms, $[\text{Co}^{\text{III}}(\text{corrin})]\text{-Me}^+$ and $[\text{Co}^{\text{III}}(\text{corrin})]\text{-Ado}^+$, represent fully dissociated LF minima and are characterized as pure LF transitions of $\text{H} \rightarrow \text{L}$ $d_{yz} + \pi \rightarrow \sigma^*(d_z^2)$ character. Low-lying excited singlets of the five-coordinate base-off models are notably closer to S_0 due to complete dissociation of the axial water. When the axial water becomes completely detached, d_z^2 anti-bonding character of the S_1 state increases, as shown for AdoCbl (Table 2.), and S_1 becomes energetically lower than the S_2 MLCT state (by ~ 1.6 eV) becoming a 90% LF transition at 2.18 eV with no significant change in Co–C bond lengths between S_0 and vertical S_1 . Upon relaxation, d_z^2 anti-bonding character further increases to a pure 99% LF S_1 state (98% for MeCbl), and the Co–C bond elongates to 2.2 Å (Figure 4.3.), corresponding to an S_1 adiabatic minimum of 1.80 eV.

The pure $\pi \rightarrow \pi^*$ transition for $\text{H}_2\text{O}\text{-}[\text{Co}^{\text{III}}(\text{corrin})]\text{-Ado}^+$ was calculated at 2.78 eV (S_6) in agreement with the experimental value of 2.67 eV and is characterized as a 61% $\text{H-2} \rightarrow \text{L}$ state. Ado π orbitals are also involved in corrin π^* excitations as ghost states, occurring in the base-off models as two CT types, $\pi_{\text{Ado}} \rightarrow \pi^*$, and $\pi_{\text{Ado}} \rightarrow \sigma^*(d_z^2)$, discussed in Section 2. The $\pi_{\text{Ado}} \rightarrow \pi^*$ state occurs as S_5 for both base-off models, and the $\pi_{\text{Ado}} \rightarrow \sigma^*(d_z^2)$ state occurs as S_7 for $[\text{Co}^{\text{III}}(\text{corrin})]\text{-Ado}^+$. Dissociation of the Co–C bond occurs smoothly in the relaxed five-coordinate base-off models accompanying an increase in d_z^2 σ^* character (points B–E, Figure 4.2). Further Co–C dissociation (to ~ 3.0 Å) couples the d_z^2 σ^* states to formation of the carbon radical and may be more accurately described as $d_{yz} + \pi \rightarrow \sigma^*(d_z^2 + \text{pC})$, and $d_{xz} + \pi \rightarrow \sigma^*(d_z^2 + \text{pC})$ for the S_1 and S_2 LF transitions, where carbon p anti-bonding character associated with the d_z^2 σ^* state is noted as increasing with Co–C dissociation.

Figure 4.2. Potential energy curves as a function of Co-C bond distance for S_1 optimized geometry of the (a) $[\text{Co}^{\text{III}}(\text{corrin})]\text{-Me}^+$ and (b) $[\text{Co}^{\text{III}}(\text{corrin})]\text{-Ado}^+$ model complexes.

The contribution of Ado π orbitals to ghost CT states is further maintained at dissociated Co-C distances (3.0 Å Co-C) where the $\pi_{\text{Ado}} \rightarrow \sigma^*(d_{z^2})$ state remains S_7 in the LF $[\text{Co}^{\text{III}}(\text{corrin})]\text{-Ado}^+$ model and appears as S_5 in the dissociated $\text{H}_2\text{O}\text{-}[\text{Co}^{\text{III}}(\text{corrin})]\text{-Ado}^+$ model (for both 3.00 Å, 2.20 Å Co-O). Although states involving Ado π orbitals are considered artifacts in this case, for the $\pi_{\text{Ado}} \rightarrow \sigma^*(d_{z^2})$ state, through-space CT is expected to be much lower than for $\pi_{\text{Ado}} \rightarrow \pi^*$, and similar analyses for protein-bound cofactors should be carefully considered when stabilization of the LF state has been implied, and mixing with excited state MO contributions may promote interactions in the far LF region. The electronic structures of photo-excited radicals, and the role of CT in biological environments is currently an area of intense research.

4.3.2. Vertical potential energy surfaces of the S_1 and S_2 states

Two-dimensional energy curves provide some explanation of Co-C photolysis, but we need

to look at both axial coordinates for a full explanation. Upon excitation the largest structural changes occur with respect to the axial bonds,¹⁰ and low-lying excited states as functions of the axial coordinates produce the most reliable description of the S_1 surface, a result of two states, MLCT and LF. Vertical excited state PESs as are presented for S_1 and S_2 in Figure 4.4., for the base-on Im-[Co^{III}(corrin)]-Me⁺ (a), Im-[Co^{III}(corrin)]-Ado⁺ (b), and for base-off H₂O-[Co^{III}(corrin)]-Me⁺ (c), H₂O-[Co^{III}(corrin)]-Ado⁺ (d) models. The S_1 PESs of base-off alkylcobalamins (Figure 4.4 b (MeCbl), d (AdoCbl)) provide some insight into experimental observations where the S_1 minima is stabilized in solution resembling cobalamin spectra with detached axial ligands.

Figure 4.4. Potential energy surfaces as a function of axial bond lengths of the singlet ground states (S_0), and the lowest two singlet excited states (S_1 , and S_2), shown as vertical projections for (a) Im-Co^{III}(corrin)]-Me⁺, (b) Im-Co^{III}(corrin)]-Ado⁺, (c) H₂O-Co^{III}(corrin)]-Me⁺, and (d) H₂O-Co^{III}(corrin)]-Ado⁺ model complexes.^{151,152,157}

Base-on alkylcobalamin photolysis, namely the wavelength-dependent photoproduct pathways of MeCbl, and the wavelength independent photolysis of AdoCbl, are readily explained by analysis of the S_1 and S_2 PESs. Initial excitations of base-on MeCbl (400-540 nm) and AdoCbl populate the MLCT minima on the S_1 surface, which is shallow with respect to Co-C elongation (Figure 4.4 a, b). The LF state of base-on MeCbl may be reached from the minimum by excitations above S_7 (< 400 nm) due to a high energetic proximity of the LF state relative to MLCT and a high barrier between the MLCT and LF regions by Co-N elongation across the seam, where these surfaces cross. The S_2 PESs of base-on cobalamins are shallow with respect to Co-N elongation (Figure 5.5 a, c) and localized above their S_1 MLCT states. Excitation to the entire S_2 surface of base-on MeCbl (> 400 nm) populates the S_1 MLCT state associated with Co-C elongation (Path A) and high energy excitations (< 400 nm) populate the LF state directly resulting in photolysis by dissociation of the axial base (Path B). The S_1 LF minimum of base-on AdoCbl is stabilized and energetically comparable to the S_1 MLCT state. The low energetic proximity of the LF state, and the low barrier between MLCT and LF regions in base-off AdoCbl, leads to an S_2 surface that mainly populates S_1 MLCT, leading to a wavelength-independent photolysis associated with initial MLCT elongation of the Co-C bond (Path A).

Base-off alkylcobalamin vertical S_1 PESs have some MLCT character above the S_0 minima but are characterized as having dominant LF states, where stabilization of the LF minima is more drastic. The S_0 PESs of the base-off alkylcobalamins are very shallow with respect to Co-O elongation (and more so for AdoCbl), resulting in a low barrier between initial MLCT and the photolytic LF region responsible by axial water detachment. The S_2 PESs of both base-off alkylcobalamins are shallow with respect to Co-O elongation, and excitations to S_2 mainly populate the S_1 LF state resulting in a wavelength independent photolysis for both base-off alkylcobalamins associated with elongation of the Co-O axial water (Path B).

4.3.3. Relaxed potential energy surfaces of the S_1 state

The topologies of the relaxed S_1 PESs are not much different than their corresponding vertical surfaces (Figure 4.5). The same features are present, MLCT and LF minima separated by a seam, but the adiabatic S_1 PESs are energetically different due to a lowered seam between these states, and a

closer energetic proximity of the S_1 surfaces to S_0 . Photolysis of the alkylcobalamins always occurs from an LF state, reached by Paths A or B with main difference being between MeCbl and AdoCbl in the base-on forms, where Paths A and B are comparable. Wavelength dependent photolysis of MeCbl (Figure 4.5 a) is maintained upon relaxation and slight Co-N contraction from $I(S_{0min})$ to $I(S_{1min})$ along Paths A (S_1-S_7) or B ($> S_7$), which is accessed from point IIB along the seam. Wavelength independent photolysis of AdoCbl is maintained upon relaxation from $I(S_{0min})$ to $I(S_{1min})$ where Path A is only active for base-on AdoCbl.

The relaxed base-off PESs are much different (Figure 4.5) where regardless of the upper ligand only Path B is active. The S_1 MLCT minima are slightly shallow with respect to Co-O coordinate, and higher in energy than the LF regions. Relaxation of the base-off forms (Figure 4.5 c, d) from $I(S_{0min})$ to $I(S_{1min})$ results in shortening of the Co-O bond; from 2.359 Å to 2.217 Å (MeCbl) and from 2.435 Å to 2.219 Å (AdoCbl), and a bending of the O-Co-C bond angle from a nearly linear, 178° (MeCbl), and 178° (AdoCbl), to a bent 164° (MeCbl), and 166° (AdoCbl). The S_1 MLCT character of the adiabatic base-off AdoCbl minimum is shallow and corresponds to increased π delocalization upon relaxation from $I(S_{0min})$ 84% $d_{xz} + \pi \rightarrow \pi^*$, 10% $d_{yz} + \pi \rightarrow \pi^*$, to $I(S_{1min})$ 79% $d_{yz} + \pi \rightarrow \pi^*$, 18% $d_{xz} + \pi \rightarrow \pi^*$ (Table 1, Figure 6d). The adiabatic population is notably inverted, where the largest contribution to S_1 decreases from 84% H-1 $\rightarrow$ L MLCT to 79 % H $\rightarrow$ L MLCT, with an increased 18% MLCT contribution to S_1 from H-1 $\rightarrow$ L. Elongation of the Co-O bond upon relaxation is essentially barrierless for both base-off forms, overcoming a small region of weak Co-H₂O bond coordination in the LF state before complete dissociation of the axial H₂O.

Figure 4.5. Relaxed potential energy surfaces as a function of axial bond lengths with photodissociation paths for (a) Im-[Co^{III}(corrin)]-Me⁺, (b) Im-[Co^{III}(corrin)]-Ado⁺, (c) H₂O-[Co^{III}(corrin)]-Me⁺, and (d) H₂O-[Co^{III}(corrin)]-Ado⁺ model complexes.

When the axial water is completely detached, relaxation results in an increased $d_{yz} + \pi \rightarrow \sigma^*$ ($d_z^2 + pC$) (LF) character from 85% to 98% in MeCbl, and 90% to 99% in AdoCbl (Table 2), and elongation of the Co–C bond of [Co^{III}(corrin)]-Me⁺ from 1.968 Å to 2.229 Å, and [Co^{III}(corrin)]-Ado⁺ from 1.996 Å to 2.335 Å. The dominant σ^* LF characters of the electronic states along the relaxed S_1 surface associated with Paths B lead to several intermediates with energetic relationships relevant to photolysis. The channel opened for strong preference towards LF stabilization based on energetic grounds is Path B and is very active due the low LF barrier. However, experiment has shown this channel is also active for fast non-radiative decay to the ground state, resulting in decreased photolysis quantum yield, from unity to 0.65 for MeCbl, and 0.13 for AdoCbl. To explain this, deactivation is considered where for base-on forms, it occurs as fast geminate recombination, while for base-off forms it occurs as IC by ring distortion. Although slower, IC deactivation occurs before photolysis due to solvent dynamics.

4.3.4. Photoreaction Path A

Photoreaction Path A is mainly associated with the base-on alkylcobalamins and is the only active pathway for AdoCbl. Path A is associated with direct Co–C dissociation from the MLCT state, proceeding from the shallow minima along the Co–C coordinate towards the LF region in the dissociation limit. The crossing between singlet and repulsive triplet occurs at ~ 2.4 Å for base-on MeCbl and AdoCbl where the difference between $I(S_{1\min})$ and the $^3(\sigma_{\text{Co-C}} \rightarrow \sigma_{\text{Co-C}}^*)$ state corresponds to the barrier to ISC: 7.1 kcal/mol for MeCbl and 3.9 kcal/mol for AdoCbl, which is unlikely in this case. According to Landau-Zener theory,¹⁵⁹⁻¹⁶⁰ high energetic gradients where these surfaces cross, and SOC matrix elements at the multiconfigurational are qualitatively large only for the base-off cobalamins,¹⁵⁷ as consistent with experiment where triplet RPs are not observed for the base-on forms.^{59, 161} The energetic relations between points along Path A of the base-on S_1 PESs correspond to BDEs of the $(\text{Im}[\text{Co}^{\text{III}}(\text{corrin})]^+ - \text{Me})_{1,\text{MLCT}}$ and $(\text{Im}[\text{Co}^{\text{III}}(\text{corrin})]^+ - \text{Ado})_{1,\text{MLCT}}$ complexes as estimated by differences in energy between $I(S_{1\min})$ and two fragments, according to the following equations:

These equations correspond to direct dissociation from the MLCT minima, to yield $\text{Im}[\text{Co}^{\text{II}}(\text{corrin})]^+$ and $\bullet\text{Me}$, and $\bullet\text{Ado}$ RPs along Path A in the excited state, with BDEs estimated at 16.6 kcal/mol for MeCbl, and 10.4 kcal/mol for AdoCbl.

The energy of the $(\text{Im}[\text{Co}^{\text{II}}(\text{corrin})]^+)_{1,\text{MLCT}}$ species is very sensitive with respect to axial base distance as demonstrated in recent studies for cob(II)alamin,¹⁵⁵ where elongation of the axial Co–N_{Im} bond changes the character of $(\text{Im}[\text{Co}^{\text{II}}(\text{corrin})]^+)_{1,\text{MLCT}}$ to $(\text{Im} \cdots [\text{Co}^{\text{II}}(\text{corrin})]^+)_{1,\text{LF}}$, accompanied by a noticeable drop in energy of the S_1 state. Detachment of the axial base results charge redistribution from corrin towards Co (as reported), consistent with an LF state mainly composed of d-d transitions (Tables 4.7, 4.8). The dissociation pathways involving the LF states of base-on MeCbl and AdoCbl may thus be summarized in the following equations:

According to these equations the BDEs associated with Path A starting from

$(\text{Im}-[\text{Co}^{\text{III}}(\text{corrin})]-\text{Me}^+)_{\text{i,MLCT}}$, resulting in $(\text{Im}\cdots[\text{Co}^{\text{II}}(\text{corrin})]^{+} + \bullet\text{Me})_{\text{i,LF}}$ and from

$(\text{Im}-[\text{Co}^{\text{III}}(\text{corrin})]-\text{Ado}^+)_{\text{i,MLCT}}$, resulting in $(\text{Im}\cdots[\text{Co}^{\text{II}}(\text{corrin})]^{+} + \bullet\text{Ado})_{\text{i,LF}}$, were estimated to be 8.2

kcal/mol for MeCbl and 2.0 kcal/mol for AdoCbl). The identification of two photodissociation intermediates indicates a branching in the extrapolated regions of the PESs, where LF and MLCT states become comparable (marked as seams in Figure 4.6 a, b). These two states along Path A correspond to S_1 MLCT dissociation energies of 10.4 kcal/mol (AdoCbl), and 16.6 kcal/mol, and S_1 LF dissociation energies of 8.2 kcal/mol (MeCbl) and 2.0 kcal/mol (AdoCbl) accessed via Co–C dissociation (Path A). Path B is only active for base-on MeCbl via excitation to higher states, resulting in a low 4.4 kcal/mol BDE of a $\bullet\text{Me}$ radical from an LF state with the axial base detached.

Figure 4.6. Schemes of photoreactions for (a) Im-[Co^{III}(corrin)]-Me⁺, (b) Im-[Co^{III}(corrin)]-Ado⁺, (c) H₂O-[Co^{III}(corrin)]-Me⁺, and (d) H₂O-[Co^{III}(corrin)]-Ado⁺ model complexes.^{151,152,157}

Although the calculated energy for Ado radical dissociation is very low, there is an additional barrier for radical escape associated with the solvent cage that competes in the dissociated LF region with deactivation from the Im $\cdots$ [Co^{II}(corrin)]⁺ state, and may be formally viewed as a (d_{yz})¹(d_z)² excited state configuration returning to a Co^{II} (d_{yz})²(d_z)¹ ground state. Due to the axial base being partially detached in the LF excited state, the deactivation process involves shortening of the Co–N_{Im} bond. After deactivation, the axial base of Im $\cdots$ [Co^{II}(corrin)]⁺ becomes bound again where the final step involves the recombination of the $\cdot$ Ado, or $\cdot$ Me radicals.

4.3.5 Photoreaction Path B

Base-on

The alternate route for Co–C bond photolysis for base-on alkylcobalamins along their S_1 PESs involves first displacement of the axial base. This path starts from I (S_{1min}) (Figure 4.6, lower), and is only active for MeCbl as discussed where photodissociation may occur by higher energy excitation directly from the LF state (4.4 kcal/mol) or compete effectively with LF photodissociation reached via Path A (8.4 kcal/mol). The barriers between MLCT and LF states along Path B are similar for base-on MeCbl (10.9 kcal/mol) and AdoCbl (8.8 kcal/mol). However, the low energetic proximity of the AdoCbl LF minima to S_0 results in LF dissociation only reached by MLCT, effectively inactivating photodissociation via Path B based on energetic grounds; although AdoCbl photolysis from the LF minima via Path B, within the TD-DFT limit (2.0 kcal/mol) and by extrapolation via Path A (1.9 kcal/mol) are comparable. From the LF state (Figure 4.6 a, b) reached along Path B only active for MeCbl via axial base dissociation, there are three possible photoreaction outcomes; IC by corrin ring distortion of 9.9 kcal/mol (MeCbl) and 11.8 kcal/mol (AdoCbl), recombination to S_0 by -8.4 kcal/mol, or Co–C photolysis of 4.4 kcal/mol (MeCbl) and 1.9 kcal/mol (AdoCbl).

Base -off

In the base-off forms of AdoCbl and MeCbl, only Path B is active corresponding to barrierless transitions from the MLCT to LF minima by elongation of the Co–O axial bonds. A very nice connection with experiment can be drawn from Figure 4.6, where regardless of upper ligand, base-off excitations along the S_1 PES consistently lead to photolysis from the stable LF minima along Path B. The reduced quantum yields of photolysis along Path B are explained by the shallow topology of the relaxed S_1 surface and complete dissociation of the axial waters in the adiabatic LF region, the point of ISC (similar to the base-on forms along Path A) corresponds to the channel for rapid IC to the ground state that competes with photolysis.

The quantum yields of the base-off cobalamins along Path B may be explained by the cage-effect, a model of solvent-dependent dynamics where the photolysis yield depends on competition between solvation of the carbon radical, and either escape or geminate recombination by deactivation of the solvent cage. Recombination for the base-on forms along Path A (-8.4 kcal/mol) does not compete with photolysis, due to late formation of the RPs that have a lower barrier to escape, with an additional

ultrafast (<100 ps) cage-escape observed for the Methyl radical via direct population of the LF state by higher excitation. Typically, when the ligand is bulky, the less cage-effect and steric influence will outweigh electronic influence in cage-deactivation and recombination, as in the base-on forms, where this is slower. Although the barriers to IC are comparable, no geminate recombination is observed for the base—off cobalamins (in the ns time range), as a result of the shallow topology of the S_1 surface leading to rapid ISC or IC (9.9 kcal/mol, MeCbl; 11.4 kcal/mol, AdoCbl), on a faster timescale than singlet-born photolysis (4.4 kcal/mol, MeCbl; 1.9 kcal/mol, AdoCbl) and deactivation.

Intuitively AdoCbl (.13) should have a higher QY than MeCbl (.65) due to the Co-C bond of AdoCbl being easier to photolyze, or considering cage dynamics, the recombination rate should be higher for the larger $\cdot$ Ado radical, and the smaller $\cdot$ Me radical should have a faster escape. Solvation energy is the dominant effect in this case, where more is required to solvate the bigger leaving group, increasing IC and ISC for base-off AdoCbl.

After vertical excitation, likely to the S_2 electronic state, $(H_2O-[Co^{III}(\text{corrin})]-Me^+)_{FC}$ and $(H_2O-[Co^{III}(\text{corrin})]-Ado^+)_{FC}$ models undergo relaxation and elongation of the Co–O bond, overcoming a low barrier, 1.1 kcal/mol (MeCbl) and 1.0 kcal/mol (AdoCbl), through the IIB intermediate to the LF region and complete dissociation of the axial water. The S_1 excited state of the $([Co^{III}(\text{corrin})]-Me^+)_{1,LF}$, and $([Co^{III}(\text{corrin})]-Ado^+)_{1,LF}$ models correspond to increased $d_{yz} + \pi \rightarrow \sigma^*$ LF character, where the S_1 states may undergo three processes; photodissociation of the Me or Ado group, internal conversion S_1/S_0 (IC) or intersystem crossing S_1/T (ISC). In the base-off forms, dissociation of water along the S_1 minimum energy pathway followed by complete dissociation of the alkyl group, represented as:

Deactivation of the $([Co^{II}(\text{corrin})]^+)_0$ intermediate to ground state (8.4 kcal/mol) and the extent of stabilization of the $(H_2O + [Co^{II}(\text{corrin})]^+ + \cdot Me)_{1,LF}$, and $(H_2O + [Co^{II}(\text{corrin})]^+ + \cdot Ado)_{1,LF}$ RPs in both solution, and enzymatic environments should be carefully considered. Triplet dissociation channels occur lower in energy than by singlet-born photolysis, consistent with experiment where dissociative RPs with the same spin do not recombine. ISC between S_1 states and triplet states (S_1/T

$^3(\sigma \rightarrow \sigma^*)$) has the lowest calculated barrier (1.3 kcal/mol, MeCbl; 1.0 kcal/mol, AdoCbl), and although the $^3(\sigma \rightarrow \sigma^*)$ electronic state is not a direct channel for dissociation, favorable ISC with triplet excited states having large S/T spin-orbit coupling near the MECP cannot be excluded.

3.7 Photodissociation along pathway B involving triplet states in the base-off forms

The S_1 states of the relaxed base-off alkylcobalamins have enhanced $d_{yz} + \pi \rightarrow \sigma^*(d_z^2)$ character and should couple to T_2 and T_3 states with similar energetic gradients and compatible orbital types, as reported explicitly for MeCbl based on CASSCF,¹⁵⁷ and by TD-DFT based on semi-qualitative SOC descriptions from Landau-Zener (LZ) theory.¹⁵⁹⁻¹⁶⁰ According to LZ theory SOC between states with different multiplicities requires a nonzero SOC matrix element and a low gradient of crossing between adiabatic PESs, i and j given by:

$$P_{ij} = \frac{-2\pi |H_{ij}|^2}{\hbar F_{ij} \left| \frac{dR}{dt} \right|} \quad (1)$$

where H_{ij} is the spin-orbit coupling matrix element, (dR/dt) is the product of the crossing speed, and (F_{ij}) is the difference in slope between states involved, given by

$$F_{ij} = \left| \frac{dE_i}{dR} - \frac{dE_j}{dR} \right|. \quad (2)$$

The probability (P_{ij}) of spin-forbidden crossover thus depends on the ratio of energetic gradients between i and j surfaces near their minimum-energy crossing points (MECPs), increasing when the denominator is small, due to a small orthogonal gradient between i and j at their MECs, resulting in increased crossing speeds. According to El-Sayed rules the rate of ISC between adiabatic states also depends on the MOs involved, favored when accompanied by a 90 ° rotation between ground or excited state.¹⁶² In other words ISC by $^1(\pi, \pi^*) \rightsquigarrow ^3(n, \pi^*)$ or $^1(\pi, n^*) \rightsquigarrow ^3(\pi, \pi^*)$ transitions should be faster than ISC by $^1(\pi, \pi^*) \rightsquigarrow ^3(\pi, \pi^*)$.

We conclude that triplet states are only involved in the photolysis of base-off alkylcobalamins, consistent with experiment, by semi-qualitative analysis at the DFT level and by analogy with multiconfigurational calculations, where SOC was calculated for MeCbl between S_1 and the

T_2 and T_3 states. ISC between S_1 and T_3 states (Figure 4.7) are expected to be slightly faster at ~ 2.05 due to rotation of S_0 orbital contributions for both MeCbl and AdoCbl corresponding to $^1(d_{yz}+n, \sigma^*) \rightsquigarrow ^3(d_{xz}+\pi, \sigma^*)$ ISCs. Although both T_2 and T_3 triplet states are good candidates for effective SOC in the excited states at each distance, El-Sayed rules are only fulfilled in the case of T_3 for $^1(d_{yz}, \sigma^*) \rightsquigarrow ^3(d_{xz}, \sigma^*)$, though SOC with T_2 cannot be entirely disregarded based on current calculations.

Figure 4.7 (a) Potential energy curves of the ground (S_0) and selected lowest-excited states (singlets – S_1 and triplets – T_1, T_2, T_3, T_4 and $3(\sigma\text{Co-C} \rightarrow \sigma^*\text{Co-C})$) of the $[Co^{III}(\text{corrin})]\text{-Ado}^+$ (left), and $[Co^{III}(\text{corrin})]\text{-Me}^+$ (right) model complexes along the Co-C coordinate, computed at the optimized geometry of the S_1 state. (b) Molecular orbitals (MOs) describing the character of singlet and triplet excited states, for two different Co-C distances corresponding to before and after points of S_1/T_3 intersystem crossing.¹⁴⁵

The axial base thus modulates the topologies of the S_1 and triplet surfaces, favoring ISC from the stabilized cob(II)alamin LF state, when detached. In the base-on forms cob(II)alamin is easily deactivated by the axial base along Path A by geminate recombination, whereas Path B is the only channel for deactivation for the base-off forms, and deactivation is controlled by IC.

3.7 Deactivation (IC) along pathway B

Internal conversion along Path B occurs for the $([\text{Co}^{\text{III}}(\text{corrin})]\text{-Me}^+)_{1,\text{LF}}$, and $([\text{Co}^{\text{III}}(\text{corrin})]\text{-Ado}^+)_{1,\text{LF}}$ models, where S_0 intersects S_1 as a function of corrin ring distortion (Figure 4.8). The S_1 PESs of the $([\text{Co}^{\text{III}}(\text{corrin})]\text{-Me}^+)_{1,\text{LF}}$, and $([\text{Co}^{\text{III}}(\text{corrin})]\text{-Ado}^+)_{1,\text{LF}}$ models were obtained from optimized excited state geometries as a functions of $\text{N}_{21}\text{-Co-N}_{23}$ angles and Co-C bond lengths, shown with corresponding S_1/S_0 seams. The starting point of IC is denoted IIIB ($S_{1\text{min}}$) and involves Co-C bond shortening and distortion of the corrin ring, to overcome the IC barriers to the ground state of MeCbl (9.9 kcal/mol) and AdoCbl (11.4 kcal/mol). These surfaces are flat, with a wide range of coordinates for Co-C bond lengths and $\text{N}_{21}\text{-Co-N}_{23}$ valence angles, indicating that changes in coordination occur in this regime without significant energy (white dotted lines, Figure 4.8).

Starting from IIIB, Co-C bond coordinates range from 2.25 Å to 2.05 Å (MeCbl), and 2.35 Å to 2.00 Å (AdoCbl), with decreasing $\text{N}_{21}\text{-Co-N}_{23}$ valence angles from 161 ° to 113 ° (MeCbl), and 164° to 111° (AdoCbl). Minimum energy pathways for IC on the S_1 PESs are connected with small changes of potential energy and reaching IC along the seam is associated with strong $\text{N}_{21}\text{-Co-N}_{23}$ deflection angles of 113 ° (MeCbl) and 111 ° (AdoCbl). The estimated barriers for S_1/S_0 IC are also likely overestimated, indicating that the real processes may involve more active coordinates. On the other hand, due to the high barrier to IC vs. photolysis from the LF minima in the base-off forms, conversion of IIIB $\rightarrow$ IVB (IC) does not directly compete with other photo-processes, namely ISC to triplet channels or geminate recombination, resulting in reduced QYs, as discussed.

Figure 4.8. (a) N₂₁-Co-N₂₃ valence angles as functions Co-C bond length in the LF electronic states of the ([Co^{III}(corrin)]-Me⁺)_{1,LF} (left), and the ([Co^{III}(corrin)]-Ado⁺)_{1,LF} (right) model complexes. (b) Potential energy surfaces for the S₁ optimized geometry of the ([Co^{III}(corrin)]-Me⁺)_{1,LF} (left), and the ([Co^{III}(corrin)]-Ado⁺)_{1,LF} (right) model complexes as functions of N₂₁-Co-N₂₃ valence angle, and Co-C bond length, with minimum energy paths for S₁/S₀ internal conversion depicted (white dotted lines). The seams along the intersections of the S₁/S₀ PESs are marked with black dotted line. (c) Geometries of the ([Co^{III}(corrin)]-Me⁺)_{1,LF} (left), and the ([Co^{III}(corrin)]-Ado⁺)_{1,LF} (right) model complexes at their points of internal conversion.¹⁴⁵

4. SUMMARY

A more general photochemical description may be presented for base-off AdoCbl photolysis. Photodissociation proceeds along the LF surface upon fast relaxation from the MLCT state that is localized above the ground state minima (Path B). Path A leading to Ado radical escape, is inactive for the base-off form, in contrast to the base-on form, where Co-C MLCT via Path A precedes LF photodissociation. The strong preference of the base-off forms towards Path B is consistent with ultrafast excited-state dynamics, where absence of the trans-nitrogenous ligand changes the topology of the S_1 surface; activating a channel for fast internal conversion to the ground state and enhancing the LF character of the S_1 state. The stability of base-off cobalamins to photodissociation is a result of a dominant picosecond channel for ground state recovery. Notably, slow formation of a cob(II)alamin radical and the absence of a prominent geminate recombination component in TAS are consistent with the formation of a geminate triplet RP and dissociation through a $^3(\sigma \rightarrow \sigma^*)$ channel. In agreement with magnetic field effect studies,¹⁶¹ photodissociation of base-on AdoCbl, on the other hand, occurs via singlet-born radical escape that competes with geminate recombination, with no observed ground state recovery from IC.⁶²

This chapter summarizes alkylcobalamin photolysis, closely related to our theoretical study for base-on AdoCbl, to show the effect of axial base on the electronic structures involved. The mechanism for base-off AdoCbl is consistent with base-off MeCbl and current experimental data from ultrafast excited-state dynamics. We show that for photodissociation to occur from a triplet state, an initial triplet must first be obtained by ISC as a result of an effective SOC between excited singlet and triplet states, as consistent with Landau–Zener theory and El-Sayed rules.

The main difference between base-on and base-off alkylcobalamin photolysis is attributed to a difference in topology between their S_1 PESs, specifically the barriers and gradients between the initial MLCT and LF regions. Although two photolytic pathways are feasible the axial base modulates which pathway is active; Path A when the axial base is attached and Path B when the axial base is detached (unless reached by higher excitation for base-on MeCbl). Possible IC by corrin ring distortion competes

with photolysis along Path B in the base-off forms, in accord with current experiment, where absence of the DBI base opens a channel for fast non-radiative decay to the ground state. The barriers to IC and deactivation from the LF minima are energetically comparable for the alkylcobalamins in both base-on and base-off forms, but the solvent-dependent energetic relationships between LF regions, the ground state and the separation of RPs associated with different radical lifetimes should be carefully considered for protein environments.

The gradients between S_1 MLCT and LF surfaces of the base-on alkylcobalamins may be regarded as resulting in singlet-born RP, while photolysis of the base-off forms results in rapid IC, reduced singlet-born QYs and possible photodissociation from triplet states. Further studies of alkylcobalamin cofactors using multi-scale approaches in various protein environments are expected to provide a better understanding of reactivity and spin-effects involved in cobalamin catalysis, enzymatic photolysis and optogenetic processes.

CHAPTER VI CONCLUSIONS AND FUTURE DIRECTIONS

This dissertation detailed the photo-homolysis of the Co-C bond in the non-alkyl and alkylcobalamins, as well as the electronic structure of cob(II)alamin. Although photoactivity of the cobalamins was first noted during their initial discovery, Co-C homolysis in alkylcobalamins and the photostability of CNCbl were regarded as more or less side reactions. The ability to generate radicals via light has become the subject of vast experimental research, as advancements in TAS and other experimental techniques allow the study of intermediates involved in photoreactions in great detail. It is now generally accepted that the photolysis of alkylcobalamins results in the formation of cob(II)alamin and alkyl RPs, similar to the intermediates from AdoCbl-dependent enzymatic catalysis. The non-alkylcobalamins, in contrast, are generally photostable, with HOCbl being the exception. HOCbl may be excited using shorter wavelength excitations to generate hydroxyl radicals *in situ*.

The photolysis of the alkylcobalamins depends upon a number of factors, such as the nature of both axial ligands, the local environment and the excitation wavelengths applied. The mechanisms of alkylcobalamin photolysis can be described by analysis of their S_1 PESs, and the lowest energy pathways along these surfaces, as functions of the axial bond coordinates. Initial excitation is MLCT, and the final LF state responsible for photolysis is reached by either dissociation of the upper ligand (Path A), or dissociation of the lower base (Path B). Path B is inactive for AdoCbl and may be reached by higher energy excitation in MeCbl. Formation of RPs results in cage-escape, geminate recombination or deactivation to the ground state by corrin ring distortion, or re-attachment of the axial base, where the electron in the d_z^2 orbital of cob(II)alamin mixes with a $d_{xy} + \pi$ orbital, leading to deactivation to the ground state.

Understanding photolysis of the alkylcobalamins at the molecular level, especially considering enzymatic and biological environments, represents a complex problem that only recently has been possible to investigate using computational methods and to provide a detailed comparison with experimental results. The most important issues to be addressed from a theoretical perspective are related to AdoCbl, which still requires better connection with experiment. For example, the deactivation of

cob(II)alamin inside of proteins may be the primary active pathway for deactivation inside proteins, where steric hindrance of the corrin ring prevents deactivation by distortion. This path is mainly associated with d-d transitions, specifically a $(d_z^2)^2(d_{xy})^1 \rightarrow (d_z^2)^1(d_{xy})^2$ nonradiative transition that leads to deactivation to the ground state. In the AdoCbl system, especially in biological environments, this effect should be carefully considered when states involving the d_z^2 orbital, such as the $\text{Ado}\pi \rightarrow d_z^2$ ghost CT transition, may mix with other excited state orbitals along this path.

Current investigations are underway to extend the understanding of other cobalamins such as ethyl, aqua, azido and thiolato cobalamins, as high quality experimental TAS data becomes available. Although it is argued that the first and most important mechanistic description requires of electronically excited states requires TD-DFT PESs as a functions of axial bond lengths, consideration of different internal coordinates may also be needed, especially for the base-off cobalamins, where SOC has been implied and other mechanisms of IC may be possible.

Multi-scale methods, such as QM/MM, which can accommodate complex electronic structures in large biological environments, are expected to provide further insight into the photophysical properties of AdoCbl, the nature of the protein environment and the consequences of orbital mixing. CT diagnostics such as the D_{CT} diagnostic of Ciofini et. al using TD-DFT and the projection methods such as TDA are of interest, as single point geometries may be extracted along specific reaction coordinates to truncate in multiconfigurational or ONIOM benchmarks. The role of deactivation and long-range CT, as well as the involvement of other amino acid residues in electron transfer events in the CarH photoreceptor leading to the bis-His “light-state” adduct, also remain to be determined. It is also interesting to consider the role of Tyrosine as an electron donor in CarH, as it is near the upper Ado moiety.

Other biological environments, such as the GLM and EAL, where enzymes with electron transfer, and radical stabilization may be involved in the catalytic mechanism, are of interest, as the electronic structures involved may also offer new connections with photolysis. The analysis and characterization of electron transfer and the catalytic events that occur in these complex systems and their connection to photochemistry remain an open area of research. Furthermore the photo mechanism of aerobic oxidation of AdoCbl to HOCbl is interesting, as the ground state of molecular oxygen is known to

be in a triplet state and SOC events may be involved depending on the gradient of the reaction coordinate. The mechanism of HOCbl aerobic conversion to AdoCbl in optogenetic regulation by the AeR protein also remains an open issue requiring further mechanistic studies.

Advancement of systems that utilize the cobalamin scaffold as pharmacological or biological tools are a promising field. The design of antivitaminins that can activate specific metabolism, and the delivery of designed therapeutic agents or reactive radicals using light, represents an era of medicine where the human and bacterial biological spaces can be more finely tuned and controlled. Additionally, the implications for CarH or AerR moieties in optogenetic applications is also attractive, as advances in clinical discovery depend on effective tools to interact with the genome and activate certain functionalities. In small molecule discovery, the further understanding of relationships between ligand functionalization and photodissociation will allow the development of new photocatalysts and photolabile drugs. Multiscale approaches seem to be the most effective route, and the development of alternate approaches to DFT in structure-based methods are expected to improve the conformational space.

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GLOSSARY OF TERMS

AdoCbl: Adenosylcobalamin
BDE: Bond Dissociation Energy
CASSCF: Complete Active Space Self-Consistent Field
CSF: Configuration State Function
CNCbl: Cyanocobalamin
CT: Charge-Transfer
DBI: Dimethylbenzimidazole
DFT: Density Functional Theory
EPR: Electron Paramagnetic Resonance
Hcy: Homocysteine
HOCbl: Hydroxocobalamin
IC: Internal Conversion
ISC: Intersystem crossing
LF: Ligand Field
MCD: Magnetic Circular Dichroism
MeCbl: Methylcobalamin
MLCT: Metal-to-ligand charge-transfer
MO: Molecular Orbital
MetH: Methionine Synthase
NTO: Natural Transition Orbital
ONIOM: our own n-layered integrated molecular orbital and molecular mechanics
RP: Radical Pair
QM/MM: Quantum Mechanics/ Molecular Mechanics
QY: Quantum Yield
SDD: Stuttgart-Dresden Pseudopotential basis set
SOC: Spin-Orbit Coupling
TAS: Transient Absorption Spectroscopy
TD-DFT: Time-Dependent Density Functional Theory
XMCQDPT2: Multiconfigurational second-order perturbation theory

APPENDIX

Figure 1.1 Molecular structure and structural model of Vitamin B₁₂ derivatives.¹⁰

Figure 1.2. Solution and Protein-bound forms of Methylcobalamin.³³

Figure 1.3 Solution and Protein-bound forms of AdoCbl.⁴⁰

Figure 1.4 Molecular structures of cob(II)alamin in solution and protein environments.³⁹

Figure 1.5 Catalytic cycle of MeCb-dependent methyltransferases.¹¹

Figure 1.6 Catalytic cycle of AdoCbl-dependent eliminases.¹¹

Figure 1.7 Photoactive OH radical generation and B₁₂ antivitamins.¹¹

Figure 1.8 (upper) Theoretical benchmarks of MeCbl Co-C bond dissociation energies, (lower) Ten lowest electronic transitions of Im-[Co^{III}(corrin)]-CN⁺ calculated with different density functionals and basis sets together with corresponding Λ diagnostic values.⁷⁸

Figure 1.9 Experimental, and optimized axial bond lengths at the DFT/BP86 level, for S_0 and TD-DFT/BP86 for S_1 excited states of the cobalamins under consideration (MeCbl,³⁴ AdoCbl,³⁶ CNCbl,³⁴ HOCbl³⁵). In all calculations the same basis sets, TZVPP for Co, C, N, and TZVP for H were used, employing the Conductor-like Screening Model (COSMO) solvent.

Figure 1.11 Photolysis and intersystem crossing in MeCbl.⁹⁰

Figure 2.1. Active space corresponding to $[\text{Co}^{\text{II}}(\text{corrin})]^+$ used in the CASSCF(11,12) and subsequent XMCQDPT2 calculations.

NTO	eV	NTO Coeff	f	α hole	α particle	β hole	β particle
D ₁	0.45	0 (α) 100 (β)	0.0000	d_z^2	π^*	$d_{yz} + \pi$	d_z^2
D ₂	0.68	0 (α) 100 (β)	0.0000	π	π^*	$d_{xz} + \pi$	d_z^2
D ₃	1.38	0 (α) 99 (β)	0.0007	$d_{xz} + \pi$	π^*	$d_{x^2-y^2}$	d_z^2
D ₄	1.52	0 (α) 99 (β)	0.0003	π	π^*	π	d_z^2
D ₅	2.13	39 (α) 61 (β)	0.0005	$d_{yz} + \pi$	π^*	$d_{yz} + \pi$	π^*

Figure 2.2. Natural Transition Orbitals (NTOs) for $[\text{Co}^{\text{II}}(\text{corrin})]^+$ based on TD-DFT calculations at the uBP86/6-311G(d,p) level.

Figure 2.3. Active orbitals of $\text{Im}[\text{Co}^{\text{II}}(\text{corrin})]^+$ used in the CASSCF(11,12) and subsequent XMCQDPT2 calculations.

NTO	eV	NTO Coeff	<i>f</i>	α hole	α particle	β hole	β particle
Im-[Co^{II}(corrin)]⁺							
D ₁	1.40	31 (α) 69 (β)	0.0001	$d_x^2 + \pi_{1m}$	π^*	$d_{yz} + \pi$	$d_x^2 + \pi_{1m}^*$
D ₂	1.50	36 (α) 64 (β)	0.0008	$d_{yz} + \pi$	π^*	$d_{yz} + \pi$	π^*
D ₃	1.59	16 (α) 83 (β)	0.0010	$d_x^2 + \pi_{1m}$	π^*	$d_{xz} + \pi$	$d_x^2 + \pi_{1m}^*$
D ₄	1.65	49 (α) 51 (β)	0.0026	$d_x^2 + \pi_{1m}$	π^*	$d_{yz} + \pi$	$d_x^2 + \pi_{1m}^*$
D ₅	1.81	8 (α) 92 (β)	0.0028	$d_{xz} + \pi_{1m}$	π^*	$d_{xz} + \pi_{1m}$	π^*
[Im- - -Co^{II}(corrin)]⁺ (2.80 Å)							
D ₁	0.72	0 (α) 100(β)	0.000	d_x^2	π^*	$d_{yz} + \pi$	d_x^2
D ₂	0.91	0 (α) 100(β)	0.0000	d_x^2	π^*	$d_{xz} + \pi$	d_x^2
D ₃	1.55	11 (α) 52 (β)	0.0017	π	π^*	$d_x^2 - y^2$	d_x^2
D ₄	1.66	25 (α) 50 (β)	0.0001	π	π^*	$d_x^2 - y^2$	d_x^2
D ₅	1.84	8 (α) 92 (β)	0.0015	π	π^*	π	d_x^2

Figure 2.4. NTOs for Im-[Co^{II}(corrin)]⁺ (upper panel) and [Im- - -Co^{II}(corrin)]⁺, Co-C = 2.80 Å, (lower panel) based on TD-DFT calculations at the uBP86/6-311G(d,p) level.⁴³

Figure 2.5. Experimental cob(II)alamin steady-state spectra (solid line), and TD-DFT transitions of cob(II)alamin at the BP86/SDD level (circles); and of the two truncated structural models with BP86/6-311g(d,p): Im-[Co^{II}(corrin)]⁺, min (filled triangles), and the [Im---Co^{II}(corrin)]⁺ LF state, Co-C = 2.80 Å, (empty triangles).

NTO	eV	NTO Coeff	<i>f</i>	α hole	α particle	β hole	β particle
D ₁	1.27	6 (α) 94 (β)	0.0001	$d_z^2 + \pi_{lm}$	π^*	$d_{yz} + \pi$	$d_z^2 + \pi$
D ₂	1.42	0 (α) 100 (β)	0.0001	$d_z^2 + \pi_{lm}$	π^*	$d_{xz} + \pi$	$d_z^2 + \pi$
D ₃	1.48	37 (α) 63 (β)	0.0005	$d_{yz} + \pi_{lm}$	π^*	$d_{yz} + \pi$	π^*
D ₄	1.72	91 (α) 8 (β)	0.0074	$d_z^2 + \pi_{lm}$	π^*	$d_{yz} + \pi$	$d_z^2 + \pi^*$
D ₅	1.78	14 (α) 85 (β)	0.0023	$d_{xz} + \pi$	π^*	$d_{yz} + \pi$	π^*

Figure 2.6. NTOs of the first 5 TDDFT excited states of the cob(II)alamin structure at the BP86/6-311G (d,p) level of theory.

Figure 2.7. Energies of frontier molecular orbitals for $\text{Im}[\text{Co}^{\text{II}}(\text{corrin})]^+$ model complex as a function of Co- N_{Im} distance. Red line – energies of alpha orbitals, black line – energies of beta orbitals, filled and empty circles correspond to the occupied and unoccupied orbitals, respectively.

Figure 2.8. Potential energy curves of the ground and nine lowest doublet TD-DFT excited states of the Im-[Co^{II}(corrin)]⁺ model complex as a function of Co-N_{Im} bond length.

Figure 3.1. Optimized energy of the S₁ state as function of the Co-C distance. Energy of the lowest vertical singlet excited state is denoted as A, and is based on the optimized geometry of the ground state. Point B corresponds to Co-C = 1.9 Å, while point C to the S₁ minimum.¹⁴⁵

Figure 3.2. Molecular orbital diagrams corresponding to the lowest singlet excited states of CNCbl representing; the optimized geometry of the S_0 state (A); the optimized geometry of the S_1 state with fixed Co-C bond distances at $1.9 \text{ \AA}$ (B); the optimized geometry of the S_1 state with fixed Co-C bond distances at $1.9 \text{ \AA}$ (B); the optimized geometry of the S_1 state (C).¹⁴⁵

Figure 3.3. Potential energy surface of the S_1 state, along with the upper portion of the ground state surface. Characteristic points on the S_1 PES correspond to: ground state S_0 geometry (A), S_1 with Co-C = 1.9 $\text{\AA}$ (B); energy minimum of the S_1 state (C); minimum energy point of the S_1/S_0 crossing seam (D).¹⁴⁵

Figure 3.4. Schematic representation of the diagonal cut bisecting the 3D PES.¹⁴⁵

Figure 3.5. Schematic representation of polarized XANES spectra monitoring structural evolution in cyanocobalamin.¹⁴⁶

Figure 3.6. Comparison of experimental and simulated XANES spectra at 1.5 ps: (a) Isotropic XANES ground- and excited- state spectra and the difference spectrum between the ground and excited state. The ground state spectrum (blue) and the difference spectrum (green), are used to estimate the excited state spectrum (red) by adding appropriate percentage of ground state spectrum into the difference spectrum; (b) Components x , y , and z of the difference spectrum are compared. The $y+z$ difference (green) is plotted on the left-hand scale. The x difference (blue) is multiplied by four and offset for clarity. The $y+z$ simulation (yellow) is decomposed into the y and z contributions (violet dashed lines) with z making the largest contribution. The y contribution (violet dashed line) is also compared with the simulated x (pink) contribution.¹⁴⁶

Figure 3.7. Potential energy surface of hydroxocobalamin shown with minimum energy paths leading to IC, and possible dissociation. In all calculations the BP86 functional was used, with TZVPP for Co, C, N, and TZVP for H basis sets, employing water as the COSMO solvent.⁶⁴

Figure 3.8. a) Potential energy curves of the ground and lowest singlet excited states of the Im-[Co^{III}(corrin)]-OH⁺ model complex along the Co-C coordinate computed at the ground state optimized geometry (green arrow – vertical excitation to the first electronic state with large oscillator strength, blue arrows – possible path of relaxation to the minimum S_1 state) . b) Scheme of radiationless deactivation for HOCbl.

Figure 3.9. Photochemical paths leading to internal conversion for HOCbl and CNCbl. PESs of the optimized S_1 state are shown as function axial bond lengths for: a) Im-[Co^{III}(corrin)]-OH⁺, characteristic points on the PES corresponds to: ground state S_0 geometry (A), energy minimum of the S_1 state (B); S_1 with Co-C = 2.0 Å (C); b) Im-[Co^{III}(corrin)]-CN⁺, characteristic points on the PES correspond to: ground state S_0 geometry (A), S_1 with Co-C = 1.9 Å (B); energy minimum of the S_1 state (C).

Figure 3.10. Molecular orbital MO diagrams of the Im-[Co^{III}(corrin)]-OH⁺ model complex representing: the optimized geometry of the S₀ state (A); the optimized geometry of the S₁ MLCT state (B); the optimized geometry of the S₁ state with fixed Co-C bond distances at 2.00 Å and 2.76 Å (C and D, respectively); the optimized geometry of the S₁ LF state (E).

Figure 3.11. Scheme of the radiationless deactivation for non-alkylcobalamins: HOCbl and CNCbl.

Figure 4.1. Experimental, and optimized axial bond lengths at the DFT/BP86 level, for S_0 and TD-DFT/BP86 for S_1 excited states of the cobalamins under consideration (Im-MeCbl, HO-MeCbl, and Im-AdoCbl, HO-AdoCbl). In all calculations the same basis sets, TZVPP for Co, C, N, and TZVP for H were used, employing the Conductor-like Screening Model (COSMO) solvent.

Figure 4.2. Potential energy curves of the ground and lowest vertically excited states of (a) Im-Co^{III}(corrin)]-Me⁺, (b) Im-Co^{III}(corrin)]-Ado⁺, and lowest optimized states of the (c) H₂O-Co^{III}(corrin)]-Me⁺ and (d) H₂O-Co^{III}(corrin)]-Ado⁺ complexes along the Co-C bond computed at the ground-state optimized geometry (a, b) and at the S₁ state optimized geometry (d, c). The dotted line corresponds to the approximate course of the triplet excited state.^{151,152,157}

Figure 4.2. Potential energy curves as a function of Co-C bond distance for S₁ optimized geometry of the (a) [Co^{III}(corrin)]-Me⁺ and (b) [Co^{III}(corrin)]-Ado⁺ model complexes.

Figure 4.4. Potential energy surfaces as a function of axial bond lengths of the singlet ground states (S_0), and the lowest two singlet excited states (S_1 , and S_2), shown as vertical projections for (a) $\text{Im-Co}^{\text{III}}(\text{corrin})\text{-Me}^+$, (b) $\text{Im-Co}^{\text{III}}(\text{corrin})\text{-Ado}^+$, (c) $\text{H}_2\text{O-Co}^{\text{III}}(\text{corrin})\text{-Me}^+$, and (d) $\text{H}_2\text{O-Co}^{\text{III}}(\text{corrin})\text{-Ado}^+$ model complexes.^{151,152,157}

Figure 4.5. Relaxed potential energy surfaces as a function of axial bond lengths with photodissociation paths for (a) Im-[Co^{III}(corrin)]-Me⁺, (b) Im-[Co^{III}(corrin)]-Ado⁺, (c) H₂O-[Co^{III}(corrin)]-Me⁺, and (d) H₂O-[Co^{III}(corrin)]-Ado⁺ model complexes.

Figure 4.6. Schemes of photoreactions for (a) Im-[Co^{III}(corrin)]-Me⁺, (b) Im-[Co^{III}(corrin)]-Ado, (c) H₂O-[Co^{III}(corrin)]-Me⁺, and (d) H₂O-[Co^{III}(corrin)]-Ado⁺ model complexes.^{151,152,157}

Figure 4.7 (a) Potential energy curves of the ground (S_0) and selected lowest-excited states (singlets – S_1 and triplets – T_1 , T_2 , T_3 , T_4 and $3(\sigma\text{Co-C} \rightarrow \sigma^*\text{Co-C})$ of the [Co^{III}(corrin)]-Ado⁺ (left), and [Co^{III}(corrin)]-Me⁺ (right) model complexes along the Co-C coordinate, computed at the optimized geometry of the S_1 state. (b) Molecular orbitals (MOs) describing the character of singlet and triplet excited states, for two different Co-C distances corresponding to before and after points of S_1/T_3 intersystem crossing.¹⁵⁷

Figure 4.6. (a) $N_{21}-Co-N_{23}$ valence angles as functions $Co-C$ bond length in the LF electronic states of the $([Co^{III}(\text{corrin})]-Me^+)_{1,LF}$ (left), and the $([Co^{III}(\text{corrin})]-Ado^+)_{1,LF}$ (right) model complexes. (b) Potential energy surfaces for the S_1 optimized geometry of the $([Co^{III}(\text{corrin})]-Me^+)_{1,LF}$ (left), and the $([Co^{III}(\text{corrin})]-Ado^+)_{1,LF}$ (right) model complexes as functions of $N_{21}-Co-N_{23}$ valence angle, and $Co-C$ bond length, with minimum energy paths for S_1/S_0 internal conversion depicted. The seams along the intersections of the S_1/S_0 PESs are marked with black dotted line. c) Geometries of the $([Co^{III}(\text{corrin})]-Me^+)_{1,LF}$ (left), and the $([Co^{III}(\text{corrin})]-Ado^+)_{1,LF}$ (right) model complexes at their points of internal conversion.¹⁵²

Table 2.1. The lowest five states of $[\text{Co}^{\text{II}}(\text{corrin})]^+$ obtained from CASSCF/MCXQDPT2 calculations, where CSF denotes the configuration state function.⁴³

State	eV	f	Weight (%) of CAS state in MCXQDPT2	CAS state	Weight of CSF [%]	Electronic configuration of CAS state	Character
D ₀	0.00		75	1	94	$(d_z^2)^1$	
			25	2	85	$(d_{yz})^1(d_z^2)^2$	$d_{yz} \rightarrow d_z^2$
D ₁	0.01	0.00000	25	1	94	$(d_{z2})^1$	
			75	2	85	$(d_{yz})^1(d_z^2)^2$	$d_{yz} \rightarrow d_z^2$
D ₂	1.35	0.00000	99	3	68	$(d_{x^2-y^2})^1(d_z^2)^2$	$d_{x^2-y^2} \rightarrow d_z^2$
						$(d_{xz})^\uparrow (d_{yz})^\downarrow$	
					15	$(d_{z2})^2(d_{xy-n})^\uparrow$	$d_{xz}/d_{yz} \rightarrow d_z^2/d_{xy-n}$
D ₃	2.05	0.00001	98	4	35	$(d_{x^2-y^2})^\uparrow (d_{xz})^\downarrow$	
						$(d_z^2)^2(d_{xy-n})^\uparrow$	$d_{x^2-y^2}/d_{xz} \rightarrow d_z^2/d_{xy-n}$
						$(d_{x^2-y^2})^\uparrow (d_{xz})^\uparrow$	
					26	$(d_z^2)^2(d_{xy-n})^\downarrow$	$d_{x^2-y^2}/d_{xz} \rightarrow d_z^2/d_{xy-n}$
					18	$(d_{xz})^\uparrow (d_z^2)^\downarrow (d_{xy-n})^\uparrow$	$d_{xz} \rightarrow d_{xy-n}$
D ₄	2.18	0.00001	99	5	62	$(d_{xz})^\uparrow (d_{yz})^\downarrow$	
						$(d_z^2)^2(d_{xy-n})^\uparrow$	$d_{xz}/d_{yz} \rightarrow d_z^2/d_{xy-n}$
					23	$(d_{xz})^\uparrow (d_{yz})^\uparrow$	
						$(d_z^2)^2(d_{xy-n})^\downarrow$	$d_{xz}/d_{yz} \rightarrow d_z^2/d_{xy-n}$

Table 2.2. The lowest five states of $[\text{Im-Co}^{\text{II}}(\text{corrin})]^+$ obtained from CASSCF/MC-XQDPT2 calculations, where CSF denotes the configuration state function.⁴³

State	eV	f	Weight (%) of CAS state in MC- XQDPT2	CAS state	Weight of CSF [%]	Electronic configuration of CAS state	Character
D ₀	0.00		100	1	92	$(d_z^2)^1$	
D ₁	0.90	0.00009	96	2	55 31	$(d_{yz})^1(d_z^2)^2$ $(d_{xz})^1(d_z^2)^2$	$d_{yz} \rightarrow d_z^2$ $d_{xz} \rightarrow d_z^2$
D ₂	1.03	0.00012	96	3	55 31	$(d_{xz})^1(d_z^2)^2$ $(d_{yz})^1(d_z^2)^2$	$d_{xz} \rightarrow d_z^2$ $d_{yz} \rightarrow d_z^2$
D ₃	2.09	0.00001	95	4	67 16	$(d_{x^2-y^2})^1(d_z^2)^2$ $(d_{xz})^\uparrow (d_{yz})^\downarrow (d_z^2)^2 (d_{xy-n})^\uparrow$	$d_{x^2-y^2} \rightarrow d_z^2$ $d_{xz}/d_{yz} \rightarrow d_z^2/d_{xy-n}$
D ₄	2.87	0.00004	100	5	86	$(d_z^2)^0(d_{xy-n})^1$	$d_z^2 \rightarrow d_{xy-n}$

Table 2.3. Select TDDFT excited states of the full cob(II)alamin structure using BP86/SDD, and truncated models [Im-Co^{II}(corrin)]⁺ (min, 2.13 Å), and [Im- - - Co^{II}(corrin)]⁺ (LF, 2.80 Å) using BP86/6-311G(d,p).⁴³

State	eV	λ(nm)	<i>f</i>	NTO Coeff.	major TDDFT MOs	Character
cob(II)alamin (min, 2.23 Å)						
D ₁₉	2.71	457.2	0.0276	46	251(α) → 255(α)	$d_{x^2-y^2} + \pi \rightarrow \pi^*$
						$d_{x^2-y^2} + \pi \rightarrow$
				29	250(β) → 255(β)	$d_z^2 + \pi_{lm}^*$
D ₂₉	2.93	422.9	0.0377	25	254(α) → 257(α)	$d_z^2 + \pi \rightarrow \pi^*$
				63	247(α) → 255(α)	$\pi_{lm} + p \rightarrow \pi^*$
				19	246(α) → 255(α)	$\pi + d_z^2 \rightarrow \pi^*$
D ₆₁	3.39	366.2	0.0263	19	247(β) → 254(β)	$\pi_{lm} \rightarrow \pi^*$
				78	252(β) → 258(β)	$d_{xz} + \pi \rightarrow \pi^*$
				22	252(α) → 258(α)	$d_{xz} + \pi_{lm} \rightarrow \pi^*$
D ₁₄₄	3.95	313.7	0.0923	60	250(β) → 259(β)	$d_{x^2-y^2} + \pi \rightarrow d_{xy-n}$
				40	242(α) → 257(α)	$\pi_p \rightarrow \pi^*$
[Im-Co ^{II} (corrin)] ⁺ (min, 2.13 Å)						
D ₂₃	3.00	413.8	0.0610	32	109(α) → 114(α)	$\pi + d_z^2 \rightarrow \pi^*$
				17	113(α) → 117(α)	$d_z^2 + \pi \rightarrow \pi^*$
				30	110(β) → 115(β)	$d_{x^2-y^2} \rightarrow d_{xy-n}$
				21		$\pi \rightarrow d_{z2} + \pi^*$
D ₃₃	3.38	366.7	0.0500	75	111(β) → 117(β)	$d_{xz} + \pi \rightarrow \pi^*$
				25	110(α) → 115(α)	$d_{x^2-y^2} \rightarrow d_{xy-n}$
D ₄₅	3.80	326.1	0.0689	89	111(α) → 117(α)	$d_{xz} + \pi + \pi_{lm} \rightarrow \pi^*$
					108(α) → 115(α)	
D ₅₆	4.09	303.0	0.2433	11	112(β) → 114(β)	$d_{xz} + \pi \rightarrow \pi^*$
				40	109(α) → 116(α)	$\pi + d_z^2 \rightarrow \pi^*$
				33	109(β) → 115(β)	$\pi + d_z^2 \rightarrow \pi^*$
				15	106(β) → 114(β)	$\pi \rightarrow d_{yz} + \pi^*$
				12		$\pi + d_{yz} \rightarrow \pi^*$
[Im- - -Co ^{II} (corrin)] ⁺ (LF, 2.80 Å)						
D ₁₇	2.73	455.0	0.0455	58	112(α) → 114(α)	$d_z^2 + \pi \rightarrow \pi^*$
					109(α) → 114(α)	
				42	109(β) → 114(β)	$d_z^2 + \pi \rightarrow \pi^*$
D ₂₆	3.09	401.2	0.0953	66	109(α) → 114(α)	$\pi + d_z^2 \rightarrow \pi^*$
				34	109(β) → 114(β)	$d_{x^2-y^2} \rightarrow \pi^*$
D ₃₃	3.44	360.0	0.0520	74	105(β) → 113(β)	$\pi_{lm} + p \rightarrow d_z^2 + \pi_{lm}^*$
				26	109(α) → 115(α)	$\pi + d_z^2 \rightarrow d_{xy-n}$
D ₅₄	4.06	305.1	0.2472	40	109(α) → 116(α)	$\pi + d_z^2 \rightarrow \pi^*$
				33	109(β) → 115(β)	$\pi + d_z^2 \rightarrow \pi^*$
				15	107(α) → 114(α)	$\pi + d_{yz} \rightarrow \pi^*$
				12	107(β) → 114(β)	$\pi + d_{yz} \rightarrow \pi^*$

Table 3.1. The ten lowest, vertical singlet electronic transitions for Im-[Co^{III}(corrin)]-OH⁺ and Im-[Co^{III}(corrin)]-CN⁺ model complexes based on TD-DFT/BP86/TZVPP.

	E(eV)	λ (nm)	f	Coeff.	Character	Exp. ^a nm (eV)
Im-[Co ^{III} (corrin)]-OH ⁺						
S ₁	1.97	628.1	0.0011	96	117 $\rightarrow$ 118 H $\rightarrow$ L $n_{OH}/(d_{xz}-d_{yz}) \rightarrow \pi^*$	
S ₂	2.34	530.5	0.0001	90	117 $\rightarrow$ 119 H $\rightarrow$ L+1 $n_{OH}/(d_{xz}-d_{yz}) \rightarrow \sigma^*(d_z^2)$	
S ₃	2.55	485.9	0.0446	68	116 $\rightarrow$ 118 H-1 $\rightarrow$ L $\pi \rightarrow \pi^*$	
				24	116 $\rightarrow$ 119 H-1 $\rightarrow$ L+1 $\pi \rightarrow \sigma^*(d_z^2)$	
						$(d_{xz}+d_{yz})/n_{OH} +$
S ₄	2.56	484.7	0.0229	75	115 $\rightarrow$ 118 H-2 $\rightarrow$ L $\pi \rightarrow \pi^*$	
						$(d_{xz}+d_{yz})/n_{OH} +$
S ₅	2.61	475.1	0.0126	41	115 $\rightarrow$ 119 H-2 $\rightarrow$ L+1 $\pi \rightarrow \sigma^*(d_z^2)$	
				36	116 $\rightarrow$ 119 H-1 $\rightarrow$ L+1 $\pi \rightarrow \sigma^*(d_z^2)$	
						$(d_{xz}+d_{yz})/n_{OH} +$
S ₆	2.62	473.3	0.0131	46	115 $\rightarrow$ 119 H-2 $\rightarrow$ L+1 $\pi \rightarrow \sigma^*(d_z^2)$	
				33	116 $\rightarrow$ 119 H-1 $\rightarrow$ L+1 $\pi \rightarrow \sigma^*(d_z^2)$	
						$p_{OH}/(d_{xz}-d_{yz}) \rightarrow$
S ₇	2.71	456.9	0.0070	67	117 $\rightarrow$ 120 H $\rightarrow$ L+2 $d_{xy}-n$	
				13	114 $\rightarrow$ 118 H-3 $\rightarrow$ L $d_x^2-y^2 \rightarrow \pi^*$	
S ₈	2.84	436.4	0.0026	40	114 $\rightarrow$ 118 H-3 $\rightarrow$ L $d_x^2-y^2 \rightarrow \pi^*$	
				40	116 $\rightarrow$ 120 H-1 $\rightarrow$ L+2 $\pi \rightarrow d_{xy}-n$	
				11	117 $\rightarrow$ 121 H $\rightarrow$ L+3 $n_{OH}/(d_{xz}-d_{yz}) \rightarrow \pi^*$	
S ₉	2.86	433.1	0.0015	49	116 $\rightarrow$ 120 H-1 $\rightarrow$ L+2 $\pi \rightarrow d_{xy}-n$	
				36	114 $\rightarrow$ 118 H-3 $\rightarrow$ L $d_x^2-y^2 \rightarrow \pi^*$	
S ₁₀	2.90	427.6	0.0001	71	117 $\rightarrow$ 121 H $\rightarrow$ L+3 $n_{OH}/(d_{xz}-d_{yz}) \rightarrow \pi^*$	
Im-[Co ^{III} (corrin)]-CN ⁺						
S ₁	2.49	497.9	0.0471	87	119 $\rightarrow$ 120 H $\rightarrow$ L $\pi \rightarrow \pi^*$	550(2.25)
S ₂	2.59	478.6	0.0076	80	119 $\rightarrow$ 121 H $\rightarrow$ L+1 $\pi \rightarrow d_{xy}+n$	517(2.40)
S ₃	2.66	466.3	0.0168	47	119 $\rightarrow$ 122 H $\rightarrow$ L+2 $\pi \rightarrow \sigma^*(d_z^2) + n$	
				42	118 $\rightarrow$ 120 H-1 $\rightarrow$ L $\pi+d_{yz} \rightarrow \pi^*$	
S ₄	2.73	454.5	0.0183	50	119 $\rightarrow$ 122 H $\rightarrow$ L+2 $\pi \rightarrow \sigma^*(d_z^2) + n$	485(2.56)
				28	118 $\rightarrow$ 120 H-1 $\rightarrow$ L $\pi+d_{yz} \rightarrow \pi^*$	
S ₅	2.79	444.7	0.0036	75	118 $\rightarrow$ 121 H-1 $\rightarrow$ L+1 $\pi+d_{yz} \rightarrow d_{xy}+n$	
S ₆	2.87	431.5	0.0062	40	117 $\rightarrow$ 120 H-2 $\rightarrow$ L $d_{xz} \rightarrow \pi^*$	
				39	118 $\rightarrow$ 122 H-1 $\rightarrow$ L+2 $\pi+d_{yz} \rightarrow \sigma^*(d_z^2) + n$	
S ₇	2.91	426.6	0.0281	44	117 $\rightarrow$ 120 H-2 $\rightarrow$ L $d_{xz} \rightarrow \pi^*$	457(2.71)
						$\pi+d_{yz} \rightarrow \sigma^*(d_z^2) + n$
				40	118 $\rightarrow$ 122 H-1 $\rightarrow$ L+2 $\pi+d_{yz} \rightarrow \sigma^*(d_z^2) + n$	
S ₈	3.05	406.7	0.0000	96	116 $\rightarrow$ 120 H-3 $\rightarrow$ L $d_x^2-y^2 \rightarrow \pi^*$	
S ₉	3.10	399.5	0.0069	92	115 $\rightarrow$ 120 H-4 $\rightarrow$ L $\pi_{Im} \rightarrow \pi^*$	
S ₁₀	3.26	379.7	0.0010	61	117 $\rightarrow$ 121 H-2 $\rightarrow$ L+1 $d_{xz} \rightarrow d_{xy}+n$	
				25	117 $\rightarrow$ 122 H-2 $\rightarrow$ L+2 $d_{xz} \rightarrow \sigma^*(d_z^2) + n$	

Table 4.1. Ten lowest, vertical singlet electronic transitions and value of $S_1 \rightarrow S_0$ adiabatic transition for H_2O - $[Co^{III}(\text{corrin})]-Me^+$ model complex.¹⁵²

	E(eV)	$\lambda(\text{nm})$	f	%	character			Exp. λ (eV)^a
S ₁	2.35	526.6	0.0036	88	103 $\rightarrow$ 105	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$	501(2.47)
S ₂	2.40	516.1	0.0286	79	104 $\rightarrow$ 105	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$	
S ₃	2.57	482.4	0.0023	69	101 $\rightarrow$ 105	H-3 $\rightarrow$ L	$d_{x^2-y^2} \rightarrow \pi^*$	
				18	102 $\rightarrow$ 105	H-2 $\rightarrow$ L	$\pi+d_{xz} \rightarrow \pi^*$	461(2.69)
				12	104 $\rightarrow$ 106	H $\rightarrow$ L+1	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$	
S ₄	2.66	466.5	0.0041	55	104 $\rightarrow$ 106	H $\rightarrow$ L+1	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$	
				25	101 $\rightarrow$ 105	H-3 $\rightarrow$ L	$d_{x^2-y^2} \rightarrow \pi^*$	
				15	102 $\rightarrow$ 105	H-2 $\rightarrow$ L	$\pi+d_{xz} \rightarrow \pi^*$	
S ₅	2.83	438.9	0.0857	56	102 $\rightarrow$ 105	H-2 $\rightarrow$ L	$\pi+d_{xz} \rightarrow \pi^*$	
				23	104 $\rightarrow$ 106	H $\rightarrow$ L+1	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$	
S ₆	2.97	417.5	0.0061	45	103 $\rightarrow$ 106	H-1 $\rightarrow$ L+1	$d_{xz}+\pi \rightarrow \sigma^*(d_z^2)$	
				36	104 $\rightarrow$ 107	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow d_{xy}+n$	
				10	103 $\rightarrow$ 107	H-1 $\rightarrow$ L+2	$d_{xz}+\pi \rightarrow d_{xy}+n$	
S ₇	3.04	407.7	0.0266	43	104 $\rightarrow$ 108	H $\rightarrow$ L+3	$d_{yz}+\pi \rightarrow \pi^*+d_{xy}$	
				28	104 $\rightarrow$ 107	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow d_{xy}+n$	
				13	103 $\rightarrow$ 106	H-1 $\rightarrow$ L+1	$d_{xz}+\pi \rightarrow \sigma^*(d_z^2)$	
S ₈	3.13	396.3	0.0100	71	102 $\rightarrow$ 106	H-2 $\rightarrow$ L+1	$\pi+d_{xz} \rightarrow \sigma^*(d_z^2)$	
S ₉	3.18	390.1	0.0040	31	104 $\rightarrow$ 108	H $\rightarrow$ L+3	$d_{yz}+\pi \rightarrow \pi^*+d_{xy}$	
				19	101 $\rightarrow$ 106	H-3 $\rightarrow$ L+1	$d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$	
				13	103 $\rightarrow$ 106	H-1 $\rightarrow$ L+1	$d_{xz}+\pi \rightarrow \sigma^*(d_z^2)$	
				12	104 $\rightarrow$ 107	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow d_{xy}+n$	
S ₁₀	3.31	374.9	0.0007	43	100 $\rightarrow$ 105	H-4 $\rightarrow$ L	$\pi+d_{yz} \rightarrow \pi^*$	
				42	102 $\rightarrow$ 107	H-2 $\rightarrow$ L+2	$\pi+d_{xz} \rightarrow d_{xy}+n$	
S₁	1.87	661.9		49	103 $\rightarrow$ 105	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$ (MLCT)	
				48	103 $\rightarrow$ 105	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$	

^a C. Giannotti, Electronic Spectra of B12 and Related Systems, in *B12*, Volume 1: Chemistry, edited by D. Dolphin, John Wiley & Sons, New York 1982, Chap. 11, pp. 393–430.

Table 4.2. Ten lowest, vertical singlet electronic transitions and value of $S_1 \rightarrow S_0$ adiabatic transition for $[\text{Co}^{\text{III}}(\text{corrin})]\text{-Me}^+$ model complex.¹⁵²

	E(eV)	$\lambda(\text{nm})$	f	%	character		
S_1	2.28	544.2	0.0027	10	98 $\rightarrow$ 100	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$
				85	99 $\rightarrow$ 101	H $\rightarrow$ L+1	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$
S_2	2.34	530.5	0.0288	32	98 $\rightarrow$ 100	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$
				56	99 $\rightarrow$ 100	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$
S_3	2.39	517.8	0.0307	53	98 $\rightarrow$ 100	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$
				31	99 $\rightarrow$ 100	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$
S_4	2.58	481.2	0.0034	35	97 $\rightarrow$ 100	H-2 $\rightarrow$ L	$d_{x^2-y^2} \rightarrow \pi^*$
				60	98 $\rightarrow$ 101	H-1 $\rightarrow$ L+1	$d_{xz}+\pi \rightarrow \sigma^*(d_z^2)$
S_5	2.62	472.9	0.0013	58	97 $\rightarrow$ 100	H-2 $\rightarrow$ L	$d_{x^2-y^2} \rightarrow \pi^*$
				31	98 $\rightarrow$ 101	H-1 $\rightarrow$ L+1	$d_{xz}+\pi \rightarrow \sigma^*(d_z^2)$
S_6	2.96	419.3	0.0154	31	96 $\rightarrow$ 100	H-3 $\rightarrow$ L	$\pi \rightarrow \pi^*$
				50	99 $\rightarrow$ 102	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow \pi^*+d_{xy}+n$
S_7	3.03	409.1	0.0908	36	96 $\rightarrow$ 100	H-3 $\rightarrow$ L	$\pi \rightarrow \pi^*$
				32	96 $\rightarrow$ 101	H-3 $\rightarrow$ L+1	$\pi \rightarrow \sigma^*(d_z^2)$
				12	99 $\rightarrow$ 102	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow \pi^*+d_{xy}+n$
				31	96 $\rightarrow$ 101	H-3 $\rightarrow$ L+1	$\pi \rightarrow \sigma^*(d_z^2)$
S_8	3.06	405.6	0.0358	26	97 $\rightarrow$ 101	H-2 $\rightarrow$ L+1	$d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$
				10	99 $\rightarrow$ 102	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow \pi^*+d_{xy}+n$
				12	96 $\rightarrow$ 101	H-3 $\rightarrow$ L+1	$\pi \rightarrow \sigma^*(d_z^2)$
				36	97 $\rightarrow$ 101	H-2 $\rightarrow$ L+1	$d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$
S_9	3.06	405.1	0.0349	11	99 $\rightarrow$ 102	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow \pi^*+d_{xy}+n$
				14	99 $\rightarrow$ 103	H $\rightarrow$ L+3	$d_{yz}+\pi \rightarrow d_{xy}+n+\pi^*$
S_{10}	3.22	385.4	0.0236	20	97 $\rightarrow$ 101	H-2 $\rightarrow$ L+1	$d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$
				48	99 $\rightarrow$ 103	H $\rightarrow$ L+3	$d_{yz}+\pi \rightarrow d_{xy}+n+\pi^*$
S_1	1.60	775.4		98	99 $\rightarrow$ 100	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$ (LF)

Table 4.3. Ten lowest vertical singlet electronic transitions and the value of the $S_1 \rightarrow S_0$ adiabatic transition for the $H_2O-[Co^{III}(\text{corrin})]-\text{Ado}^+$ model complex based on TD-DFT calculations.

	E(eV)	$\lambda(\text{nm})$	f	%	character			Exp. λ (eV)^a
S_1	2.38	522.0	0.0053	84	164 $\rightarrow$ 166	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$	515 (2.41)
				10	165 $\rightarrow$ 166	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$	
S_2	2.39	518.3	0.0238	77	165 $\rightarrow$ 166	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$	465 (2.67)
				11	164 $\rightarrow$ 166	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$	
S_3	2.54	488.1	0.0006	60	165 $\rightarrow$ 167	H $\rightarrow$ L+1	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$	
				21	163 $\rightarrow$ 166	H-2 $\rightarrow$ L	$\pi \rightarrow \pi^*$	
				17	162 $\rightarrow$ 166	H-3 $\rightarrow$ L	$d_{x^2-y^2} \rightarrow \pi^*$	
S_4	2.62	473.0	0.0009	73	162 $\rightarrow$ 166	H-3 $\rightarrow$ L	$d_{x^2-y^2} \rightarrow \pi^*$	465 (2.67)
				21	165 $\rightarrow$ 167	H $\rightarrow$ L+1	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$	
S_5	2.66	465.8	0.0003	99	161 $\rightarrow$ 166	H-4 $\rightarrow$ L	$\pi_{\text{Ado}} \rightarrow \pi^*$	
S_6	2.78	446.2	0.0668	61	163 $\rightarrow$ 166	H-2 $\rightarrow$ L	$\pi \rightarrow \pi^*$	
S_7	2.86	433.9	0.0044	65	164 $\rightarrow$ 167	H-1 $\rightarrow$ L+1	$d_{xz}+\pi \rightarrow \sigma^*(d_z^2)$	
				21	165 $\rightarrow$ 168	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow (d_{xy}-n) + \pi^*$	465 (2.67)
S_8	3.00	413.9	0.0051	47	165 $\rightarrow$ 168	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow (d_{xy}-n) + \pi^*$	
				25	160 $\rightarrow$ 166	H-5 $\rightarrow$ L	$n_{\text{Ado}} \rightarrow \pi^*$	
				15	165 $\rightarrow$ 169	H $\rightarrow$ L+3	$d_{yz}+\pi \rightarrow (d_{xy}-n) - \pi^*$	
S_9	3.03	409.9	0.0165	42	163 $\rightarrow$ 167	H-2 $\rightarrow$ L+1	$\pi \rightarrow \sigma^*(d_{z2})$	465 (2.67)
				31	160 $\rightarrow$ 166	H-5 $\rightarrow$ L	$n_{\text{Ado}} \rightarrow \pi^*$	
S_{10}	3.04	407.6	0.0237	36	160 $\rightarrow$ 166	H-5 $\rightarrow$ L	$n_{\text{Ado}} \rightarrow \pi^*$	
				34	163 $\rightarrow$ 167	H-2 $\rightarrow$ L+1	$\pi \rightarrow \sigma^*(d_z^2)$	
S_1	1.80	661.9	0.0009	79	165 $\rightarrow$ 166	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$ (MLCT)	
				18	164 $\rightarrow$ 166	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$	

Table 4.4. Ten lowest, vertical singlet electronic transitions and the value of the $S_1 \rightarrow S_0$ adiabatic transition for the $[\text{Co}^{\text{III}}(\text{corrin})]\text{-Ado}^+$ model complex based on TD-DFT calculations.

	E(eV)	$\lambda(\text{nm})$	<i>f</i>	%	character		
S ₁	2.18	568.7	0.0042	90	160 $\rightarrow$ 162	H $\rightarrow$ L+1	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$
S ₂	2.34	529.1	0.0175	57	160 $\rightarrow$ 161	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$
				30	159 $\rightarrow$ 161	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$
S ₃	2.39	517.9	0.0156	63	159 $\rightarrow$ 161	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$
				23	160 $\rightarrow$ 161	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$
S ₄	2.47	501.9	0.0033	92	159 $\rightarrow$ 162	H-1 $\rightarrow$ L+1	$d_{xz}+\pi \rightarrow \sigma^*(d_z^2)$
S ₅	2.56	483.9	0.0000	100	157 $\rightarrow$ 161	H-3 $\rightarrow$ L	$\pi_{\text{Ado}} \rightarrow \pi^*$
S ₆	2.62	473.7	0.0021	85	158 $\rightarrow$ 161	H-2 $\rightarrow$ L	$d_x^2-y^2 \rightarrow \pi^*$
S ₇	2.65	467.8	0.0002	100	157 $\rightarrow$ 162	H-3 $\rightarrow$ L+1	$\pi_{\text{Ado}} \rightarrow \sigma^*(d_z^2)$
S ₈	2.93	423.9	0.0028	43	160 $\rightarrow$ 163	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow (d_{xy}-n) + \pi^*$
				28	158 $\rightarrow$ 162	H-2 $\rightarrow$ L+1	$d_x^2-y^2 \rightarrow \sigma^*(d_z^2)$
				12	156 $\rightarrow$ 161	H-4 $\rightarrow$ L	$\pi+d_{x^2-y^2} \rightarrow \pi^*$
				26	155 $\rightarrow$ 161	H-5 $\rightarrow$ L	$n_{\text{Ado}}+d_{z^2} \rightarrow \pi^*$
S ₉	2.95	420.5	0.0081	22	158 $\rightarrow$ 162	H-2 $\rightarrow$ L+1	$d_x^2-y^2 \rightarrow \sigma^*(d_z^2)$
				22	160 $\rightarrow$ 163	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow (d_{xy}-n) + \pi^*$
				12	156 $\rightarrow$ 162	H-4 $\rightarrow$ L+1	$\pi+ d_x^2-y^2 \rightarrow \sigma^*(d_z^2)$
				11	160 $\rightarrow$ 164	H $\rightarrow$ L+3	$d_{yz}+\pi \rightarrow (d_{xy}-n) - \pi^*$
S ₁₀	2.97	417.2	0.0050	66	155 $\rightarrow$ 161	H-5 $\rightarrow$ L	$n_{\text{Ado}}+d_{z^2} \rightarrow \pi^*$
				15	158 $\rightarrow$ 162	H-2 $\rightarrow$ L+1	$d_x^2-y^2 \rightarrow \sigma^*(d_z^2)$
S₁	1.43	864.5	0.0034	99	160 $\rightarrow$ 161	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$ (LF)

Table 4.5. Fifteen lowest vertical triplet electronic transitions for the $[\text{Co}^{\text{III}}(\text{corrin})]\text{-Ado}^+$ model complex based on TD-DFT calculations.

	E(eV)	$\lambda(\text{nm})$	%	character		
T ₁	1.69	734.7	87	160 $\rightarrow$ 161	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$
T ₂	1.72	720.1	85	160 $\rightarrow$ 162	H $\rightarrow$ L+1	$d_{yz}+\pi \rightarrow \sigma^*(d_z^2)$
			11	160 $\rightarrow$ 161	H $\rightarrow$ L	$d_{yz}+\pi \rightarrow \pi^*$
T ₃	1.92	646.3	92	159 $\rightarrow$ 162	H-1 $\rightarrow$ L+1	$d_{xz}+\pi \rightarrow \sigma^*(d_z^2)$
T ₄	2.15	577.9	90	159 $\rightarrow$ 161	H-1 $\rightarrow$ L	$d_{xz}+\pi \rightarrow \pi^*$
T ₅	2.24	553.4	85	158 $\rightarrow$ 162	H-2 $\rightarrow$ L+1	$d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$
T ₆	2.36	525.1	49	160 $\rightarrow$ 163	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow (d_{xy}-n) + \pi^*$
			44	160 $\rightarrow$ 164	H $\rightarrow$ L+3	$d_{yz}+\pi \rightarrow (d_{xy}-n) - \pi^*$
T ₇	2.43	510.8	78	158 $\rightarrow$ 161	H-2 $\rightarrow$ L	$d_{x^2-y^2} \rightarrow \pi^*$
			14	156 $\rightarrow$ 161	H-4 $\rightarrow$ L	$\pi + d_{x^2-y^2} \rightarrow \pi^*$
T ₈	2.49	497.0	48	156 $\rightarrow$ 162	H-4 $\rightarrow$ L+1	$\pi + d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$
			12	156 $\rightarrow$ 161	H-4 $\rightarrow$ L	$\pi + d_{x^2-y^2} \rightarrow \pi^*$
T ₉	2.53	490.2	12	155 $\rightarrow$ 162	H-5 $\rightarrow$ L+1	$n_{\text{Ado}} + d_z^2 \rightarrow \sigma^*(d_z^2)$
			37	159 $\rightarrow$ 163	H-1 $\rightarrow$ L+2	$d_{xz}+\pi \rightarrow (d_{xy}-n) + \pi^*$
			35	159 $\rightarrow$ 164	H-1 $\rightarrow$ L+3	$d_{xz}+\pi \rightarrow (d_{xy}-n) - \pi^*$
			14	156 $\rightarrow$ 161	H-4 $\rightarrow$ L	$\pi + d_{x^2-y^2} \rightarrow \pi^*$
T ₁₀	2.56	484.0	100	157 $\rightarrow$ 161	H-3 $\rightarrow$ L	$\pi_{\text{Ado}} \rightarrow \pi^*$
T ₁₁	2.58	480.6	52	156 $\rightarrow$ 161	H-4 $\rightarrow$ L	$\pi + d_{x^2-y^2} \rightarrow \pi^*$
			14	159 $\rightarrow$ 163	H-1 $\rightarrow$ L+2	$d_{xz}+\pi \rightarrow (d_{xy}-n) + \pi^*$
			13	158 $\rightarrow$ 161	H-2 $\rightarrow$ L	$d_{x^2-y^2} \rightarrow \pi^*$
T ₁₂	2.65	468.0	97	157 $\rightarrow$ 162	H-3 $\rightarrow$ L+1	$\pi_{\text{Ado}} \rightarrow \sigma^*(d_z^2)$
T ₁₃	2.66	466.0	44	158 $\rightarrow$ 164	H-2 $\rightarrow$ L+3	$d_{x^2-y^2} \rightarrow (d_{xy}-n) - \pi^*$
			38	158 $\rightarrow$ 163	H-2 $\rightarrow$ L+2	$d_{x^2-y^2} \rightarrow (d_{xy}-n) + \pi^*$
T ₁₄	2.73	455.0	47	160 $\rightarrow$ 164	H $\rightarrow$ L+3	$d_{yz}+\pi \rightarrow (d_{xy}-n) - \pi^*$
			43	160 $\rightarrow$ 163	H $\rightarrow$ L+2	$d_{yz}+\pi \rightarrow (d_{xy}-n) + \pi^*$
T ₁₅	2.79	445.1	30	155 $\rightarrow$ 162	H-5 $\rightarrow$ L+1	$n_{\text{Ado}} + d_{z^2} \rightarrow \sigma^*(d_z^2)$
			21	156 $\rightarrow$ 162	H-4 $\rightarrow$ L+1	$\pi + d_{x^2-y^2} \rightarrow \sigma^*(d_z^2)$
			14	159 $\rightarrow$ 164	H-1 $\rightarrow$ L+3	$d_{xz}+\pi \rightarrow (d_{xy}-n) - \pi^*$

Table 4.6. Ten lowest, vertical triplet electronic transitions for [Co^{III}(corrin)]-Me⁺ model complex based on the TD-DFT calculations.¹⁵²

	E(eV)	λ (nm)	%	character		
T ₁	1.70	730.4	70	99 → 100	H → L	d _{yz} + π → π^*
T ₂	1.83	678.2	69	99 → 101	H → L+1	d _{yz} + π → $\sigma^*(d_z^2)$
T ₃	2.04	608.8	68	98 → 101	H-1 → L+1	d _{xz} + π → $\sigma^*(d_z^2)$
T ₄	2.15	577.7	68	98 → 100	H-1 → L	d _{xz} + π → π^*
T ₅	2.36	526.1	65	97 → 101	H-2 → L+1	d _{x²-y²} → $\sigma^*(d_z^2)$
T ₆	2.41	514.0	46	99 → 102	H → L+2	d _{yz} + π → π^* +d _{xy} +n
			49	99 → 103	H → L+3	d _{yz} + π → d _{xy} +n+ π^*
T ₇	2.45	506.6	43	96 → 100	H-3 → L	π → π^*
			53	97 → 100	H-2 → L	d _{x²-y²} → π^*
T ₈	2.51	494.5	53	96 → 100	H-3 → L	π → π^*
			-40	97 → 100	H-2 → L	d _{x²-y²} → π^*
T ₉	2.60	477.6	46	98 → 102	H-1 → L+2	d _{xz} + π → π^* +d _{xy} +n
			47	98 → 103	H-1 → L+3	d _{xz} + π → d _{xy} +n+ π^*
T ₁₀	2.63	471.5	64	96 → 101	H-3 → L+1	π → $\sigma^*(d_z^2)$

Table 4.7. Selected geometrical parameters and NBO charges for H₂O-[Co^{III}(corrin)]-Me⁺ model complex and other species involved in the photoreaction process.¹⁵²

H ₂ O- [Co ^{III} (corrin)]-Me ⁺	Geometry		NBO charges				
	I (S _{0min})	I (S _{1min})		q _{S0}	q _{S0} ^{a)}	q _{S1}	Δq ^{b)}
	Bond distances [Å]			(S _{0min})	(S _{1min})		
Co-C	1.969	1.962	Co	0.765	0.778	0.967	0.189
C-O	2.359	2.217	C	-0.658	-0.673	-0.637	0.036
Co-N ₂₁	1.876	1.879	O	-0.925	-0.913	-0.895	0.018
Co-N ₂₂	1.929	1.966	Me	-0.067	-0.083	-0.001	0.082
Co-N ₂₃	1.928	1.976	H ₂ O	0.075	0.096	0.125	0.029
Co-N ₂₄	1.871	1.881	Corr	0.227	0.208	-0.092	-0.300
	Bond angles [deg]						
C _{CN} -Co-O	175.6	164.5					
N ₂₁ -Co-N ₂₃	171.2	170.8					
N ₂₂ -Co-N ₂₄	173.4	172.7					
[Co ^{III} (corrin)]-Me ⁺	IIIB (S _{0min})	IIIB (S _{1min})		q _{S0}	q _{S0}	q _{S1}	Δq ^{a)}
	Bond distances [Å]			(S _{0min})	(S _{1min})		
Co-C	1.968	2.229	Co	0.738	0.777	0.876	0.099
Co-N ₂₁	1.866	1.857	C	-0.620	-0.617	-0.823	-0.206
Co-N ₂₂	1.920	1.927	Me	-0.016	-0.013	-0.238	-0.225
Co-N ₂₃	1.919	1.939	Corr	0.278	0.235	0.362	0.126
Co-N ₂₄	1.862	1.856					
	Bond angles [deg]						
N ₂₁ -Co-N ₂₃	167.4	160.4					
N ₂₂ -Co-N ₂₄	172.7	173.5					
[Co ^{II} (corrin)] ⁺	VIB (S _{0min})	VIB (S _{1min})		q _{S0}	q _{S0}	q _{S1}	Δq ^{a)}
	Bond distances [Å]			(S _{0min})	(S _{1min})		
Co-N ₂₁	1.875	1.842	Co	0.989	0.983	0.841	-0.142
Co-N ₂₂	1.926	1.915	Corr	0.011	0.017	0.159	0.142
Co-N ₂₃	1.926	1.915					
Co-N ₂₄	1.875	1.843					
	Bond angles [deg]						
N ₂₁ -Co-N ₂₃	172.0	170.2					
N ₂₂ -Co-N ₂₄	172.0	170.2					

^{a)} q_{S0} – charges in ground state in geometry of excited state

^{b)} Δq – difference between charge in excited state and ground state in geometry excited state

Table 4.8. Selected geometrical parameters and NBO charges for the H₂O-[Co^{III}(corrin)]-Ado⁺ model complex and other species involved in the photoreaction process.

H ₂ O- [Co ^{III} (corrin)]-Ado ⁺	Geometry		NBO charges				
	I (S _{0min})	I (S _{1min})		q _{S0}	q _{S0} ^{a)}	q _{S1}	Δq ^{b)}
	Bond distances [Å]			(S _{0min})	(S _{1min})		
Co-C	1.994	1.995	Co	0.779	0.786	0.963	0.177
C-O	2.435	2.219	C	-0.420	-0.447	-0.406	0.041
Co-N ₂₁	1.875	1.885	O	-0.949	-0.915	-0.880	0.035
Co-N ₂₂	1.929	1.968	Ado	-0.050	-0.069	0.045	0.114
Co-N ₂₃	1.923	1.972	H ₂ O	0.050	0.093	0.141	0.048
Co-N ₂₄	1.872	1.885	Corr	0.222	0.190	-0.149	-0.339
	Bond angles [deg]						
C-Co-O	178.1	166.4					
N ₂₁ -Co-N ₂₃	169.5	169.6					
N ₂₂ -Co-N ₂₄	172.9	172.3					
[Co ^{III} (corrin)]-Ado ⁺	IIIB	IIIB		q _{S0}	q _{S0}	q _{S1}	Δq ^{a)}
	(S _{0min})	(S _{1min})					
	Bond distances [Å]			(S _{0min})	(S _{1min})		
Co-C	1.996	2.335	Co	0.742	0.781	0.857	0.076
Co-N ₂₁	1.868	1.852	C	-0.393	-0.371	-0.542	-0.171
Co-N ₂₂	1.921	1.929	Ado	-0.006	0.025	-0.206	-0.231
Co-N ₂₃	1.917	1.925	Corr	0.264	0.195	0.349	0.154
Co-N ₂₄	1.864	1.858					
	Bond angles [deg]						
N ₂₁ -Co-N ₂₃	165.4	162.2					
N ₂₂ -Co-N ₂₄	171.8	173.4					
[Co ^{II} (corrin)] ⁺	VIB	VIB		q _{S0}	q _{S0}	q _{S1}	Δq ^{a)}
	(S _{0min})	(S _{1min})					
	Bond distances [Å]			(S _{0min})	(S _{1min})		
Co-N ₂₁	1.875	1.842	Co	0.989	0.983	0.841	-0.142
Co-N ₂₂	1.926	1.915	Corr	0.011	0.017	0.159	0.142
Co-N ₂₃	1.926	1.915					
Co-N ₂₄	1.875	1.843					
	Bond angles [deg]						
N ₂₁ -Co-N ₂₃	172.0	170.2					
N ₂₂ -Co-N ₂₄	172.0	170.2					

^{a)} q_{S0} – charges in ground state in geometry of excited state

^{b)} Δq – difference between charge in excited state and ground state in geometry excited state

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CURRICULUM VITA

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EDUCATION

Ph.D., Computational Chemistry. University of Louisville, 2013- 2018

Dissertation: “Computational Modelling of Electronically Excited States in Cobalamin-Dependent Reactions” (Prof. Pawel M. Kozlowski)

Research, University of Louisville School of Medicine, 2016-17

Computational design of field-sensitive Gd contrast agents. Outcome: 10^4 increase in temporal resolution, and 10-100-fold improvement in spatial resolution. (Prof. Dr. Robert Bert)

M.Sc., Chemistry. Western Kentucky University, 2010-2013

Thesis: “Synthesis and Computational Studies of a New Class of Lanthanide Niobate Cluster:

$[\text{Ln}_4(\text{H}_2\text{O})_8(\text{SO}_4)_5(\text{NbO}_3)_2]\cdot 3\text{H}_2\text{O}$; Ln=Dy, Tb ” (Prof. Jeremy Maddox, and Prof. Bangbo Yan). (first di-niobate/ lanthanide POM)

B.Sc., Chemistry & Mathematics. Western Kentucky University, 2010 (Research with Prof. Tingying Helen Zeng (MIT) in photovoltaic nanocomposites, and Prof. Y.-S. Shon (UCLB) in dendritic polymer nanocomposites)

RESEARCH HIGHLIGHTS, UNIVERSITY OF LOUISVILLE, 2013-2017

- Photochemistry of cobalamin cofactors; theoretical studies published in high impact journals including an invitation to *Coordination Chemistry Reviews*.
- First example of relativistic effects in an enzymatic reaction. Mercury methylation by HgcA proceeds concerted and replacement of the axial base with Cysteine lowers the transition state energy
- First example of a nitrogen hydride via DFT. Ligand-centered catalytic evolution of H_2 via dimeric proton-coupled electron transfer.
- Computational design of field-sensitive Gd contrast agents with significant improvement in activity.
- Photolysis of AdoCbl in the photo regulated gene expression of the CarH photoreceptor via TD-DFT/MM.

TECHNICAL

Programming Languages: Python, MPI, Mathematica, Fortran

Technical Expertise: Quantum chemical calculations, Multiscale Protein/Ligand Modelling (QM/MM), Born-Oppenheimer Molecular Dynamics, Enhanced Sampling, Time-dependent Density Functional Theory, Reaction Mechanism Elucidation, Relativistic Effects, Multireference Self-Consistent Field Calculations, Parallel/HPC Programming

Computational Chemistry Software: Gaussian, NWChem, ADF, GAMESS, Dalton, Molcas, Turbomole, CP2K, Amber, Schrödinger

Pipelining Toolkits: Knime, ChemAxon, RDKit

TEACHING

UNIVERSITY OF LOUISVILLE, Louisville, KY, 2011-2017

Teaching Assistant, Advanced Physical Chemistry, Recitations. 2014-2017

Teaching Assistant, 2013-2017

- Introduction to General Chemistry I, II, Introduction to Chemical Analysis, I, II, Introduction to Chemical Analysis, I, II (Honors), Elements of Physical Chemistry (for chemistry majors)
- Undergraduate Research
- **M.Sc. Instructor**, 2011-2013
- Introduction to Chemical Analysis I, II

FELLOWSHIPS | HONORS | AWARDS

- Doctoral Dissertation and Completion Award, Spring 2018
- Travel Award for Molecular Response Properties Summer School, Virginia Tech, 2017
- Graduate Assistant Teaching Award, 2017
- Student Athlete Mentor Award, 2014
- Summer Research fellowship (B.Sc.), Oak Ridge National Lab with Tingying Helen Zeng, Project Title: Green synthesis of functionalized core-shell TiO₂-Au hybrid photovoltaic nanoparticles
- Perkin-Elmer Award in Chemistry (B.Sc.), Monolayer-Protected Dendritic Au Nanoparticles and Nanocomposites. Kentucky Academy of Sciences

WORKSHOPS

- **Molecular Response Properties** Summer School, Virginia Tech, Blacksburg Va. 2017. Prof. Patrick Norman (KTH Royal Institute of Technology), Prof. Trond Saue (Université, Toulouse), Prof. Daniel Crawford (Virginia Tech), Prof. Kenneth Ruud (UiT Norway)
- **Mathematica Parallel Computing** online symposium, 2015

PRESENTATIONS (M.SC, B.SC)

- Prediction of Photoinduced Electron Transfer in Lanthanide and D-block Hybrid Systems. Kentucky Academy of Sciences. Richmond, Ky, Oct. 2012 (oral).
- Optically Active Rare-Earth Polyoxometalate Systems. WKU Graduate Research Conference, Bowling Green, Ky, Mar. 2012 (oral).
- Synthesis and structures of novel 3D Metal Organic Framework Materials. 17th Annual Ky EPSCoR Conference, Lexington, Ky, Feb. 2012 (poster).
- A Novel Method for the Superimposition of Protein Structures through Weighted RMSD. UT-ORNL-KBRIN Bioinformatics Summit, Paris Landing State Park, Tn., 2007 (poster).
- Chemical and Heating Treatments of Stable Ionic Monolayer-Protected Gold Clusters. PITTCO, Orlando, FL, 2006 (**poster**).
- Green Synthesis of TiO₂-Au Hybrid Photovoltaic Nanoparticles. Sigma Xi Conference, WKU, Bowling Green, Ky., March 2005 (oral).

PUBLICATIONS

2 Manuscripts in Preparation; 16 Articles Published, 130 Citations

- Garabato B.D.; Toda, M.J.; Lodowski, P.; Kozłowski, P.M. Photolytic dissociation of biologically active forms of Vitamin B₁₂. 2018. *Coordination Chemistry Reviews*. ([invited article](#))

- Garabato B.D.; Toda, M.J.; Lodowski, P.; Mamun, A.A.; Kozłowski, P.M. Photolysis and long-range charge transfer in the activation of the CarH transcription-regulation photoreceptor. 2018, target journal: *Angewandte Chemie*
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- 14. Demissie, T. B.; Garabato, B. D.; Ruud, K.; Kozłowski, P. M., Mercury Methylation by Cobalt Corrinoids: Relativistic Effects Dictate the Reaction Mechanism. *Angewandte Chemie* 2016, 1-5. (first example of relativity in an enzymatic reaction. *Angewandte Hot Paper, Highlights: C&EN, ChemViews*)
- 13. Haddad, A. Z.; Garabato, B. D.; Kozłowski, P. M.; Buchanan, R. M.; Grapperhaus, C. A., Beyond Metal-Hydrides: Non-Transition-Metal and Metal-Free Ligand-Centered Electrocatalytic Hydrogen Evolution and Hydrogen Oxidation. *Journal of the American Chemical Society* 2016, 138 (25), 7844-7847. (first nitrogen hydride reported via DFT; catalytic H₂ by dimeric PCET)
- 12. Garabato, B. D.; Kumar, N.; Lodowski, P.; Jaworska, M.; Kozłowski, P. M., Electronically excited states of cob(II)alamin: insights from CASSCF/XMCQDPT2 and TD-DFT calculations. *Physical Chemistry Chemical Physics* 2016, 18 (6), 4513-4526.
- 11. Garabato, B. D.; Lodowski, P.; Jaworska, M.; Kozłowski, P. M., Mechanism of Co-C photodissociation in adenosylcobalamin. *Physical Chemistry Chemical Physics* 2016, 18 (28), 19070-19082.
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- 9. Lebedzińska, A.; Marszał, M. L.; Grembecka, M.; Czaja, J.; Szefer, P.; Kuta, J.; Garabato, B.D.; Kozłowski, P. M. Detection of B₆ Vitamers in Grain Products: Experimental and Computational Studies. *Food Analytical Methods*, 2017.
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