Vibrational Properties of Quinones in Photosynthetic Reaction Centers

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ABSTRACT

Fourier transform infrared difference spectroscopy (FTIR DS) is widely used to study the structural details of electron transfer cofactors in photosynthetic protein complexes. In photosynthetic proteins quinones play an important role, functioning as a cofactor in light-driven electron transfer.

In photosystem I (PS I) phylloquinone (PhQ) functions as an intermediary in electron transfer. To investigate the properties of PhQ that occupies the, so called, A1 binding site in PS I, time-resolved step-scan FTIR DS, with 5µs time resolution at 77K has been used. By replacing PhQ in the A1 binding site with specifically isotope labeled version, information on the vibrational frequencies associated specifically with the quinone in the binding site were obtained,
which could be compared to the vibrational properties of quinone in solution or quinones in other protein binding sites. To further aid in assessing the origin of bands in the spectra, quantum mechanics /molecular mechanics (QM/MM) ONIOM type calculations were undertaken. ONIOM is an acronym for Our own N-layered Integrated molecular Orbital and molecular Mechanics. We find that the phytyl tail of PhQ does not play an important role in the orientation of PhQ in the A1 binding site. We also find that PhQ, in both neutral and reduced states, is strongly hydrogen bonded.

To test and verify the applicability of our QM/MM approach, ONIOM calculations were also undertaken for ubiquinone and a variety of other quinones incorporated into the, so called, QA binding site in purple bacteria photosynthetic reaction centers. The calculated and experimental spectra agree well, demonstrating the utility and applicability of our ONIOM approach. Hydrogen bonding to the carbonyl groups of quinones in the QA binding site was shown to be relatively weak, and it was found that hydrogen bonding to neutral ubiquinone in purple bacterial reaction centers can be considered in purely electrostatic terms, contrary to the widely held belief that the hydrogen bonding amino acids should be treated quantum mechanically.

INDEX WORDS: Photosynthesis, Quinone, Time-resolved step-scan Fourier transform infrared (TRSS FTIR) spectroscopy, Density functional theory (DFT), and Quantum mechanics/Molecular mechanics (QM/MM)
VIBRATIONAL PROPERTIES OF QUINONES IN PHOTOSYNTHETIC REACTION CENTERS

by

NAN ZHAO

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in the College of Arts and Sciences
Georgia State University 2014
VIBRATIONAL PROPERTIES OF QUINONES IN PHOTOSYNTHETIC REACTION CENTERS

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Office of Graduate Studies
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Georgia State University
August 2014
DEDICATION

Dedicated to my loving parents, Guodong Zhao and Xiaoyun Yin
ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to those who have contributed to this dissertation and supported me during this amazing journey.

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<tr>
<td>2MNQ</td>
<td>2-methyl-1,4-napthoquinone</td>
</tr>
<tr>
<td>Ala</td>
<td>Alanine</td>
</tr>
<tr>
<td>Amber</td>
<td>Assisted model building with energy refinement</td>
</tr>
<tr>
<td>Arg</td>
<td>Arginine</td>
</tr>
<tr>
<td>ATP</td>
<td>Adenosine triphosphate</td>
</tr>
<tr>
<td>B3LYP</td>
<td>Becke, three-parameter, Lee-Yang-Parr exchange-correlation functional</td>
</tr>
<tr>
<td>Bchl</td>
<td>Bacteriochlorophyll</td>
</tr>
<tr>
<td>Bpheo</td>
<td>Bacteriopheophytin</td>
</tr>
<tr>
<td>Chl</td>
<td>Chlorophyll</td>
</tr>
<tr>
<td>DFT</td>
<td>Density functional theory</td>
</tr>
<tr>
<td>DMF</td>
<td>Dimethylformamide</td>
</tr>
<tr>
<td>DMNQ</td>
<td>2,3-dimethyl-1,4-napthoquinone</td>
</tr>
<tr>
<td>DDS</td>
<td>Double difference spectrum</td>
</tr>
<tr>
<td>DQ</td>
<td>Duroquinone, 2,3,5,6-tetramethyl-1,4-benzoquinone</td>
</tr>
<tr>
<td>DS</td>
<td>Difference spectrum</td>
</tr>
<tr>
<td>DTGS</td>
<td>Deuterated triglycine sulfate</td>
</tr>
<tr>
<td>EE</td>
<td>Electronic embedding</td>
</tr>
<tr>
<td>ENDOR</td>
<td>Electron nuclear double resonance</td>
</tr>
<tr>
<td>EPR</td>
<td>Electron paramagnetic resonance</td>
</tr>
<tr>
<td>ESEEM</td>
<td>Electron spin echo envelope modulation</td>
</tr>
<tr>
<td>FTIR</td>
<td>Fourier transform infrared</td>
</tr>
<tr>
<td>His</td>
<td>Histidine</td>
</tr>
<tr>
<td>Ile</td>
<td>Isoleucine</td>
</tr>
<tr>
<td>Glu</td>
<td>Glutamic acid</td>
</tr>
<tr>
<td>Leu</td>
<td>Leucine</td>
</tr>
<tr>
<td>MCT</td>
<td>Mercury cadmium telluride</td>
</tr>
<tr>
<td>ME</td>
<td>Mechanical embedding</td>
</tr>
<tr>
<td>Met</td>
<td>Methionine</td>
</tr>
<tr>
<td>MM</td>
<td>Molecular mechanics</td>
</tr>
<tr>
<td>MPA</td>
<td>Mulliken population analysis</td>
</tr>
<tr>
<td>MQO</td>
<td>2,3-dimethoxy-5,6-dimethyl-1,4-benzoquinone</td>
</tr>
<tr>
<td>NADP</td>
<td>Nicotinamide adenine dinucleotide phosphate</td>
</tr>
<tr>
<td>NHE</td>
<td>Normal hydrogen electrode</td>
</tr>
<tr>
<td>NMR</td>
<td>Nuclear magnetic resonance</td>
</tr>
<tr>
<td>NPA</td>
<td>Natural population analysis</td>
</tr>
<tr>
<td>ONIOM</td>
<td>Our own N-layered Integrated molecular Orbital and molecular Mechanics</td>
</tr>
<tr>
<td>P*</td>
<td>Excited bacteriochlorophyll dimer</td>
</tr>
<tr>
<td>P700</td>
<td>Chlorophyll dimer</td>
</tr>
<tr>
<td>P700*</td>
<td>Excited chlorophyll dimer</td>
</tr>
<tr>
<td>PBRC</td>
<td>Purple bacterial reaction center</td>
</tr>
<tr>
<td>PCM</td>
<td>Polarizable continuum model</td>
</tr>
<tr>
<td>PDB</td>
<td>Protein data bank</td>
</tr>
<tr>
<td>PED</td>
<td>Potential energy distribution</td>
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<td>Phe</td>
<td>Phenylalanine</td>
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</table>
PhQ- Phylloquinone
PQ9- Plastoquinone-9
PS I- Photosystem I
PS II- Photosystem II
QA- A side quinone
QB- B side quinone
QM- Quantum mechanics
Rb. sphaeroides- Rhodobacter sphaeroides
RC- reaction center
Rp. viridis- Rhodopseudomonas viridis
S6803- Synechocystis sp. PCC 6803
Ser- Serine
THF- Tetrahydrofuran
Trp- Tryptophan
UFF- Universal force field
UQ- Ubiquinone
VK- Vitamin K
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obtained for PS I particles with PhQ incorporated is subtracted from the A_{1^-}/A_1 FTIR DS obtained for PS I particles with 2MNQ incorporated. The noise level is also shown in (C) (error bars), and is obtained by taking the square root of spectrum 6 in (B) squared plus spectrum 6 in (A) squared. The vertical bar in (C) represents an optical density (OD) difference of \~0.1x10^{-3}.

Figure 2.8 Comparison of the (2MNQ-PhQ) FTIR DDS calculated from two approaches. (A) The direct subtraction of P700^{+}A_{1^-}/P700A_1 spectra of menB PS I particles with 2MNQ or PhQ incorporated, and (B) the subtraction of A_{1^-}/A_1 FTIR DS for menB PS I particles with 2MNQ or PhQ incorporated.

Figure 2.9 Calculated and experimental DS of PhQ^- and 2MNQ^- (A) Experimental FTIR DDS obtained by subtracting A_{1^-}/A_1 spectrum of 2MNQ from that of PhQ (B) Calculated DS of PhQ^- and 2MNQ^- in the gas phase by using DFT methods (Model 1); (C) in the presence of a truncated Leu residue by using DFT methods (Model 2); and (D) by using ONIOM method (Model 3). Frequencies in B, C and D were scaled by 0.973/0.973/0.96, respectively.

Figure 2.10 Calculated and experimental DS of PhQ and 2MNQ (A) Experimental FTIR DDS obtained by subtracting A_{1^-}/A_1 spectrum of 2MNQ from that of PhQ (B) Calculated DS of PhQ and 2MNQ in the gas phase by using DFT methods (Model 1); (C) in the presence of a truncated Leu residue by using DFT methods (Model 2); and (D) by using ONIOM method (Model 3). Frequencies in B, C and D were scaled by 0.965/0.965/0.952, respectively.

Figure 2.11 Kinetics of absorption changes at 1754, 1748, 1495 and 1415 cm^{-1} obtained following 532 nm laser flash excitation of menB PS I particles with PhQ incorporated into the A_1 binding site at 77K. Data were collected in 5 \mu s increments. The four kinetics were fitted.
simultaneously to a single-exponential function plus a constant. The fitted functions shown (red) are characterized by a time constant of 301 µs.

Figure 2.12 Kinetics of absorption changes at 1754, 1748, 1504 and 1427 cm\(^{-1}\) obtained following 532 nm laser flash excitation of menB PS I particles with 2MNQ incorporated into the A₁ binding site at 77K. Data were collected in 5 µ increments. The four kinetics were fitted simultaneously to a single-exponential function plus a constant. The fitted functions shown (red) are characterized by a time constant of 245 µs.

Figure 3.1 Structures and numbering scheme for DFT calculations of (A) PhQ in the gas phase (Model 1) and (B) PhQ in the presence of a truncated Leu residue (Model 2).

Figure 3.2 IR absorption spectra at 77K for unlabeled (A) and \(^{13}\)C labeled (B) trimeric PS I particles from menB mutants (solid) and S6803 (dotted).

Figure 3.3 TR P700\(^+\)A₁/P700A₁ FTIR DS collected at 77 K for fully \(^{13}\)C labeled PS I particles (A solid) and fully \(^{13}\)C labeled PS I particles from menB mutants with unlabeled PhQ (B solid) incorporated into the A₁ binding site. The spectra shown are the average of 4 (\(^{13}\)C labeled PhQ) and 2 (unlabeled PhQ) separated experiments. The standard deviation spectra associated with the TR experiments for \(^{13}\)C labeled PhQ (A) and unlabeled PhQ (B) are shown (dotted). These standard deviation spectra give a true measure of the experimental variability (noise level). (C) (\(^{13}\)C PhQ- \(^{12}\)C PhQ) TR FTIR DDS obtained by subtracting spectrum B (solid) from spectrum A (solid). That is the TR P700\(^+\)A₁/P700A₁ FTIR DS obtained for fully \(^{13}\)C labeled menB PS I particles with unlabeled PhQ incorporated is subtracted from the TR P700\(^+\)A₁⁻ /P700A₁ FTIR DS obtained for \(^{13}\)C labeled PS I particles. The noise level is also shown in (C) (error bars), and is obtained by taking the square root of spectrum in (B dotted) squared plus
spectrum in (A dotted) squared. The vertical bar in (C) represents an optical density (OD) difference of ~0.1x10^{-3}.

Figure 3.4 Experimental (A) [87] and calculated (^{18}\text{O}-^{16}\text{O}) isotope edited FTIR DDS for reduced PhQ. (B) DFT calculation for isolated reduced PhQ in the gas phase. (C) DFT calculation for PhQ in the presence of a Leu residue. (D) ONIOM calculations for reduced PhQ in the A\textsubscript{1} binding site. Calculated normal mode frequencies were scaled by 0.974, 0.974 and 0.96, respectively.

Figure 3.5 Experimental (A) and calculated (^{13}\text{C}-^{12}\text{C}) isotope edited FTIR DDS for reduced PhQ. (B) DFT calculation for isolated reduced PhQ in the gas phase. (C) DFT calculation for PhQ in the presence of a Leu residue. (D) ONIOM calculations for reduced PhQ in the A\textsubscript{1} binding site. Calculated normal mode frequencies were scaled by 0.974, 0.974 and 0.96, respectively.

Figure 3.6 Experimental (A) and calculated (^{18}\text{O}-^{16}\text{O}) isotope edited FTIR DDS for neutral PhQ. (B) DFT calculation for isolated neutral PhQ in the gas phase. (C) DFT calculation for PhQ in the presence of a Leu residue. (D) ONIOM calculations for neutral PhQ in the A\textsubscript{1} binding site. Calculated normal mode frequencies were scaled by 0.963, 0.963 and 0.953, respectively.

Figure 3.7 Experimental (A) and calculated (^{13}\text{C}-^{12}\text{C}) isotope edited FTIR DDS for neutral PhQ. (B) DFT calculation for isolated neutral PhQ in the gas phase. (C) DFT calculation for PhQ in the presence of a Leu residue. (D) ONIOM calculations for neutral PhQ in the A\textsubscript{1} binding site. Calculated normal mode frequencies were scaled by 0.963, 0.963 and 0.953, respectively.
Figure 4.1 Ball and bond structural model and numbering scheme of the heavy atoms comprising the QM layer in ONIOM calculations. The hydrogen atoms of the H bonding amino acids are also shown (atoms 23 and 49). Blue/red/grey/white/purple colored balls represent nitrogen/oxygen/carbon/hydrogen/iron atoms, respectively.

Figure 4.2 Experimental (red) and ONIOM calculated (black) Q\textsubscript{A}/Q\textsubscript{A} isotope edited DDS for neutral UQ. UQ has been specifically (A) \textsuperscript{13}C\textsubscript{1}, (B) \textsuperscript{13}C\textsubscript{4}, (C) \textsuperscript{13}C\textsubscript{4}\textsuperscript{18}O, (D) \textsuperscript{13}C, (E) \textsuperscript{13}C\textsuperscript{18}O and (F) \textsuperscript{18}O isotope labeled. For \textsuperscript{18}O labeling, only the carbonyl oxygen atoms are labeled. Experimental spectra are reprinted with permission from references [47] and [109]. In calculations 1-5 spectra have been scaled by 0.9718, 0.9634, 1.0842, 0.9638 and 0.9637, respectively.

Figure 4.3 Experimental (red) and ONIOM calculated (black) isotope edited DDS for neutral UQ. UQ has been specifically (A) \textsuperscript{13}C\textsubscript{4}, (B) \textsuperscript{18}O and (C) \textsuperscript{13}C\textsuperscript{18}O isotope labeled (only the carbonyl oxygen atoms are \textsuperscript{18}O labeled). Experimental spectra are reprinted with permission from [47] and [109].

Figure 5.1 Structure and numbering of ubiquinone (2,3-dimethoxy, 5-methyl, 6-prenyl benzoquinone) (UQ\textsubscript{n}), 2,3-dimethoxy, 5,6-methyl benzoquinone (MQ\textsubscript{0}), 2,3,5,6-methyl benzoquinone (duroquinone, DQ), 2,3-dimethyl, 1,4-naphthoquinone (DMNQ) and 2-methyl, 3-phytyl 1,4-naphthoquinone (VK). The numbering scheme employed here for the naphthoquinone structures is nonstandard, and was chosen to facilitate comparison between naphthoquinone and ubiquinone structures.

Figure 5.2 Ball and stick representation of the calculated structure of (A) DMNQ, (B) VK, (C) MQ\textsubscript{0} and (D) UQ\textsubscript{1} in the Q\textsubscript{A} binding site in PBRCs from \textit{Rb. sphaeroides}. Structure shown is after geometry optimization using ONIOM methods. Possible H-bonds are shown.
(dotted). Hydrogen atoms, except the ones involved in H-bonding, have been omitted. Distances quoted are in Å. (E, F) Overlap of structures obtained from ONIOM calculations for (E) DMNQ and DQ and (F) DMNQ and UQ\textsubscript{1}. Overlap is based on using the (fixed) backbone atoms of HisM219 and AlaM260. The amino acid side chains are virtually unaltered in the structures shown.

Figure 5.3 (A) ONIOM calculated $^{18}$O isotope edited DDS for neutral VK (dotted) and DMNQ (solid) in the Q\textsubscript{A} binding site. Experimental spectra for VK (B) and DMNQ (C) are also shown, and were taken from reference [157], with permission. (D) DFT calculated $^{18}$O isotope edited DDS for neutral VK (dotted) and DMNQ (solid) are also shown. ONIOM/gas phase calculated spectra were scaled by 0.9718/0.9608, respectively.

Figure 5.4 (A) ONIOM calculated $^{18}$O isotope edited DDS for neutral DQ in the Q\textsubscript{A} binding site. Experimental spectra are shown in (B), and were taken from reference [157] with permission. (C) DFT calculated $^{18}$O isotope edited DDS for neutral DQ. ONIOM and gas phase calculated spectra were scaled by 0.9718 and 0.9608, respectively.

Figure 5.5 (A) ONIOM calculated $^{18}$O isotope edited DDS for neutral MQ\textsubscript{0} (solid) and UQ\textsubscript{1} (dotted) in the Q\textsubscript{A} binding site. Experimental spectrum for (B) MQ\textsubscript{0} and (C) UQ\textsubscript{1} are also shown, and were taken from reference [157] with permission. (D) DFT calculated $^{18}$O isotope edited DDS for neutral MQ\textsubscript{0} (solid) and UQ\textsubscript{1} (dotted). ONIOM and gas phase calculated spectra were scaled by 0.9718 and 0.9608, respectively.

Figure 5.6 (A) ONIOM calculated $^{13}$C isotope edited DDS for neutral VK in the Q\textsubscript{A} binding site. Experimental spectrum is also shown (B), taken from [163] (with permission). (C) DFT calculated $^{13}$C isotope edited DDS for neutral VK in the gas phase. ONIOM and gas phase calculated spectra were scaled by 0.9718 and 0.9608, respectively.
1 INTRODUCTION

On average, approximately $1.8 \times 10^{17}$ W of solar radiation strikes the earth’s surface [1]. At this level, one can calculate that enough solar energy hits the earth in one hour to satisfy the energy needs of mankind for one year [2]. Solar energy clearly has the potential to satisfy mankind’s energy needs. Unfortunately, this clean and abundant energy resource is vastly underutilized, partly because of considerable challenges related to conversion, storage and transmission. The quantum efficiency of light conversion during the initial stages of photosynthesis is close to 100%. Such a high efficiency of transformation without destruction or harmful side effects is achieved by fine turning the properties of pigments bound in large protein complexes.

Ultrafast transient absorption spectroscopy, and electron paramagnetic resonance spectroscopy, as well as infrared (IR) spectroscopy have provided much insight into the interaction between cofactor and protein complexes. Fourier transfer infrared (FTIR) spectroscopy, in particular, in combination with isotope labeling, is an established tool to probe molecular bonding interactions of protein-bound pigment cofactors. However, the rich information obtained from experimental spectra is seldom straightforward. To address this problem, computational methods are undertaken to aid in assignment of bands in IR spectra, and their interpretation in terms of chemical or physical effects. A combination of experiment and computation is a potent approach for a deeper understanding of the spectral behavior associated with pigments in protein complexes and their biochemical reactions.
1.1 Photosynthesis

Photosynthesis is an important biological process in which solar energy is converted into chemical energy. The overall photosynthetic process can be divided into two distinct phases, light and dark reactions. Light reaction occurs in the thylakoid membrane and the organization of thylakoid membrane, is shown in Figure 1.1. For oxygenic photosynthesis organisms, such as plants, algae and cyanobacteria, oxygen is released as a byproduct in photosynthesis. The light reaction of oxygenic photosynthesis process occurs in four steps: (1) solar energy harvesting; (2) light-induced redox reactions; (3) oxidation of water; and (4) ATP synthesis and NADP\(^+\) reduction. The first step is light harvesting in which solar energy is efficiently collected and transferred to the reaction center (RC). The second step takes place in the RC. The harvested energy is used to drive charge separation which initiates a series of electron transfer reactions and proton translocations across the membrane. Oxidation of water in the third step is also called oxygen evolution. This reaction can be simply described as the split of water molecules into electrons, protons and oxygen molecules. Oxygen is released into the atmosphere as a byproduct. The generated protons form a proton gradient across the membrane, which is the driving force for ATP synthase in the fourth step. Finally, NADP\(^+\) is reduced to NADPH by the ferredoxin-NADP\(^+\) oxidoreductase. Both ATP and NADPH are very important for the biosynthesis of carbohydrates and other compounds in the dark reaction.

Unlike oxygenic photosynthesis, light energy is trapped and converted to chemical energy without the production of oxygen in anoxygenic photosynthesis. There are several groups of phototrophic bacteria that undergo anoxygenic photosynthesis including, purple bacteria, green sulfur bacteria and heliobacteria.
1.2 Reaction centers of photosystems

In all natural photosynthetic systems, the RC carries out photochemical charge separation and electron transfer. The RCs can be classified into two different types, depending on the nature of terminal electron accepters [3]. Type I RCs contain iron-sulfur clusters as electron acceptors, while type II RCs use quinone as electron acceptors. Photosynthetic organisms may have one or the other of these two RCs. For instance, the green sulfur bacteria, heliobacteria and cyanobacteria have a type I RC. On the other hand, purple bacteria, the green filamentous bacteria, and green-plant have a type II RC.

1.2.1 Structure of photosystem I (PS I) reaction center

For the type I RCs, a crystal structure of thermophilic cyanobacterium Synechococcus elongatus PS I at 2.5 Å resolution is available [4]. Isolated cyanobacteria PS I exists as a trimer, which is shown in Figure 1.2a. Each PS I monomer (Figure 1.2b) consists of 12 protein subunits.
(PsaA, B, C, D, E, F, I, J, K, L, M and X) and 127 cofactors comprising 96 chlorophylls (Chl), 2 phylloquinones (PhQ), 3 iron-sulfur clusters, 22 carotenoids and 4 lipids.

Figure 1.2 Structural model of PS I at 2.5 Å resolution (PDB 1JB0). a. View along the membrane normal form the stromal side. The twelve proteins (PsaA to F, I to M and X) that make up of the PS I complex and the antenna system are shown. b. Side view of the arrangement of all protein in one monomer of PS I (colors as in a).

Subunits PsaA and PsaB are assembled by a pseudo-C₂ axis, and provide ligands for the majority of the electron transfer cofactors. Two iron sulfur clusters, Fₐ and Fₐ, which are the terminal electron acceptors, are bound by the subunit PsaC. Subunits PsaD and PsaE stabilize and facilitate the interaction between PsaA/B, PsaC and the electron acceptor, which are ferredoxin and flavodoxin [5]. Subunits PsaI, L and M form the contacts between the monomers [6, 7]. Subunits PsaF, J, K and X contribute to the stabilization of the PS I core-antenna system and may also play an important role in forming interactions with the membrane intrinsic peripheral antenna system [8]. In green plants, several additional subunits are not found in cyanobacteria, namely PsaG, H, N and O, and some of these subunits have roles in the docking of light-harvesting complexes [9-12].
Subunits PsaA, B and C, which are related with electron transfer, are shown in Figure 1.3a. The arrangement of the electron transfer cofactors without protein background is shown in Figure 1.3b, and the individual cofactors are labeled with their names.

Figure 1.3 Structure of photosynthetic RC from the cyanobacterium Synechococcus elongatus (PDB 1JB0)[4]. a. The three-dimensional structure of the RC showing the core subunits and cofactors involved in the electron transfer. b. Arrangement of electron transfer cofactors in PS I without protein background. Subscripts refer to protein subunits PsaA or B to which the cofactors are bound.

1.2.2 Electron transfer pathway in PS I reaction centers

The electron transfer pathway of PS I RCs is formed by six chlorophylls, two phylloquinones and three iron sulfur clusters. The special pair P700 is a dimer of Chls. The remaining cofactors (accessory Chl A\text{A} and A\text{B}; Chl A\text{0A} and A\text{0B}; PhQ A\text{1A} and A\text{1B}; iron sulfur clusters F\text{A} and F\text{B}) form two nearly symmetrical branches, which are shown in Figure 1.3b. The inter-cofactor distances are nearly identical in both of the branches. In PS I, both branches of cofactors are involved in the electron transfer [13-15].

Figure 1.4 shows an outline of the light induced electron transfer in PS I. In early studies, the electron transfer across the membrane was considered to begin with the transition of P700 to the excited state P700*. The charge separation occurs between P700* and A\text{0} with formation of
P700\(^{+}\)A\(_{0}\)\(^{-}\) within 1~3 ps, and the electron is subsequently transferred from A\(_{0}\)\(^{-}\) to A\(_{1}\) in 30 ps [16, 17]. Forward electron transfer from A\(_{1}\)\(^{-}\) to F\(_{X}\) is characterized by two time constants of 20 ns for A branch and 200 ns for B branch [13, 18]. The fast phase is found to be temperature independent, while the slow phase is decelerated about 100 times at low temperature [19-21].

The charge recombination reactions can be observed when terminal electron acceptors are removed. Typical recombination times are 20-200 ns for P700\(^{+}\)A\(_{0}\)\(^{-}\), 10~250 \(\mu\)s for P700\(^{+}\)A\(_{1}\)\(^{-}\) and about 1 ms for P700\(^{+}\)F\(_{X}\)\(^{-}\), and ~60 ms for P700\(^{+}\)F\(_{A/B}\)\(^{-}\) recombination [17].

![Figure 1.4 Approximation standard free energy levels and kinetics of charge separation in PS I [17]. The stander free energy of the ground state of P700 was arbitrarily set to zero.](image)

According to ultrafast transient absorption spectroscopy [22], the accessory Chl that is located between P700 and A\(_{0}\) was considered to be the primary electron donor instead of P700 in PS I of cyanobacterium *Chlamydomonas reinhardtii*. The rate constant of the primary charge separation was not affected by mutual arrangements close to P700, while the rate constant of the secondary charge process is changed slightly. However, this hypothesis may be contrary to
recent data obtained by pump-probe femtosecond spectroscopy for PS I [23]. The semi-continuum calculations of PS I cofactors also suggest that accessory Chl as the primary acceptor seems unlikely, because in this case the electron transfer could be thermodynamically unfavorable[24].

1.2.3 Structure of purple bacterial reaction centers

The RCs of purple bacteria are well characterized and have been used to study Photosystem II (PS II) as a structural and functional model. The crystal structure of the purple bacteria RC from *Rhodobacter (Rb.) sphaeroides* has been determined at 2.2 Å resolution [25]. Compared with the PS I RCs, the RC of *Rb. sphaeroides* is much smaller, and includes only three protein subunits (L, H and M), which bind bacteriochlorophylls (BChl), two bacteriopheophytins (BPheo), two ubiquinone molecules, one nonheme iron atom lying between two quinones and one carotenoid. The L and M subunits are nearly symmetrical with respect to the axis perpendicular to the membrane plane. The L and M subunits form the core structure which binds the electron transfer cofactors. The H subunit forms a globular domain that attaches to the L and M subunits. The crystal structure reveals that the cofactors are arranged into two symmetrical branches (A and B). Although the two pigment branches are structurally symmetrical, they are functionally asymmetrical.
1.2.4 **Electron transfer pathway in reaction center of purple bacteria**

In the RC of *Rb. sphaeroides*, electron transfer occurs almost exclusively along the A branch, and B branch only functions in the final electron transfer step. The Electron transfer scheme in the RC of *Rb. sphaeroides* is shown in Figure 1.6. As a result of light absorption, electron transfer begins with the transition of a dimer of BChl molecules P to the excited state P*. This exited state P* decays in 3 ps and an electron is transferred to a nearby BChl on the A branch, termed B_A, generating a P^+B_A^- state within the RC [26]. Next, an electron transferred from B_A^- radical anion reduces a nearby BPheo molecule within a single picosecond, generating a P^+H_A^- state [27, 28]. The P^+H_A^- state is relatively long-lived compared to P* and P^+B_A^-, lasting~200ps before an electron transferred from the H_A anion to a nearby quinone Q_A [28]. Further electron transfer from the primary quinone Q_A to the secondary quinone Q_B occurs in the time scale of tens of microseconds and slows with decreasing temperature [29]. Subsequently,
the secondary electron transferred from P* leads double reduction of Q_B, converting Q_B from a semiquinone (Q_B\(^{-}\)) to a quinol (Q_B\(^{2-}\)). The quinol leaves the RC and is replaced by another quinone from the intramembranous pool \[30, 31\]. The P\(^{+}\) state is reduced with either exogenous cytochrome of c-type in \textit{Rb. sphaeroides} \[32\]. The cofactors in the RC of \textit{Rp. viridis} are different from those in \textit{Rb. sphaeroides}. \textit{Rp. viridis} contains BChla and BPheoa molecules but \textit{Rb. sphaeroides} contains BChlb and BPheob molecules. Both Q_A and Q_B in \textit{Rb. sphaeroides} are ubiquinones (UQ), while Q_A in \textit{Rp. viridis} is menaquinone and Q_B is UQ\[33\].

![Figure 1.6 Approximation standard free energy levels and kinetics of charge separation in Rb. sphaeroides \[33\]](image-url)
1.3 Function of quinones in electron transfer pathways

Quinones involved in photosynthetic reactions include plastoquinone in PS II; UQ and menaquinone in purple bacteria; and PhQ in PS I. All quinones can undergo one-electron reduction to form a semiquinone species.

Here, we focus on PhQ in PS I and UQ in purple bacteria. In PS I, the secondary electron acceptor is PhQ, which is an analog of naphthoquinone with a phytol and a methyl substituent. UQ is a substituted benzoquinone with a long side chain. As shown in Figure 1.7, both quinones have a methyl group and an unsaturated hydrophobic tail as ring substituents at adjacent positions between the two C=O groups. However, the interactions between quinones and protein in different systems, such as hydrogen bonding and π stacking, are different. Questions related to how the protein-cofactor interactions control the similar functional properties of the quinone in the two types of RCs are largely unanswered.

![Phyloquinone and Ubiquinone](image)

Figure 1.7 Structures and number schemes of PhQ and UQ.

1.3.1 Phyloquinone

As early as 1941, Dam and coworkers discovered PhQ in higher plants. Until 1986, PhQ was identified as an intermediary electron carrier in the acceptor chain of PS I by Malkin [34]. Subsequently, Thurnauer and coworkers used time-resolved electron paramagnetic resonance (EPR) to identify that PhQ acts as the secondary electron acceptor in the PS I electron transfer chain [35]. PhQ in the PS I RC has an unusually low midpoint potential of ~ -800mV [36], which
is ~350 mV more negative than in aprotic solvent [37]. As can been seen in the X-ray structure of the A₁A binding site (Figure 1.8), the carbonyl oxygen at C₄ is H bonded to the backbone nitrogen of LeuA722, and the head group of quinone is π-stacked with TrpA697 [4]. The A₁B and A₁A binding sites are similar. The role of hydrogen bond has been investigated using point mutations to selectively alter residue LeuA722. It has shown that the change in the H bond causes a shift of the quinone midpoint potential, which affects the rate of forward electron transfer [38-40]. The π-π interaction between PhQ and TrpA697 was also monitored by mutagenesis [41, 42]. Partial or total removal the π-stacked Trp residue can change the energy difference between A₁ and Fₓ to affect the forward electron transfer [43, 44]. Electronic structure calculations of the phyllosemiquinone (PhQ⁻) radical in the A₁A binding site of PS I indicate that the TrpA697 and PheA689 affect the spin density distribution of PhQ⁻ [45].

![Figure 1.8](image_url) The A₁A binding site in PS I RC from the 2.5Å X-ray crystal structure of T. elongatus. Figure was contracted by using the program Chimera. The H-bonds from MetA688 to SerA692, SerA692 to TrpA697 and from LeuA722 to PhQ are shown and the distances are labeled.
1.3.2 Ubiquinone

In purple bacteria RCs from *Rb. sphaeroides* UQ occupies both the QA and QB binding sites. In spite of this, the functional roles of UQ in both sites are quite different. QA is reduced only to semiquinone but QB can accept two electrons and can eventually form quinol. QA, which has a sufficiently long lifetime, is considered to be the stable primary electron accepter. X-ray crystal structures of the RCs from *Rb. sphaeroides* [25] show that C1=O carbonyl group is hydrogen bonded (H-bonded) to the backbone NH group of AlaM260, while the C4=O carbonyl group is H bonded to the side chain of HisM219 (Figure 1.9). HisM129 is also a ligand to the nonheme iron, Fe2+. Light induced QA+/QA Fourier transform infrared (FTIR) difference spectra obtained for *Rb. sphaeroides* with a specifically isotope labeled quinone incorporated into QA site suggest that the H bond between C4=O group and HisM219 is much stronger than the hydrogen bond between C1=O group and AlaM260 [46, 47]. However, recent ONIOM calculated spectra that agree with FTIR experiments do not predict that one of the carbonyl groups of UQ− in QA site is very strongly H-bonded [48].

EPR studies indicate that hydrogen bonds of QA− are asymmetric and affect the spin density distribution and electronic structure of the quinone radical [49, 50]. However, to study the structure and properties of QA− radicals using EPR, electron nuclear double resonance (ENDOR) or electron spin echo envelop modulation (ESEEM) the ferromagnetic Fe2+ ion must be removed and replaced with another bivalent metal such as Zn2+, since the paramagnetic properties of iron strongly cause a large shift and broadening of the EPR spectrum of the acceptor species [51]. All EPR spectra and kinetic properties of Zn-substitued RC are the same as wild type RC [52, 53]. Recent FTIR work in our lab supports this hypothesis.
1.4 Infrared spectroscopy

IR spectroscopy is a useful method for structure determination of small molecules, as well as large biological systems. IR spectra offer insight into much information, such as chemical structure of the vibrating group, bond and angle parameters, hydrogen bonding and electric field.

1.4.1 Advantages of infrared spectroscopy

In studies of biological systems, IR spectroscopy offers some advantages compared to other techniques. Firstly, IR spectroscopy can be used to determine positions of hydrogen atoms, van der Waals force, H bonding and electrostatic intermolecular interactions which cannot be resolved in crystal structures of biological system. Secondly, samples used for IR spectroscopy may be solid, liquid, powder or polymers. Thirdly, unlike nuclear magnetic resonance (NMR)
spectroscopy, IR spectroscopy can be used to study not only small biomolecules, but also large complex biological system. Fourthly, IR spectroscopy can provide structural data and molecular properties of intermediate species during the protein reaction when difference spectroscopy is used.

1.4.2 Theory of infrared absorption

The physical basis of IR light absorption is very similar to light absorption in the ultraviolet-visible range which causes electronic transitions. The energy differences between two vibrational energy levels are in the order of 0.5 and 0.001eV, corresponding to wavelength range from 2.5μm to 1mm. Molecular vibrational transition can be excited by either the absorption of IR light (IR spectra) or the inelastic scattering of photons (Raman spectra). Vibrations that modulate molecular dipole moment change can be observed in IR spectra, whereas vibrations that modulate polarizability change appear in Raman spectra.

1.4.2.1 Molecular vibration

A molecule of N atoms has total of 3N degrees of freedom, of which three correspond to transitional degrees of freedom and two or three correspond to rotational degrees of freedom. The remaining 3N-6 or 3N-5 degrees of freedom correspond to the vibrations of a non-linear molecule and a linear molecule, respectively, which are so-called normal modes. In each normal mode, all atoms of a molecule are vibrating in phase and have the same frequency. The frequency of this periodic motion is known as vibrational frequency.

Molecules can be considered as an array of point masses that are connected with each other by elastic springs representing the intramolecular interactions between the atoms. For the simplest case of a diatomic molecule, the vibrational frequency $\tilde{v}$ can be calculated using the equation:
\[ \tilde{\nu} = \frac{1}{2\pi c} \sqrt{\frac{k}{\mu}} \]

Where \( \tilde{\nu} \) is the vibrational frequency in wavenumber units; \( c \) is the speed of light; \( k \) is force constant; and \( \mu \) is reduced mass.

The reduced mass is used for simplifying calculations by combining the individual atomic mass. For a diatomic molecule, the reduced mass is defined by:

\[ \frac{1}{\mu} = \frac{1}{m_1} + \frac{1}{m_2} \]

Where \( \mu \) is the reduced mass, and \( m_1 \) and \( m_2 \) are the masses of the two atoms in the diatomic molecule.

Generally, force constant of bond, mass of atoms and molecular geometry determine vibrational frequencies and relative motion of molecule. Force constants do not only depend on the chemical bonds connecting the individual atoms but also result from the non-bonding intermolecular interactions. With the increasing size of molecules, the normal mode frequencies become more and more complicated. The frequencies as well as IR intensities of vibrations are characteristic of particular bond or group [54].

1.4.2.2 Intensity of vibrational bands

The normal mode associated with a change in dipole moment is active in IR spectra. The IR intensity of active normal mode follows the Beer-Lambert law:

\[ A = \log \left( \frac{I_0}{I} \right) = \varepsilon cl \]

Where \( A \) is absorbance; \( I_0 \) is the intensity of incident radiation; \( I \) is the intensity after passing through the sample; \( \varepsilon \) is the molar extinction coefficient or absorptivity; \( c \) is the concentration; and \( l \) is the path length.
The molar extinction coefficient $\varepsilon$ of normal mode is related to the change of dipole moment. For a given concentration and path length, the larger the dipole moment change, then the more intense the absorption band will be [55].

### 1.4.3 Fourier Transform infrared spectroscopy

The Fourier transfer method was introduced to IR spectroscopy in the 1960s, and now FTIR is widely applied in the research. FTIR spectroscopy has several significant advantages over other IR spectroscopy such as high signal to noise ratio, high speed and wavenumber precision.

1.4.3.1 Interferometer and interferogram

The heart of an FTIR spectrometer is a Michelson interferometer shown in Figure 1.10. It consists of a beam splitter and two plane mirrors oriented perpendicularly to each other. One of the mirrors is fixed and the other one is movable. The beam from IR source is divided into two parts by a beam splitter. Half of the incoming beam is reflected by the beam splitter and then reflected by the fixed mirror, while the other half of the incoming beam passes the beam splitter and is reflected by the movable mirror. The beams reflected by two mirrors are recombined via the beam splitter. 50% of the combined beam is reflected towards the detector. The moving mirror produces an optical path difference between the two arms of the interferometer. When the two beams recombine, they interfere constructively or destructively depending on the optical path difference. The helium neon laser is applied to measure the optical path difference and align accessories. The spectral resolution of FTIR spectroscopy is limited by optical path difference.
Figure 1.10 Schematic of a Michelson interferometer [56].

A plot of light intensity versus optical path difference is called an interferogram. The resultant interference pattern obtained by IR spectroscopy is shown in Figure 1.11. For polychromatic radiation, the interferogram is a sum of monochromatic waves. The intensity of interferogram falling in the detector, $I(\delta)$, is

$$I(\delta) = \int_{0}^{+\infty} A(\tilde{\nu}) \cos(2\pi\tilde{\nu}\delta) \, d\tilde{\nu}$$

Where $\delta$ is the path difference between two beams, $\tilde{\nu}$ is the wavenumber, and $A$ is the spectral power density.
Figure 1.11 Interferograms obtained for (a) source of monochromatic radiation and (b) a source of polychromatic radiation [56].

Fourier transformation mathematic method is applied to transform the digitized information on the interferogram into spectrum. The intensity of light can be represented as a function of wavenumber as follows:

\[ A(\tilde{\nu}) = \int_{-\infty}^{+\infty} I(\delta) \cos(2\pi\tilde{\nu}\delta) d\delta \]

\( A(\tilde{\nu}) \) is the intensity of the light detected as a function of wavelength, and is called a single beam spectrum. Figure 1.12 shows a typical single beam spectrum collected on our FTIR spectrometer.
A typical single beam spectrum obtained using our FTIR spectrometer. The spectrometer was open to the atmosphere, without purging with nitrogen gas. The single beam spectrum is the Fourier transform of the interferogram. Notice the bands due to water vapor centered near 3600 and 1600 cm\(^{-1}\), and the bands due to CO\(_2\) at \(~2400\) cm\(^{-1}\)[57]

The mathematical process of Fourier transformation assumes infinite boundaries, while in practice the transformation carries out an integration stage over a finite displacement; therefore, apodization is required before Fourier transformation. In addition, phase correction is also required and this correction procedure ensures that the sample intervals are the same on each side of the first interval and should correspond to the path difference of zero [58].

1.4.3.2 Source and Detector

Different measurements require different light sources. Commonly, a high pressure mercury lamp can be used as a light source in the far-IR region. A Globar or Nernst source is used for the mid-IR region, and tungsten halogen lamps are used for the near-IR region.
There are two classes of detectors applied for the mid-IR region: thermal and photo detectors. Pyroelectric detectors such as deuterated triglycine sulfate (DTGS) are thermal detectors which are operated at room temperature in FTIR spectroscopy. The IR radiation absorbed by pyroelectric detector causes an increase in temperature, and induces changes to the surface density. The changes in the surface charge can be detected by the subsequent preamplifier. For more sensitive and faster work, a photon detector such as mercury cadmium telluride (MCT) can be used, but these have to be cooled to liquid nitrogen temperature. The principle of photon detectors is based on change of the conductivity caused by the absorption of IR photon. The increase of conductivity is monitored by the subsequent preamplifier as an increase in current flowing through detectors if a constant voltage is applied [59].

1.4.3.3 Time-resolved step-scan Fourier Transform infrared spectroscopy

In the step-scan technique, the movable mirror is held in a fixed position and the reaction is triggered by a laser flash. At this position, a time-resolved measurement is performed and the time-dependent change of IR intensity after the flash is recorded by the detector. Then the mirror moves to the next position and the time-resolved experiment repeats. After a series of measurements at different mirror positions, the interferogram at each time slice of the time scale can be obtained by combining all the data.

The time resolution of this technique is limited by the response time of the detector and the electronics (amplifier and transient recorder). Step-scan techniques require that the reaction of interest can be repeated many times within the same sample.

1.4.4 Application of infrared spectroscopy on biological system

The size of biological systems studied by IR spectroscopy can vary substantially. The larger size of the biological system, the more complex a spectrum becomes. As the spectrum
becomes more complex, it becomes more difficult to determine which peaks are from which molecules. Figure 1.13 shows an IR absorption spectrum for trimeric PS I particles from *Synechocystis sp. PCC 6803 (S6803)*, and only several broad bands could be observed. Because all the biomolecules in this sample absorb IR radiation, much information is hidden under the broad, featureless absorption bands. The overlapping bands in the absorption spectrum of proteins limit the information that can be obtained from an absorption spectrum. To solve this problem, difference spectroscopy (DS) is required. For example, the light-induced IR DS of photosynthetic RC can be calculated from spectra recorded before and after illumination. The DS only display contributions from those groups undergoing molecular change during the illumination, and all bands that remain unchanged cancel each other out.

Figure 1.13 IR absorption spectrum of PS I particles from *S6803* in aqueous solution.
Based on DS, site-directed mutagenesis and isotopic labeling of ligands, cofactors and amino acids can be used to assign different signals to individual molecular groups.

Site-directed mutagenesis is a very powerful approach in the studies of biological systems by IR spectroscopy. Due to the interaction between a specific amino acid and target molecule an IR signal is modified when this amino acid has been selectively replaced. Then the modified IR signal should be caused by the interaction between a specific amino acid and target molecule.

Isotopic labeling is also an indispensable tool in IR spectroscopy for assigning bands to specific groups in a large protein. Due to mass effects on vibrational frequencies, IR absorption bands of a labeled group are shifted with respect to those of the unlabeled groups and can be identified in the spectrum. Although isotope labeling can avoid perturbation of the protein structure, the costs of isotope labeling can be very high.

1.5 Computational methods for spectral analysis

Information on molecular structural can be obtained by a variety of spectroscopies techniques. Extraction of information is seldom straightforward. Many effects can alter spectra, and the role of specific effects is not easy to separate and evaluate. To distinguish them from other contributions in the experiments, specific pigments or amino acids should be labeled or mutated without changing other parts.

Computational spectroscopy is a very useful tool for analyzing experimental spectra in terms of chemical or physical effects. The interaction between protein and pigments could be effectively switched on and off computationally in order to analyze their role on the overall observation. A combination of experiments and calculations provide a deeper understanding of the spectral behavior associated with complex biological systems and processes. For instance, H bonding lowers the frequency of stretching vibrations, since it weakens the restoring force [59].
The strength of a H bond is difficult to control in experiments, but in calculations it is could easy to change amino acids to make H bonds stronger or weaker.

ONIOM is an acronym for Our own N-layered Integrated molecular Orbital and molecular Mechanics. ONIOM methods are applied to a large system where two or three layers within the structure that is treated at different levels of accuracy [60, 61]. In a 2-layer ONIOM calculation, the model system which includes active portion is treated with the most accurate method i.e. quantum mechanics (QM), while real system which consists of the entire molecule are treated with inexpensive method, i.e. molecular mechanics (MM). QM is able to describe the changes in the electronic structure of a system undergoing a chemical or biological reaction. However, due to the very demanding computational cost, the application of QM is still limited to a relatively small system. MM has been widely used for large and complex organic and biological systems in molecular dynamics, but is unable to describe bond forming or breaking.

Figure 1.14 illustrates 2-layer ONIOM assignments for modeling the QA binding site in Rb. sphaeroides RCs. In this case, the real system (Figure 1.14c) was defined as 49 amino acids, 7 water and a non-heme iron atom within the UQ-centered spheres of 10 Å radius, and the model system (Figure 1.14d) includes the UQ, AlaM260 and HisM219 which are H-bonded to UQ, a non-heme iron atom and its ligands. The wireframe and ball-and-stick correspond to the real and model system in Figure 1.14b, respectively. The model system is performed using density functional theory (DFT) which is a promising QM method with an excellent compromise between accuracy and computational cost, while the real system is treated with MM for geometry optimization. DFT with B3LYP function is applied to model system because it is widely used for the calculation of vibrational frequencies and found to reproduce experimental data in a satisfactory manner when using a standard 6-31G* basis set [62].
Figure 1.14 ONIOM layer definitions for modeling $Q_A$ binding site in Rb. *sphaeroides* RC. (a) 10Å sphere of $Q_A$ binding site prepared for ONIOM calculation (b) ONIOM model (c) real system (d) model system
1.6 Thesis overview

Chapter 1 provided fundamental information on structures and functions of PS I and purple bacteria RCs, with particular attention paid to quinones in photosynthetic RCs. An overview of IR spectroscopy and ONIOM type QM/MM calculations are also described.

In Chapter 2, we present the recent time-resolved step-scan (TRSS) FTIR studies of 2-methyl-1,4-napthoquinone (2MNQ) incorporated into A₁ binding site of PS I particles from menB mutants. To further aid in assessing bands in the spectra, DFT based calculation and ONIOM type QM/MM calculations are undertaken. By comparing calculated spectra to the corresponding experimental spectra, the vibrational modes associated specifically with quinone in the binding site are identified. The impact of the phytol tail on the orientation of PhQ in the A₁ binding site is discussed.

Isotope labeling was used for further band assignments of the A₁'/A₁ FTIR DS in Chapter 3. We have shown isotope edited TRSS FTIR DS obtained using PS I particles from fully ¹³C labeled menB mutants reconstituted with PhQ and from fully ¹³C labeled wild type at 77K. DFT based calculations and QM/MM ONIOM type calculations are undertaken to calculate vibrational frequency shifts of PhQ in the A₁ binding site, upon ¹³C and ¹⁸O labeling.

To test and verify the applicability of our QM/MM approach, ONIOM calculations are also undertaken for UQ in purple bacteria photosynthetic RCs. Chapter 4 presents the ONIOM calculations of the vibrational properties of neutral UQ in the Qₐ binding site. In these calculations we have treated the hydrogen bonding amino acids either quantum mechanically or molecular mechanically. Isotope edited Qₐ'/Qₐ FTIR DS are obtained using different models and methods. The nature of H-bonding to the neutral UQ is discussed. This work has been published recently [63].
In Chapter 5, we use ONIOM methods to calculate isotope edited FTIR DS for RCs with a variety of unlabeled and $^{18}$O labeled foreign quinones incorporated into the QA binding site. Isotope edited spectra were calculated for RCs with 2,3-dimethoxy-5,6-dimethyl-1,4-benzoquinone, 2,3,5,6-tetramethyl-1,4-benzoquinone, and 2,3-dimethyl-1,4-naphthoquinone incorporated, and compared to corresponding experimental spectra. The normal modes that contribute to the bands in the calculated spectra, their composition, frequency and intensity, and how these quantities are modified upon $^{18}$O labeling, are presented. This work has been also published recently [64].
2 TIME-RESOLVED FTIR SPECTROSCOPIC STUDIES OF PHOTOSYSTEM I PARTICLES WITH FOREIGN QUINONES INCORPORATED INTO THE A₁ BINDING SITE

Abstract

Low temperature, time-resolved step-scan FTIR difference spectroscopy (DS) with 5 μs resolution was used to produce A₁/A₁ FTIR DS for PS I particles with phylloquinone (PhQ) (2-methyl, 3-phytyl, 1, 4-naphthoquinone) or vitamin K₃ (2-methyl, 1, 4-naphthoquinone (2MNQ)), incorporated into the A₁ binding site.

The time-resolved spectra suggest that 2MNQ and PhQ, in both the neutral and reduced states are similarly hydrogen (H) bonded. To aid in spectral assessment, we have undertaken density functional theory based, ONIOM type QM/MM calculations for PhQ and 2MNQ in the A₁ binding site. The ONIOM calculated spectra agree well with the experimental spectra. Calculations for quinones in the gas phase do not adequately model the experimental spectra. The ONIOM calculations confirm that, both PhQ and 2MNQ, in both the neutral and reduced states, are strongly H-bonded to a backbone NH group of Leu, and the phytol tail of PhQ has no significantly effect on the orientation of quinone head in the A₁ binding site.

2.1 Introduction

Solar energy is captured and converted in photosynthetic oxygen evolving organisms by two photosystems, referred to photosystem I (PS I) and photosystem II (PS II). The PS I reaction center (RC) consists of 12 or more protein subunits, carrying out photochemical charge separation and electron transport across the thylakoid membrane. The majority of the electron transfer cofactors are located on PsaA and PsaB subunits. These cofactors form two almost
identical branches for electron transfer, which are connected by a pseudo C2 axis and simply called A and B braches (Figure 2.1). Both branches are active in electron transfer [13].

The arrangement of electron transfer cofactors in the PS I complex is depicted in Figure 2.1. The initial light induced charge separation has historically been considered to occur from the excited state of P700 dimeric Chla species). The primary electron acceptor A₀ (a Chla molecule) receives an electron from P700* rapidly, and then transfers it to A₁ within ~30 ps [17]. In PS I, phylloquinone (PhQ) occupies the A₁ binding site [65], the structure of which is shown in Figure 2.3. To further stabilize the charge separated state, the electron is transferred from A₁⁻ to Fₓ, and then to Fₐ/ Fₐ. Fₓ, Fₐ and Fₐ are iron sulfur clusters [66]. Forward electron transfer from A₁⁻ to Fₓ exhibits biphasic kinetics with lifetime of ~200 ns for PhQ⁻ in the A branch and ~20 ns for PhQ⁻ in the B branch at room temperature [67]. At 77K, the yield of forward electron transfer to the iron sulfur clusters decreases, and the P700⁺ₐ state forms and recombines with a time constant of 245µs in the cyanobacterial PS I particles [20].
Figure 2.1 Arrangement of the two branches of electron transfer cofactors in PS I. Subscript A refers to protein subunits PsaB, while subscript B refers to protein subunits PsaA. Figure 2.1 is generated using the 2.5 Å X-ray crystal structure of trimeric PS I particles from the cyanobacterium *Synechococcus elongatus* (PDB 1JB0) [4].

The PhQ molecule occupying the $A_1$ binding site has a midpoint potential closed to -800 mV [68]. and this makes it one of the most reducing quinones in biology. This unprecedented redox potential is in part a result of interactions of PhQ with the surrounding protein environment. A detailed view of the $A_1$ binding pocket is shown in Figure 2.2. The indole ring of TrpA697 (*Synechococcus elongatus* numbering) is $\pi$-stacked with the PhQ ring plane. The hydroxyl side chain of SerA692 could be hydrogen (H) bonded to the backbone oxygen atom of MetA688. The indole NH group of TrpA697 may also be H-bonded to the hydroxyl oxygen atom of SerA692. The crystal structure suggests that the $C_1=O$ group of PhQ is not H-bonded, whereas the $C_3=O$ group is H-bonded to the backbone NH group of LeuA722. Electron
paramagnetic resonance (EPR) and electron nuclear double resonance (ENDOR) studies on photo-accumulated \( A_1^- \) radicals and on spin correlated \( P700^+A_1^- \) radical pairs, have shown an asymmetric spin density distribution on the PhQ ring \([69-74]\), indicating a single H-bond to PhQ\(^-\) in the \( A_1 \) binding site.

![Figure 2.2 View of PhQ in the \( A_{1\alpha} \) binding site. Possible H-bonding interactions of the PhQ carbonyl groups with the protein are shown (dotted). Nitrogen/oxygen/sulfur/carbon atoms are blue/red/yellow/grey, respectively.](image)

Foreign quinones such as naphthoquinone analogues, anthraquinones, and benzoquinones (BQ) could be incorporated into the \( A_1 \) binding site after extraction of native PhQ with organic solvent \([75, 76]\). The \( A_1 \) binding site appears versatile enough to accept a variety of substituted quinones, but only a very limited number of quinones were able to restore forward electron transfer to the iron sulfur clusters. Biggins and his coworkers found that the 3-phytyl or 3-alkyl
tail of naphthoquinone was required to promote electron transfer to F_X though the hydrophobic interaction [75]. However, EPR studies have showed that the saturated alkyl tail of naphthoquinone analogues occupied the position of PhQ methyl group, instead of phytol chain in the A_1 binding site [77].

Later, genes involved in the biosynthetic pathway of PhQ were identified in *Synechocystis* sp. PCC 6803 (S6803) [78]. In menB mutant strain of S6803, the menB gene is inactive and the biosynthetic pathway of PhQ is blocked. In the absence of PhQ, plastoquinone-9 (PQ9) has been shown to occupy the A_1 site, where it functions as an efficient cofactor in electron transfer from A_0 to the iron sulfur clusters [78-80]. PQ9 is a BQ analogue, which is shown in Figure 2.3. Compared to PhQ, the tail of PQ9 is much longer and less saturated, but electron spin echo envelope modulation (ESEEM) experiments have shown that the distance between P700^+ and PQ9^- is identical to the distance between P700^+ and PhQ^- . In addition, the orientation of PQ9^- head group was found to be the same as PhQ^-, indicating that the phytol tail of PhQ does not affect the orientation of the quinone in the PS I [81]. On the other hand, EPR studies have shown that 2-methyl-1, 4-naphthoquinone (2MNQ) is positioned and oriented identically to the native PhQ in the A_1 binding site, suggesting that the long tail of PhQ does not play a major role in orienting quinone in PS I [69, 72, 73]. 2MNQ is a PhQ analogue that lacks a phytol tail (Figure 2.3).

To study molecular properties of quinones in A_1 binding site of PS I, time-resolved step-scan (TRSS) FTIR difference spectroscopy (DS) has been used to produce A_1/A_1 FTIR DS for PS I particles [82-87]. Density functional theory (DFT) was used to calculate the vibrational properties of PhQ and PhQ^- in the gas phase, and the band assignments for the A_1/A_1 FTIR DS have been proposed. Moving on from this work, DFT based vibrational frequency calculations
were undertaken for PhQ/PhQ$^-$ with the C$_4$=O group H-bonded to the backbone NH group of a Leu residue. These calculations predicted that the two C=O modes are separated for PhQ and coupled for PhQ$^-$, suggesting that asymmetric H-bond weakens upon PhQ$^-$ formation [82, 87].

Pulsed EPR and ENDOR techniques applied to PS I suggest that PhQ$^-$ and 2MNQ$^-$ are H-bonded to NH group of Leu residue in very similar ways. The length of the asymmetric H-bond was simulated to be 1.64 Å using the point-dipole approximation, which corresponds to a relatively short and strong H-bond [69].

Time-resolved (TR) optical DS and transient EPR spectroscopy show that the replacement of the π-stacked Trp residue with Phe or Ala affects the rate of forward electron transfer from A$_1^-$ to Fx [41, 42]. Theoretical studies also show that hyperfine coupling constants of PhQ$^-$ in the A$_{1A}$ site are sensitive to interactions with neighboring groups, especially TrpA697 and PheA689 [45]. However, in previous studies, only the H-bond between Leu residue and the C$_4$=O group of quinone was considered in the DFT calculations, and all other quinone-protein interactions were ignored.

Here we describe TR FTIR spectroscopic studies using menB PS I particles with PhQ and 2MNQ incorporated into the A$_1$ binding site. The A$_1^+$/A$_1$ FTIR DS obtained using PS I particles with PhQ/2MNQ incorporated were produced, suggesting that PhQ and 2MNQ are H-bonded to NH group of Leu residue in very similar ways. This result indicates that the phytol tail of PhQ does not affect the H-bond between quinone and NH group of Leu.

We also perform ONIOM type QM/MM calculations on quinone in the A$_1$ binding site [60, 61]. ONIOM is an acronym for our Own N-layered Integrated molecular Orbital and molecular Mechanics package. In ONIOM calculations, H-bonding and π-stacked interactions for the quinones with protein residues side chains are treated quantum mechanically, and all
other intermolecular interactions are treated molecular mechanically (UFF [88]). Following geometry optimization of quinone in the A₁ binding site using ONIOM methods, the vibrational properties of quinone were calculated using DFT methods. The calculated vibrational modes based on ONIOM methods are very different from that obtained using DFT calculations for only PhQ (or PhQ and Leu residue) in the gas phase.

![Figure 2.3 Quinone structure and numbering scheme.](image)

### 2.2 Materials and Methods

#### 2.2.1 Preparation of PS I particles

Trimeric PS I particles were isolated from menB mutants following the procedures described previously [78], and stored in 25 mM Tris buffer (pH 8.3) with 0.04% n-Dodecyl β-D-Maltoside (β-DM).

#### 2.2.2 Incorporation of quinone into the A₁ binding site

To incorporate quinones into the A₁ binding site, PSI particles are incubated in the presence of a large molar excess of the quinone of interest. Quinones were dissolved in ethanol.
and added to a suspension of PS I particles to attain the ratio of ~1000 quinones per RC. This procedure was undertaken in such a way that the volume of ethanol in the mixture never exceeds 2% of the total volume. The PS I particle/quinone mixture was incubated at 4 °C in dark for ~24 hours with stirring.

2.2.3 FTIR absorption spectra of quinones

PhQ and 2MNQ were dissolved in tetrahydrofuran (THF). The thickness of the sample was adjusted using spacers so that the optical density of the main quinone band (at 1662/1666 cm\(^{-1}\)) is ~ 0.6. An IR spectrum of pure THF was used to interactively subtract the well-known THF bands present in the quinone/THF spectrum.

2.2.4 Photo-accumulated FTIR difference spectroscopy

Before TR FTIR measurements were undertaken, light-induced P700\(^+\)/P700 FTIR DS were recorded at 77K. PS I particles were washed by 50mM Tris buffer with 0.04% β-DM detergent, then ultra-centrifuged to produce a soft pellet, which was then squeezed between two circular 1 inch diameter CaF\(_2\) windows. The sample thickness (spacing between the two windows) was adjusted so that the peak of the amide I band (at ~1654 cm\(^{-1}\)) had an optical density less than 1.0.

For light-induced photo-accumulation measurements, a 20 mW, Helium-neon laser was used for light excitation. The light-dark spectra were constructed as described previously [89].

2.2.5 Microsecond time-resolved step-scan FTIR difference spectroscopy at 77K

TRSS FTIR experiments with 5 µs time resolution, at 77 K, were undertaken as described previously and P700\(^+\)A\(_1\)/P700A\(_1\) FTIR DS were recorded [82]. Data were collected in the 1950-
1100 cm\(^{-1}\) region at 4 cm\(^{-1}\) spectral resolution. Long pass filters were used to block light above 1950 cm\(^{-1}\), and the CaF\(_2\) windows themselves blocked light below 1100 cm\(^{-1}\).

2.2.6 Estimating the noise level in double difference spectra

TR and photo-accumulated FTIR DS were scaled using a min-max algorithm in which the minimum/maximum y-value was set to 0.0/2.0. For each PS I sample, the TR and photo-accumulated measurements were repeated several times and then averaged, respectively. The standard deviation of the average spectra was taken as the most appropriate measure of experimental variability (noise level).

\(A_1/A_1\) FTIR DS were produced by subtracting P700\(^+\)/P700 FTIR DS from P700\(^-\)A\(_1\)/P700A\(_1\) FTIR DS. The error associated with \(A_1/A_1\) FTIR DS of PS I particles with PhQ or 2MNQ incorporated into A\(_1\) binding site was calculated using equation (1)

\[\delta f = \sqrt{\delta A^2 + b^2 \delta B^2} \]  

Where \(\delta f\) is the error associated with \(A_1/A_1\) FTIR DS; \(\delta A\) is the standard deviation of the average spectra of P700\(^+\)A\(_1\)/P700 A\(_1\) FTIR DS obtained from TR measurements; \(\delta B\) is the standard deviation of the average spectra of P700\(^+\)/P700 FTIR DS obtained from photo-accumulated measurements; and \(b\) is the scaling factor used to normalize the difference bands in P700\(^+\)/P700 FTIR DS.

The total error for the (2MNQ-PhQ) \(A_1/A_1\) FTIR DDS was calculated using the equation (2)

\[\delta f = \sqrt{\delta A^2 + \delta B^2} \]  

Where \(\delta f\) is the total error for the (2MNQ-PhQ) \(A_1/A_1\) FTIR DDS; and \(\delta A\) and \(\delta B\) are the error associated with the \(A_1/A_1\) FTIR DS obtained from PS I particles with PhQ and 2MNQ incorporated, respectively.
The total error for the (2MNQ-PhQ) A\textsubscript{1} / A\textsubscript{1} FTIR DDS is shifted and centered on zero before being used to construct error bars, which shows the intensity variation of difference bands over the spectra range.

### 2.2.7 DFT based vibrational frequency calculations

Models used in DFT calculations were constructed starting from the PS I X-ray crystal structure (PDB entry 1JB0) [4]. The PhQ species in the A\textsubscript{1}\textsubscript{A} binding site was used, where the phytol tail was truncated to a simpler CH\textsubscript{2}CHCH\textsubscript{2} unit. Hydrogen atoms were added using Gaussview 4. For DFT calculations the B3LYP functional was used in combination with the 6-31G+ (d) basis set.

In initial DFT calculations two simple molecular models were considered. The first (Model 1) consists only of a PhQ or 2MNQ molecule. Model 1 for PhQ in the gas phase was studied previously [90], and included 28 atoms. The optimized geometry of Model 1 for PhQ in the gas phase is shown in Figure 2.4A.

To account for the asymmetric H-bonding, a second molecular model (Model 2) was considered, and is shown in Figure 2.4B. In Model 2, PhQ and LeuA722 were included, along with part of AlaA721. The side chain of LeuA722 was truncated to a methyl group, while the NH\textsubscript{2} and CH\textsubscript{3} groups of AlaA721 were replaced by hydrogen atoms. For 2MNQ, the tail at C\textsubscript{3} was simply replaced by a hydrogen atom. DFT calculations were undertaken for both neutral and reduced PhQ/2MNQ. The geometry optimized structures (Figure 2.4) were then used as inputs for DFT based vibrational frequency calculations. All calculations were undertaken using Gaussian03 [91].
2.2.8 **ONIOM type QM/MM based vibrational frequency calculations**

Models 1 and 2 do not consider the larger protein environment surrounding the quinone of interest. To account for this environment, ONIOM type QM/MM calculations were undertaken. The molecular model used in ONIOM calculations (Model 3) was constructed starting from the PS I crystal structure [4], which consisted of PhQ or 2MNQ, and amino acid residues PheA685-LeuA700 and ArgA720-IleA725. Quinone and important bonding amino acids (LeuA722, TrpA697, PheA689, SerA692, and MetA688) were treated using QM method [DFT using B3LYP/6-31G(d)], and the remaining atoms were treated using MM methods (UFF method [88]).

The phytyl tail of PhQ was again truncated to CH₂CHCH₂. The QM layer of Model 3 is shown in Figure 2.5A. Linking between the QM and MM layers was achieved using the hydrogen link atom approach. Charges for the MM layer were generated using the qEq method, and electrostatic embedding was employed. For geometry optimization of ONIOM calculations all heavy atoms (non-hydrogen atoms) except those of PhQ (or 2MNQ) are constrained. Such a procedure is similar to that used in ONIOM calculations for PhQ EPR parameters [45].
As outlined above, for 2MNQ in the A$_1$ binding site, the phytyl tail of PhQ at C$_3$ is replaced by a hydrogen atom. ONIOM calculations were also undertaken for reduced PhQ and 2MNQ by simply specifying the total charge of the QM layer as -1. From a consideration of calculated atomic charge (from Mullikan population analysis) it is found that nearly all of the negative charge is distributed over the atoms of the quinone.

Following geometry optimization, linking between the QM and MM layers were replaced by hydrogen atoms. These hydrogen atoms and the entire QM layer were optimized using the B3LYP functional with 6-31G (d) basis set, and all the atoms in the QM layer were fixed except the hydrogen atoms newly added.

After optimizing the hydrogen atoms newly added to QM layer, the entire QM layer was then used in DFT vibrational frequency calculations using the B3LYP functional and the 6-31G (d) basis set. This led to a very large number of vibrational frequencies for the surrounding

Figure 2.5 QM layer of ONIOM calculations for (A) PhQ and (B) 2MNQ in the A$_1$ binding site.
amino acids, but these frequencies essentially cancelled when \((2\text{MNQ} - \text{PhQ})\) double difference spectra (DDS) were calculated.

Assignment of calculated vibrational frequencies to molecular groups is undertaken by visual identification of the molecular groups that most prominently contribute to the vibration. This visual identification is carried out using GaussView 4, in which the atomic motions associated with each of the vibrational modes can be animated.

### 2.3 Results and Discussions

#### 2.3.1 Absorption spectra of quinones in tetrahydrofuran

![Absorption spectra of quinones in tetrahydrofuran](image)

Figure 2.6 FTIR absorption spectra for (A) PhQ and (B) 2MNQ in tetrahydrofuran (THF). The spectra were scaled so that the intensities of the bonds at 1662 and 1666 cm\(^{-1}\) are similar.
Figure 2.6 shows FTIR absorption spectra obtained for PhQ and 2MNQ in THF. For PhQ, the bands at 1462 and 1377 cm\(^{-1}\) are assigned to \(\delta\text{CH}_2\) and \(\delta\text{CH}_3\) modes of the phytyl chain [90]. In agreement with this prediction, these two bands disappear in the 2MNQ spectrum. A band is observed at 1597 cm\(^{-1}\) in both the PhQ and 2MNQ spectra. This band is due to C=C stretching of the aromatic part of the naphthoquinone ring [90].

The band at 1619 cm\(^{-1}\) in the PhQ spectrum is due to C=C stretching of the quinonic part of the naphthoquinone ring [90] and upshifts 8 cm\(^{-1}\) to 1627 cm\(^{-1}\) for 2MNQ. For PhQ, in THF the antisymmetric C=O stretching of both carbonyl groups occurs at 1662 cm\(^{-1}\) [90]. Replacement of the phytyl tail at C\(_3\) with a hydrogen atom (2MNQ) leads to a 4 cm\(^{-1}\) upshift in frequency of the antisymmetric coupled C=O mode.

### 2.3.2 Geometry

Key bonding distances and angles obtained from the geometry optimization of Models 1-3 are given in Table 2.1 and Table 2.2, for PhQ and 2MNQ, respectively.

As expected, the C\(_4\)=O bond length is calculated to be greater than the C\(_1\)=O bond length, when the C\(_4\)=O carbonyl group is H-bonded. This is true for both neutral and reduced states of PhQ or 2MNQ.

Compared to PhQ, the H-bond length of PhQ\(^{-}\) is decreased by up to ~0.2 Å and 0.19 Å for Model 2 and 3, respectively. The H-bond length between PhQ\(^{-}\) and Leu residue calculated by DFT method in Model 2 is ~1.8 Å, which is longer than the previous studies [69]. In Model 3 the H-bond length between PhQ\(^{-}\) and Leu residue calculated by ONIOM method is just ~1.64 Å, which agrees with the previous ONIOM calculations [45] and simulations using point-dipole approximation [69].
For the ONIOM models (Model 3) of both PhQ and PhQ', the C₃-C₄-O-N dihedral angle and the C₃-O-N angle are similar to that found in X-ray crystal structure (Table 2.1). For Model 2, these angles corresponding to PhQ' are also similar to those found in X-ray crystal structure, suggesting that the orientation of PhQ' is mainly constrained by the antisymmetric H-bond between Leu residue and PhQ'. However, for neutral PhQ the C₃-C₄-O-N dihedral angle changed ~304° in Model 2, compared to X-ray crystal structure, suggesting that the protein environment constrains the orientation of the neutral quinone ring relative to Leu residue. Therefore, the DFT calculations of Model 2 do not accurately describe the geometry of quinone in the A₁ binding site. The geometry optimization of models that contain 2MNQ is very similar to those of models including PhQ.

Table 2.1 Comparison of the geometries of neutral and reduced PhQ in different models

<table>
<thead>
<tr>
<th></th>
<th>PhQ</th>
<th>PhQ'</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X-ray [4]</td>
<td>Model 1</td>
</tr>
<tr>
<td>C₁=O</td>
<td>1.416</td>
<td>1.229</td>
</tr>
<tr>
<td>C₄=O</td>
<td>1.424</td>
<td>1.229</td>
</tr>
<tr>
<td>Bond length LeuNH-O</td>
<td>2.053</td>
<td>1.834</td>
</tr>
<tr>
<td>Bond length LeuN-O</td>
<td>2.694</td>
<td>3.069</td>
</tr>
<tr>
<td>Angle LeuN-C₄-O</td>
<td>146</td>
<td>155</td>
</tr>
<tr>
<td>Dihedral angel LeuN-C₄-O-C₃</td>
<td>143</td>
<td>-161</td>
</tr>
</tbody>
</table>

Table 2.2 Comparison of the geometries of neutral and reduced 2MNQ in different models

<table>
<thead>
<tr>
<th></th>
<th>2MNQ</th>
<th>2MNQ'</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 1</td>
<td>Model 2</td>
</tr>
<tr>
<td>C₁=O</td>
<td>1.227</td>
<td>1.227</td>
</tr>
<tr>
<td>C₄=O</td>
<td>1.229</td>
<td>1.235</td>
</tr>
<tr>
<td>Bond length LeuNH-O</td>
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</tr>
<tr>
<td>Bond length LeuN-O</td>
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</tr>
<tr>
<td>Angle LeuN-C₄-O</td>
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<td>139</td>
</tr>
<tr>
<td>Dihedral angel LeuN-C₄-O-C₃</td>
<td>-167</td>
<td>112</td>
</tr>
</tbody>
</table>
2.3.3 Calculated vibrational mode frequencies

The asymmetric H-bonding to the backbone NH group of the Leu has a significant effect on the calculated vibration frequency of the C\textsubscript{4}=O carbonyl group. Table 2.3 shows how the vibrational frequencies of PhQ and 2MNQ change on going from the isolated to the H-bonded species. The vibrational frequencies of the H-bonded C\textsubscript{4}=O mode of PhQ and 2MNQ, downshift 21 cm\textsuperscript{-1} and 17 cm\textsuperscript{-1}, relative to the C\textsubscript{1}=O vibration, in Model 2, respectively. The vibrational frequency of the C\textsubscript{1}=O mode is hardly changed by the H-bonding to C\textsubscript{4}=O. For calculated spectra of PhQ in Model 1 and 2, the stretching of the C\textsubscript{1}=O mode occurs at 1662 cm\textsuperscript{-1}. Replacement of the tail at the 3-position with a hydrogen atom (2MNQ) leads to a 7 cm\textsuperscript{-1} upshift of the C\textsubscript{1}=O mode frequency.

In Model 3, the 6-31G (d) basis set was applied to the QM layer to reduce computational cost. The vibrational frequency of C\textsubscript{1}=O mode of PhQ occurs 1739 cm\textsuperscript{-1} (unscaled), which is slightly lower than DFT calculation of Model 1 and 2 (1741 cm\textsuperscript{-1} unscaled) obtained using the 6-31G (d). The ONIOM calculated spectra of PhQ and 2MNQ are scaled by 0.952 to compare with experiment data. After scaled, vibrational frequencies of the C\textsubscript{1}=O mode of PhQ and 2MNQ appear at 1656 and 1663 cm\textsuperscript{-1}, which are similar to the vibrational frequencies for PhQ and 2MNQ in THF (Figure 2.6). In the ONIOM calculations of PhQ, the C\textsubscript{4}=O stretching is coupled with the C\textsubscript{2}=C\textsubscript{3} stretching. The coupled vibrations occur at 1596 and 1584 cm\textsuperscript{-1}, respectively. The large downshift of the H-bonded C\textsubscript{4}=O mode indicates a strong H-bond. In the ONIOM calculations of 2MNQ, the symmetrical and antisymmetrical coupling of C\textsubscript{4}=O and C\textsubscript{2}=C\textsubscript{3} stretching appear at 1618 and 1589 cm\textsuperscript{-1}, respectively.
Table 2.3 Calculated vibrational frequencies with their assignments for neutral PhQ and 2MNQ. The calculated vibrational frequencies are scaled by 0.965 for Model 1 and 2, and 0.952 for Model 3.

<table>
<thead>
<tr>
<th></th>
<th>Model 1</th>
<th></th>
<th>Model 2</th>
<th></th>
<th>Model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PhQ</td>
<td>2MNQ</td>
<td>PhQ</td>
<td>2MNQ</td>
<td>PhQ</td>
</tr>
<tr>
<td>1662</td>
<td>1669</td>
<td>-7</td>
<td>C=O</td>
<td>-7</td>
<td>C=O</td>
</tr>
<tr>
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<td>1625</td>
<td>-17</td>
<td>C=C=O</td>
<td>-14</td>
<td>C=O</td>
</tr>
<tr>
<td>1583</td>
<td>1583</td>
<td>0</td>
<td>C=C=O</td>
<td>0</td>
<td>C=C=O</td>
</tr>
</tbody>
</table>

The subscripts a and q refer to the aromatic and quinonic part of the naphthoquinone ring; as refers to antisymmetric; and s refers to symmetric.

Table 2.4 shows the calculated vibrational frequencies for PhQ\(^{-}\) and 2MNQ\(^{-}\) obtained using ONIOM calculations. In Model 1, the most intense band appears at 1493 cm\(^{-1}\) and is due to the antisymmetric stretching of both C=O groups of PhQ\(^{-}\), with corresponding mode of 2MNQ\(^{-}\) at 1502 cm\(^{-1}\). The band near 1439 cm\(^{-1}\) is mainly due to C-C stretching of both aromatic and quinonic rings of PhQ\(^{-}\), coupling to C-H bending of the aromatic part of the PhQ\(^{-}\) ring. This mode involves very little C-O stretching and downshifts to 1435 cm\(^{-1}\) when the phytlyl tail of PhQ is replaced by a hydrogen atom.

In the presence of a Leu residue (Model 2), the band at 1495 cm\(^{-1}\) is due to the antisymmetric stretching of both C=O groups of PhQ\(^{-}\), which upshifts 10 cm\(^{-1}\) to 1505 cm\(^{-1}\) for 2MNQ\(^{-}\). Unlike the situation found for neutral quinone, the two C=O modes of PhQ\(^{-}\) or 2MNQ\(^{-}\) are coupled. The band at 1433 cm\(^{-1}\) is due to the C-C stretching of both aromatic and quinonic rings of PhQ\(^{-}\), and corresponds to the band at 1438 cm\(^{-1}\) of 2MNQ\(^{-}\).

In Model 3, the stretching of C\(_{1}\)=O mode of PhQ\(^{-}\) and 2MNQ\(^{-}\) occur at 1496 and 1510 cm\(^{-1}\), respectively. The C-H scissoring of the C\(_{2}\)-methyl group occurs at 1469 cm\(^{-1}\) for PhQ\(^{-}\), and corresponds to the band at 1477 cm\(^{-1}\) for 2MNQ\(^{-}\). The band at 1409 cm\(^{-1}\) is due to the stretching of C\(_{4}\)=O mode of PhQ\(^{-}\), coupling with C-C stretching of the aromatic ring of the PhQ\(^{-}\). The C-H bending of the truncated tail of PhQ\(^{-}\) also contributes to the band at 1409 cm\(^{-1}\). Similarly, the
band at 1418 cm\(^{-1}\) is mainly due to the stretching of C=O group of 2MNQ\(^{+}\), coupling with C-C stretching of the aromatic part of the 2MNQ\(^{+}\).

Table 2.4 Calculated vibrational frequencies with their assignments for the PhQ\(^{-}\) and 2MNQ\(^{-}\). The calculated vibrational frequencies are scaled by 0.973 for Model 1 and 2, and 0.960 for Model 3.

<table>
<thead>
<tr>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>PhQ</td>
<td>2MNQ(^{-})</td>
<td>PhQ</td>
</tr>
<tr>
<td>1517</td>
<td>1526</td>
<td>-9 C=O(_{s})</td>
</tr>
<tr>
<td>1493</td>
<td>1502</td>
<td>-9 C=O(_{as})</td>
</tr>
<tr>
<td>1439</td>
<td>1435</td>
<td>4 C=C(<em>{a}), C=C(</em>{q})</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The subscripts \(a\) and \(q\) refer to the aromatic and quinonic part of the naphthoquinone ring; \(as\) refers to asymmetric; and \(s\) refers to symmetric.

2.3.4 \(A_{1}^{\text{+}}/A_{1}^{\text{-}}\) FTIR difference spectra

Prior to TR measurements, P700\(^{+}/\)P700 FTIR DS were first obtained from static photoaccumulation experiments (at 77K). P700\(^{+}/A_{1}^{\text{+}}/\)P700A\(_{1}\) FTIR DS were obtained from TR measurements at 77K. P700\(^{+}/\)P700 FTIR DS were scaled so that the amplitude of 1716(+)/1698(-) cm\(^{-1}\) difference bands were similar. The spectrum that results from the subtraction of P700\(^{+}/\)P700 FTIR DS from P700\(^{+}/A_{1}^{\text{+}}/\)P700A\(_{1}\) FTIR DS is named as \(A_{1}^{\text{-}}/A_{1}^{\text{+}}\) FTIR DS.

Figure 2.7 shows FTIR DS obtained at 77 K for \(menB\) PS I particles with 2MNQ (A) or PhQ (B) incorporated. Spectrum 1 is a TR P700\(^{+}/A_{1}^{\text{+}}/\)P700A\(_{1}\) FTIR DS, while spectrum 3 is a static photo-accumulated P700\(^{+}/\)P700 FTIR DS. Spectrum 5 is an \(A_{1}^{\text{-}}/A_{1}^{\text{+}}\) FTIR DS that results from subtracting the P700\(^{+}/A_{1}^{\text{+}}/\)P700A\(_{1}\) FTIR DS from the P700\(^{+}/\)P700 FTIR DS. The standard deviations associated with the average of spectra obtained from TR and static photo-accumulated measurements are spectrum 2 and 4, respectively. Spectrum 6 was calculated using spectrum 2 and 4 with equation 1. The scaled factor, \(b\), is 1/1.17 for static photo-accumulated P700\(^{+}/\)P700 FTIR DS obtained using PS I particles with 2MNQ/PhQ incorporated. Figure 2.7C displays the result of subtracting the \(A_{1}^{\text{-}}/A_{1}^{\text{+}}\) FTIR DS for PS I with PhQ incorporated from the corresponding
spectrum obtained using PS I with 2MNQ incorporated. This latter spectrum will be referred to a (2MNQ-PhQ) A_1^-/A_1 FTIR DDS. The bands in the (2MNQ-PhQ) A_1^-/A_1 FTIR DDS should be primarily associated with vibrational modes of quinones in the A_1 binding site, with major contributions from protein modes being subtracted. Error bars in Figure 2.7C present an estimate of noise using equation 2. Difference bands at 1663(+)/1656(-), 1504(+)/1494(-), and 1427(+)/1415(-) cm\(^{-1}\) are above the noise associated with the (2MNQ-PhQ) A_1^-/A_1 FTIR DDS.

The amplitude of a difference band at 1504(+)/1494(-) cm\(^{-1}\) is ~3x10\(^{-4}\) (in OD units) which is three times larger than the noise level. The amplitude of a difference band at 1427(+)/1415(-) cm\(^{-1}\) is ~2x10\(^{-4}\) and the noise level is close to 10\(^{-5}\). The difference band at 1663(+)/1656(-) cm\(^{-1}\) is observed in the neutral quinone region, albeit at a slightly lower signal to noise ratio.

By directly subtracting TR P700\(^{+}\)A_1/P700A_1 spectra of PS I particles from menB mutants with PhQ or 2MNQ incorporated into the A_1 binding site, a (2MNQ-PhQ) FTIR DDS can also be obtained. A comparison of the FTIR DDS obtained using both approaches is shown in Figure 2.8. The DDS obtained by two approaches are somewhat similar. Differences are due to differences in that P700\(^{+}\)/P700 FTIR DS obtained using PS I with PhQ or 2MNQ incorporated into the A_1 binding site.

In Figure 2.7C, the 1756(+)/1749(-) cm\(^{-1}\) difference band in the A_1^-/A_1 FTIR DS was previously assigned to a 13\(^{3}\) ester carbonyl group of chlorophyll a species, most likely the A_0 chlorophyll a molecule that is in close proximity to A_1 [82]. The difference band at 1756 cm\(^{-1}\)/1749 cm\(^{-1}\) appears in the (2MNQ-PhQ) FTIR DDS obtained by both approaches (Figure 2.8), which suggests that the long-range electrostatic interaction between A_0 and A_1 is effected by the phytol tail of PhQ. The isotope-induced shift of the difference band features at 1674-1677(+) and
1666(-) cm\(^{-1}\) indicate that these bands are due to amide I protein vibrations [82]. The observed amide modes in the DDS suggest alteration of the protein backbone (possibly in the vicinity of A\(_1\), but also possibly near P700) upon quinone reduction.

The TRSS FTIR DS for menB PS I particles with PhQ or 2MNQ incorporated is similar to that obtained using regular wild-type PS I particles, indicating that PhQ or 2MNQ is incorporated into nearly all of the menB PS I RCs [83].
Figure 2.7 P700⁺A₁/P700A₁ TR FTIR DS (1) and P700⁺/P700 FTIR DS (3) collected at 77 K for *men*B PS I particles with PhQ (A) and 2MNQ (B) incorporated into the A₁ binding site. The spectra shown are the average of 10 (2MNQ) and 11 (PhQ) separated experiments. The standard deviation spectra associated with the static (spectrum 4) and TR experiments (spectrum 2) for 2MNQ (B) and PhQ (A) are shown (*dotted*). These standard deviation spectra give a true measure of the experimental variability (noise level). The spectra have been shifted vertically for clarity. The TR and static spectra were normalized so that the 1718(+)1697(−) cm⁻¹ difference band in both had similar intensity. Also shown in (A) and (B) are so called A₁⁻/A₁ FTIR DS (5) that result from subtracting spectrum 3 from spectrum 1. The noise level (spectrum 6) associated with the A₁⁻/A₁ FTIR DS is also shown. Spectrum 6 is obtained by taking the square root of spectrum 2 squared plus spectrum 4 squared. (C) 2MNQ – PhQ FTIR DDS obtained by subtracting spectrum 5 in (A) from spectrum 5 in (B). That is the A₁⁻/A₁ FTIR DS obtained for PS I particles with PhQ incorporated is subtracted from the A₁⁻/A₁ FTIR DS obtained for PS I particles with 2MNQ incorporated. The noise level is also shown in (C) (*error bars*), and is obtained by taking the square root of spectrum 6 in (B) squared plus spectrum 6 in (A) squared. The vertical bar in (C) represents an optical density (OD) difference of ~0.1x10⁻³.

Figure 2.8 Comparison of the (2MNQ-PhQ) FTIR DDS calculated from two approaches. (A) The direct subtraction of P700⁺A₁/P700A₁ spectra of *men*B PS I particles with 2MNQ or PhQ incorporated, and (B) the subtraction of A₁ / A₁ FTIR DS for *men*B PS I particles with 2MNQ or PhQ incorporated.
2.3.5  

Band assignment for quinone in the A$_1$ binding site

![Diagram of FTIR spectra for 2MNQ - PhQ in different models.](image)

Figure 2.9 Calculated and experimental DS of PhQ$^-$ and 2MNQ$^-$ (A) Experimental FTIR DDS obtained by subtracting A$_1$/A$_s$ spectrum of 2MNQ from that of PhQ (B) Calculated DS of PhQ$^-$ and 2MNQ$^-$ in the gas phase by using DFT methods (Model 1); (C) in the presence of a truncated Leu residue by using DFT methods (Model 2); and (D) by using ONIOM method (Model 3). Frequencies in B, C and D were scaled by 0.973/0.973/0.96, respectively.

The calculated and experimental (2MNQ-PhQ) DDS expanded in anion quinone spectral region (1550-1390 cm$^{-1}$) were compared and shown in Figure 2.9. Figure 2.9A shows the experimental (2MNQ-PhQ) FTIR DDS. Figure 2.9 B shows the calculated (2MNQ-PhQ) DDS obtained using Model 1. Figure 2.9C shows the calculated (2MNQ-PhQ) DDS for Model 2, a PhQ molecule in the presence of a truncated Leu residue. The ONIOM calculated DS (2MNQ-PhQ) DDS is given in Figure 2.9D. In the anion quinone spectra region, bands of 2MNQ$^-$ are positive, while bands of PhQ$^-$ are negative.
One prominent observation for the experimental and calculated DDS is the difference band at 1494 (-) /1504(+) cm\(^{-1}\). Isotope edited FTIR DS have suggested that the band at 1494 cm\(^{-1}\) in A\(_1\)/A\(_1\) FTIR DS is due to a C-H=O mode of PhQ\(^{-}\) and downshifts 12 cm\(^{-1}\), 41 cm\(^{-1}\)and 14 cm\(^{-1}\) upon deuteration, \(^{13}\)C and \(^{18}\)O isotope labeling previously [82, 87]. The experimental (2MNQ-PhQ) FTIR DDS suggests that the PhQ\(^{-}\) band at 1494 cm\(^{-1}\) upshifts 10 cm\(^{-1}\) to 1504 cm\(^{-1}\), upon replacing PhQ with 2MNQ in the A\(_1\) binding site. This result is in good agreement with calculated spectra from Model 1-3. In DFT based vibrational frequency calculations (Model 1 and 2), the band at 1494 cm\(^{-1}\) was assigned to antisymmetric stretching of two C-H=O mode of PhQ\(^{-}\). However, in Model 3, the band at 1494 cm\(^{-1}\) is mainly due to the stretching of C-H=O mode of PhQ\(^{-}\) and upshifts ~15 cm\(^{-1}\) for 2MNQ\(^{-}\) when the phytol tail is replaced by a hydrogen atom.

Another very clear feature in the DDS is the difference band at 1415/1427 cm\(^{-1}\), indicating a band of PhQ\(^{-}\) at 1415 cm\(^{-1}\) with the corresponding band of 2MNQ at 1427 cm\(^{-1}\).

In Model 1 and 2, the 1415 cm\(^{-1}\) band in A\(_1\)/A\(_1\) FTIR DS is suggested to be predominantly due to a C-H bending vibrations and weakly coupled to aromatic C-C stretching and antisymmetric C-H=O stretching vibration. The experimental DDS indicates that this mode upshifts 12 cm\(^{-1}\) to 1427 cm\(^{-1}\) for 2MNQ\(^{-}\). Upon replacement of the phytol chain of PhQ\(^{-}\) with a hydrogen, Model 1 suggests that the band at 1415 cm\(^{-1}\) downshifts 4 cm\(^{-1}\), while Model 2 suggest that the band at 1415 cm\(^{-1}\) upshifts 7 cm\(^{-1}\). However, the intensity of the difference band at 1439 (+)/1432 (-) cm\(^{-1}\) in the calculated spectrum obtained from Model 2 is too small. In Model 3, the band at 1409 cm\(^{-1}\) is mainly assigned to the C-H=O mode stretching coupled to C-H bending of the truncated tail of PhQ\(^{-}\) and upshifts 9 cm\(^{-1}\) for the corresponding mode of 2MNQ\(^{-}\) at 1418 cm\(^{-1}\). Therefore, the antisymmetric H-bond should be involved in the model for vibrational frequency calculations, and both intensities and positions of difference bands in the calculated
spectrum from Model 3 are closed to experimental results. In the calculated spectrum from Model 3, the difference band at 1427(+)/1415(-) cm\(^{-1}\), which is due to C\(_4\)=O mode of reduced quinone, downshifts \(-80\) cm\(^{-1}\) compared to C\(_1\)=O mode of reduced quinone. The ONIOM calculations suggest that asymmetric H-bond uncouples the two C=O modes of PhQ\(^{-}\).

Another feature in the experimental DDS is the difference band at 1469/1477 cm\(^{-1}\), perhaps indicating a band of PhQ\(^{-}\) at 1469 cm\(^{-1}\) with a corresponding band in 2MNQ at 1477 cm\(^{-1}\). The ONIOM calculation (Model 3) suggests the band at 1484 cm\(^{-1}\) is due to the stretching of the C\(_4\)=O group coupling to C-H bending of the methyl group at 2-position, with a corresponding band in 2MNQ\(^{-}\) at 1469 cm\(^{-1}\).

Figure 2.10 Calculated and experimental DS of PhQ and 2MNQ (A) Experimental FTIR DDS obtained by subtracting A\(_1\)/A\(_s\) spectrum of 2MNQ from that of PhQ (B) Calculated DS of PhQ and 2MNQ in the gas phase by using DFT methods (Model 1); (C) in the presence of a truncated Leu residue by using DFT methods (Model 2); and (D) by using ONIOM method (Model 3). Frequencies in B, C and D were scaled by 0.965/0.965/0.952, respectively.
Experimental (2MNQ-PhQ) DDS in the region of 1700~1550 cm$^{-1}$ is shown in the Figure 2.10. Calculated DS relative to experiments with different models are also shown in Figure 2.10. Figure 2.10 B shows the DS of PhQ and 2MNQ in gas phase by using DFT methods. Figure 2.10C shows the calculated DS of PhQ and 2MNQ in the presence of a truncated Leu residue. The ONIOM calculated DS of PhQ and 2MNQ is given in Figure 2.10D. In the neutral region of DDS, bands of 2MNQ are negative, while bands of PhQ are positive. The neutral quinone spectra is complicated and poorly understood.

A very clear feature in the experimental DDS from 1800~1550 cm$^{-1}$ is the difference band at 1663/1656 cm$^{-1}$, indicating a band of PhQ at 1656 cm$^{-1}$ with a corresponding band in 2MNQ at 1663 cm$^{-1}$. A C=O absorption band of PhQ in solvent is observed at ~1662 cm$^{-1}$. More specifically, the normal mode, which gives rise to most of the intensity of the 1662 cm$^{-1}$, band is an asymmetric stretching vibration of both C=O groups. The frequency of this normal mode upshifts to 1666 cm$^{-1}$ when the phytlyl chain is replaced by a hydrogen atom (Figure 2.6).

FTIR spectroscopy studies also suggested that the negative band near 1655 cm$^{-1}$ in the trimeric A$_1$/A$_1$ FTIR DS is little impacted by deuteration and downshifts ~26 cm$^{-1}$ upon $^{18}$O labeling [82, 87]. Therefore, a frequency of 1655 cm$^{-1}$ is due to a PhQ C=O mode that is free from H-bonding. ONIOM calculation of PhQ in the neutral state also shows that the band at 1656 cm$^{-1}$ is due to the C$_1$=O stretching of PhQ, which is free from H-bonding. In addition, ONIOM calculation suggests that frequency of 2MNQ C$_1$=O stretching in the A$_1$ binding site is 7 cm$^{-1}$ higher than that of PhQ. Therefore, the ONIOM calculations suggest that the difference band at 1663/1656 cm$^{-1}$ in the (2MNQ-PhQ) DDS is due to the C$_1$=O stretching of 2MNQ/PhQ.

ONIOM calculations of PhQ and 2MNQ show that a negative band at 1638 cm$^{-1}$ in the experimental (2MNQ-PhQ) DDS is not due to quinone. In the previous studies, it was found the
difference band at 1643/1634 cm\(^{-1}\) in the \(A_1/A_1\) FTIR DS downshifted \(8\text{--}10\text{ cm}\)^{-1} upon deuteration, suggesting it could be due to amide I mode [82].

In summary, in the anion quinone region of (2MNO-PhQ) DDS, the bands of 2MNQ at 1504 and 1428 cm\(^{-1}\) corresponds to the bands of PhQ at 1495 and 1415 cm\(^{-1}\). The comparison of these bands is taken to further support the C=O character previously assigned to the 1654, 1495, and 1415 cm\(^{-1}\) bands of PhQ in the \(A_1\) binding site. In the calculated spectrum of ONIOM calculations, the vibrational frequency of \(C_4=O\) group of PhQ downshifts \(\sim 80\text{ cm}\)^{-1} compared to the vibrational frequency of \(C_1=O\) group. This observation agrees with the notion of a strong H-bonding to semiquinone derived from ENDOR studies of \(A_1^-\). The band at 1656 cm\(^{-1}\) in the (2MNQ-PhQ) FTIR DDS is due to PhQ, with corresponding mode of 2MNQ at 1663 cm\(^{-1}\). The ONIOM calculation also predict that the antisymmetric H-bond also uncouples the two C=O modes of neutral PhQ, and \(C_4=O\) group of PhQ downshifts \(\sim 60\text{ cm}\)^{-1} compared to the vibrational frequency of \(C_1=O\) group. The close analogy between the DDS calculated for RCs reconstituted either with PhQ or with 2MNQ shows that the phytol chain of PhQ imparts no specific constraint on the geometry of the menaquinone head group in its binding site for both the neutral and reduced state.
2.3.6 *Kinetics of infrared absorption change at 77K*

Figure 2.11 Kinetics of absorption changes at 1754, 1748, 1495 and 1415 cm\(^{-1}\) obtained following 532 nm laser flash excitation of *menB* PS I particles with PhQ incorporated into the A\(_1\) binding site at 77K. Data were collected in 5 \(\mu\)s increments. The four kinetics were fitted simultaneously to a single-exponential function plus a constant. The fitted functions shown (red) are characterized by a time constant of 301 \(\mu\)s.

To gain an appreciation of the noise level achievable/required for these TRSS FTIR measurements on PS I particles, it is useful to consider the kinetics of the absorption changes at various IR frequencies. Figure 2.11 shows the time course of the absorption changes at several frequencies in the A\(_1\)/A\(_1\)FTIR DS obtained using *menB* PS I particles with PhQ incorporated into the A\(_1\) binding site at 77K. Kinetics of the absorption changes observed at 1754, 1748, 1495, and 1415 cm\(^{-1}\) were obtained following 532 nm laser flash excitation of PhQ-containing PS I particles from *menB* mutants at 77K. Data was collected in 5 \(\mu\)s increments. The initial amplitude of the 1754 cm\(^{-1}\) time-course is \(\sim 2 \times 10^{-4}\), and the noise level is close to \(10^{-5}\).

The four kinetic traces were fitted simultaneously to a single decaying exponential component plus a constant component. The fitted functions shown (red) are characterized by a
time constant of 301 µs, which is similar to previous study [82]. The kinetic at 1754 cm\(^{-1}\) contains contributions from the decay of P700\(^+\) and A\(_1\)^\(-\), while the kinetic at 1748 cm\(^{-1}\) contains contributions from the recovery of P700 and A\(_1\). The kinetic at 1495 and 1415 cm\(^{-1}\) are mostly due to the decay of PhQ\(^-\) in the A\(_1\) binding site.

Figure 2.12 Kinetics of absorption changes at 1754, 1748, 1504 and 1427 cm\(^{-1}\) obtained following 532 nm laser flash excitation of menB PS I particles with 2MNQ incorporated into the A\(_1\) binding site at 77K. Data were collected in 5 µ increments. The four kinetics were fitted simultaneously to a single-exponential function plus a constant. The fitted functions shown (red) are characterized by a time constant of 245 µs.

Figure 2.12 shows kinetics of absorption changes at 1754, 1748, 1504, and 1427 cm\(^{-1}\) obtained following 532 nm laser excitation of menB PS I particles with 2MNQ incorporated into the A\(_1\) binding site at 77K. By fitting the four kinetics in Figure 2.12 simultaneously to a single-exponential component (plus a constant component), we find that the decays are characterized by a time constant of 245 µs, which is faster than menB PS I particles with PhQ incorporated into the A\(_1\) binding site at 77K. As discussed above, the band at 1504 and 1427 cm\(^{-1}\) are due to
2MNQ, therefore this 245 ms time constant is the indicative of recombination of the \( \text{P}700^+ \text{A}_1^- \) state for \textit{menB} PS I particles with PhQ incorporated into the \( \text{A}_1 \) binding site at 77K.

The midpoint potential of 2MNQ (-420 mV vs. NHE) is +50 mV more oxidizing than that of PhQ (-470 mV vs. NHE) when measured in dimethylformamide (DMF) [92]. The midpoint potential of quinone in the \( \text{A}_1 \) binding site of PS I (\( E_m \)) can be calculated as following [93]:

\[
E_m + 700mV = 0.69(E + 387mV)
\]

Where \( E \) is the midpoint potential of quinone measured in DMF.

By employing a value of -420 mV (vs. NHE) for the midpoint potential of 2MNQ in DMF, a midpoint potential of ~723 mV was estimated for 2MNQ in the \( \text{A}_1 \) binding site, which is +35 mV more oxidizing than that of PhQ in the \( \text{A}_1 \) binding site. The change in midpoint potential of would result in increasing the rate of electron transfer between \( \text{A}_1 \) and \( \text{F}_X \).

The rate of electron transfer in protein can be described by a simplified empirical equation, which is given by [94-97]:

\[
lgk_{et} = 15 - 0.6R - 3.1(\Delta G + \lambda)^2/\lambda
\]

Where, \( R \) is the edge-to-edge distance between the two redox cofactors; \( \Delta G \) is the free energy difference between the two redox cofactors; and \( \lambda \) is the reorganization energy. As the \( \Delta G \) decreases, the rate of electron transfer increases.

If a consensus midpoint potential -688 mV was assign to \( \text{F}_X \), the free energy gap between 2MNQ and \( \text{F}_X \) in PS I is 35 mV, whereas the free energy gap between PhQ and \( \text{F}_X \) in PS I is 70mV. Since 2MNQ is positioned and oriented identically to the native PhQ in the \( \text{A}_1 \) binding site, the distance between 2MNQ and \( \text{F}_X \) should be similar to that of PhQ. The lower free energy difference and similar distance between quinone and \( \text{F}_X \) would lead to a higher rate of electron transfer from 2MNQ to \( \text{F}_X \) in PS I. Consequently, forward electron transfer from 2MNQ to \( \text{F}_X \)
would become slower and the recombination between P700 $^+$ and $F_A/F_B^-$ would become faster. At 77K, the rate of forward electron transfer is limited to the formation and the charge recombination of P700$^+$$A_1^-$ is the dominant reversible process. Therefore, the decay of the bands due to 2MNQ$^-$ should be faster than that of PhQ$^-$ in the $A_1$ binding site, which agrees with the above experimental results.

2.4 Conclusion

We have incorporated PhQ and 2MNQ back into the $A_1$ binding site of PS I particles from menB mutants. Using these PS I particles, we have produced $A_1/A_1$ FTIR DS for PhQ and 2MNQ, respectively. To identify the bands which are associated with quinone in the $A_1/A_1$ FTIR DS, DFT and ONIOM based vibrational frequency calculations are undertaken. By comparing these calculations with experimental work, we have found that the phytol tail of PhQ does not play an important role in the orientation and vibrational properties of PhQ in the $A_1$ binding site. The ONIOM based calculations show that the bands of 2MNQ at 1504 and 1428 cm$^{-1}$ corresponds to the bands of PhQ at 1495 and 1415 cm$^{-1}$ in the DDS, which are due to $C_1$=O mode and $C_4$=O mode of reduced PhQ, suggesting a single H-bond to the C=O group of PhQ$^-$. 
3 TIME-RESOLVED FTIR SPECTROSCOPY FOR STUDY OF THE A1 BINDING SITE WITH ISOTOPE LABELED QUINONE IN PHOTOSYSTEM I

Abstract

To distinguish bands associated neutral or reduced phylloquinone (PhQ) from protein bands in the A1/A1 FTIR difference spectra (DS), we have adopted the fully $^{13}$C labeled photosystem I (PS I) particles from *menB* mutants reconstituted with unlabeled PhQ. The comparison of time-resolved FTIR DS obtained for $^{13}$C labeled PS I particles with unlabeled and $^{13}$C labeled PhQ allows a clear discrimination of bands due to neutral or reduced PhQ from bands associated with protein vibrations.

Density function theory based vibrational frequency calculations are undertaken for unlabeled and $^{18}$O or $^{13}$C isotope labeled PhQ in the presence of a leucine residue. ONIOM type (QM/MM) calculations are also performed to investigate the vibrational frequencies for unlabeled and $^{18}$O or $^{13}$C isotope labeled PhQ in the A1 binding site of PS I. The calculated vibrational frequencies of both neutral and reduced PhQ in the A1 binding site suggest that the strong hydrogen bond between LeuA722 and PhQ results in the large downshift of H-bonded C4=O mode of PhQ and PhQ$^-$. 

3.1 Introduction

In type I photosynthetic reaction centers, two phylloquinone (PhQ) molecules are bound to the protein subunits and act as the secondary electron acceptor, A1. PhQ in the A1 binding site has a midpoint closed to -800 mV, and PhQ is one of the most reducing quinones in biological systems [81, 98, 99]. The unprecedented redox potential of PhQ$^-$ in the A1 binding site is in part a result of interactions between PhQ and the surrounding protein environment. The crystal structure of photosystem I (PS I) at 2.5 Å provides a detailed view of the amino acids
surrounding PhQ, and suggests several possible pigment-protein interactions [4]. Figure 2.1 shows a view of the PhQ molecule bound to Psaa (denoted A_{1-A}) and neighboring amino acids.

The ring of PhQ is π-stacked with the indole ring of TrpA697, and one of the carbonyl groups of PhQ is hydrogen (H) bonded to the peptide NH group of LeuA722. The hydroxyl side chain of SerA692 could be H-bonded to the backbone oxygen of MetA688, whereas the indole NH group of TrpA697 could be H-bonded to the hydroxyl oxygen of SerA692. MetA688 also ligates the central magnesium atom of the A_{0} chlorophyll-a. The interaction with the Trp residue was assumed to destabilize the negative charge on the semiquinone anion radical, thereby lowering its redox potential of PhQ^{-} [20]. In contrast, the H-bond withdraws electron density and stabilizes the negative charge on the semiquinone anion radical, thereby raising its redox potential PhQ^{-} [38, 100].

Fourier transfer infrared (FTIR) difference spectroscopy (DS) has contributed greatly to investigate the structural details of electron transfer cofactors in the photosynthetic complexes [15, 82-84, 87, 101, 102]. Time-resolved step-scan (TRSS) FTIR DS with 5 μs resolution was used to generate P700^{+}A_{1}/P700A_{1} FTIR DS at 77K. A_{1}/A_{1} FTIR DS was produced by subtracting the static P700^{+}/P700 FTIR DS from the time-resolved (TR) P700^{+}A_{1}/P700A_{1} FTIR DS. Though the contributions of P700 and P700^{+} were removed, the features of other components such as A_{0}, amide I and II still appear in A_{1}/A_{1} FTIR DS [82]. By changing the reduced mass, the isotope edited FTIR spectroscopy can assign a specific group from a large protein. Multiple assignments have been suggested for A_{1} and A_{1}^{-} vibrational bands with specific isotope labeling [82, 87, 102]. For PS I particles from menB mutants with ^{18}O labeled PhQ incorporated into the A_{1} binding site, the band at 1495 cm^{-1} due to an antisymmetric vibration of both C=O stretching for PhQ^− downshifts 14 cm^{-1} to 1481 cm^{-1}. Furthermore, the band at
1654 cm\(^{-1}\), which downshifts 28 cm\(^{-1}\) upon \(^{18}\)O labeling, is identified as C\(_1\)=O stretching of the non H-bonded carbonyl group [87]. FTIR spectroscopic studies confirmed the occurrence of a single H-bond to A\(_1\), which was suggested by the X-ray crystal structure [4]. Density functional theory (DFT) based vibrational frequency calculations have suggested that in the presence of a single H-bond, the C=O stretching of two carbonyl groups of PhQ could split into two modes, and the vibrational frequency of C=O stretching due to the H-bonded carbonyl group should downshift. However, the C=O mode of the H-bonded carbonyl group was not well resolved in the experiment, and only one intense difference band for PhQ\(^-\) was observed in the \(^{18}\)O-\(^{16}\)O FTIR double difference spectrum (DDS) [87].

In recent years, DFT based calculations have been undertaken on small H-bonded complexes in solution or protein environment. In previous studies, the model used for calculating vibrational modes of PhQ in the A\(_1\) binding site only includes a PhQ molecule and a truncated Leu residue (or a water molecule) [90]. However, electron paramagnetic renonuce (EPR) studies have suggested that mutations of amino acids such as TrpA697 or SerA692 in close contact with the PsA side quinone lead to change the spin density distribution of the reduced quinone [41]. Theoretical studies have also shown that the fixed \(\pi\)-stacked arrangement of PhQ\(^-\) and Trp results in lowering the redox potential of P700\(^+\)A\(_1\) \(^-\) [43]. The recent ONIOM calculation also suggests that the \(^{17}\)O anisotropic hyperfine coupling is sensitive to interactions with neighboring groups, especially TrpA697 and PheA689 [45].

ONIOM type QM/MM method can model a very large system by defending two or more layers within the structure, which are treated at different levels of accuracy. In one layer, the chemical properties of the principal species can be calculated at a quantum mechanics (QM)
level, whereas the surrounding protein environment is included in the other layer using less computationally expensive molecular mechanics (MM) methods.

To understand A₁/A₁ spectra and the interactions between quinone and protein environment, we have undertaken such QM/MM calculations for PhQ in the A₁ binding site. In our calculations, quinone and H-bonding ligand are considered at the QM level using DFT based methods, whereas surrounding residues are treated with the MM level using universal force field (UFF) [88].

In this chapter, we have used microsecond TR FTIR DS to probe the molecular properties of PhQ in the A₁ binding site at 77K. To distinguish bands associated with neutral or reduced PhQ from protein bands in TR FTIR DS, we compared the fully $^{13}$C labeled PS I particles from *menB* mutants incorporated with unlabeled and fully $^{13}$C labeled PS I particles. Assignments for specific bands in the DS are proposed from a consideration of the isotope-induced band-shifts. To complement the experimental work and aid in FTIR difference band assignment, we have used ONIOM methods to calculate FTIR spectra associated with the isotope labeled quinones occupying the A₁ binding site. In addition, by comparing with the simpler isolated H-bonded models, we are able to examine the influence of the neighboring protein matrix on the vibrational modes of neutral and reduced PhQ.

### 3.2 Materials and Methods

#### 3.2.1 Preparation of fully $^{13}$C labeled PS I particles and incorporation of PhQ into PS I particles

For uniform $^{13}$C labeling of cells, fully $^{13}$C labeled glucose (Sigma) was added to the growth medium [82]. $^{13}$C labeled trimeric PS I particles from *Synechocystis* sp. PCC. 6803 (*S6803*) and *menB* mutants were prepared as described previously [103-105]. The extent of
incorporation of the $^{13}$C labeling was estimated to be >98% by monitoring the shift of the amide II absorption band (Figure 3.2). Similar estimates were also obtained by comparing photo-accumulated P700$^+/P700$ FTIR DS obtained for unlabeled and $^{13}$C labeled PS I particles at RT and 77K. To incorporate unlabeled PhQ back into the A$_1$ binding site, fully $^{13}$C labeled PS I particles from menB mutants PS I particles were incubated in the presence of a large molar excess of unlabeled PhQ (dissolved in ethanol) as described in Chapter 2.

### 3.2.2 Photo-accumulated and microsecond time-resolved step-scan FTIR difference spectroscopy at 77K

Light induced photo-accumulation and TRSS FTIR measurements at 77K were described in Chapter 2. P700$^+/P700$ and P700$^+$/P700A$_1$ FTIR DS were recorded for both fully $^{13}$C labeled PS I particles from S6803 and fully $^{13}$C labeled PS I particles from menB mutants with unlabeled PhQ incorporated.

### 3.2.3 Estimating the noise level in double difference spectra

DS were scaled using a min-max algorithm in which the minimum/maximum y-value was set to 0.0/2.0. For each PS I sample, the TR measurements were repeated several times and then averaged. The standard deviation of the average spectra was taken as the most appropriate measure of experimental variability (noise level).

The error associated with the ($^{13}$C PhQ-$^{12}$C PhQ) FTIR DDS was calculated using equation (1),

$$\delta f = \sqrt{\delta A^2 + b^2 \cdot \delta B^2} \quad (1)$$

Where $\delta f$ is the total error for the ($^{13}$C PhQ-$^{12}$C PhQ) FTIR DDS; $\delta A$ is the standard deviation of P700$^+$/P700A$_1$ FTIR DS obtained using fully $^{13}$C PS I particles from S6803; $\delta B$ is the standard deviation of P700$^+$/P700A$_1$ FTIR DS obtained using fully $^{13}$C menB PS I particles.
with unlabeled PhQ incorporated; and $b$ is the scale factor used to normalize the difference bands in $P700^+A_1/P700A_1$ FTIR DS obtained using fully $^{13}$C labeled menB PS I particles with unlabeled PhQ incorporated.

The total error for the ($^{13}$C PhQ-$^{12}$C PhQ) TR FTIR DDS is shifted and centered on zero before being used to construct error bars.

### 3.2.4 DFT based vibrational frequency calculations

Models 1 and Model 2 (Figure 3.1) used for DFT based vibrational frequency calculations in Chapter 2 were also applied to calculate isotopic frequency shifts of PhQ or PhQ$^-$ in the gas phase. Following the geometry optimization, vibrational frequency calculations were undertaken for both isotope labeled and unlabeled PhQ/PhQ$^-$ using the B3LYP functional and the 6-31G+(d) basis set. All carbon atoms of PhQ/PhQ$^-$ were $^{13}$C isotope labeled in order to estimate the isotopic frequency shifts caused by $^{13}$C labeling. Carbonyl oxygen atoms of PhQ/PhQ$^-$ were $^{18}$O isotope labeled in order to estimate the isotopic frequency shifts caused by $^{18}$O labeling.

![Figure 3.1 Structures and numbering scheme for DFT calculations of (A) PhQ in the gas phase (Model 1) and (B) PhQ in the presence of a truncated Leu residue (Model 2).](image)
3.2.5 ONIOM type QM/MM vibrational frequency calculations

Model 3 used for ONIOM type vibrational frequency calculations in Chapter 2 were also used to predict the isotopic frequency shifts for the normal modes of PhQ and PhQ\textsuperscript{−}. Following the geometry optimization, DFT based vibrational frequency calculations (B3LYP/6-31G\textsuperscript{+} (d)) were performed on the QM layer. All carbon atoms of PhQ/PhQ\textsuperscript{−} were \textsuperscript{13}C isotope labeled in order to estimate the isotopic frequency shifts caused by \textsuperscript{13}C labeling. Carbonyl oxygen atoms of PhQ/PhQ\textsuperscript{−} were \textsuperscript{18}O isotope labeled in order to estimate the isotopic frequency shifts caused by \textsuperscript{18}O labeling. Calculated vibrational frequencies were scaled by 0.951 and 0.96 for neutral and reduced PhQ, respectively. Calculated (\textsuperscript{13}C-\textsuperscript{12}C) or (\textsuperscript{18}O-\textsuperscript{16}O) DDS have been produced by subtracting unlabeled spectrum from labeled spectrum. Vibrational frequencies due to the surrounding amino acids were cancelled and only isotopic groups of PhQ/PhQ\textsuperscript{−} were shown in the (\textsuperscript{13}C-\textsuperscript{12}C) or (\textsuperscript{18}O-\textsuperscript{16}O) DDS. All calculations were performed with the Gaussian 03 program [91].

Assignment of calculated vibrational frequencies to molecular groups is undertaken by visual identification of the molecular groups that most prominently contribute to the vibration. This visual identification is carried out using GaussView 4, in which the atomic motions associated with each of the vibrational modes can be displayed.
3.3 Results and discussions

3.3.1 IR absorption spectra of unlabeled and $^{13}$C labeled PS I particles

Figure 3.2 IR absorption spectra at 77K for unlabeled (A) and $^{13}$C labeled (B) trimeric PS I particles from menB mutants (solid) and S6803 (dotted).

Figure 3.2 (solid) shows IR absorption spectra in the 1800-1400 cm$^{-1}$ region for unlabeled (A) and $^{13}$C labeled (B) PS I particles from menB mutants. The IR absorption spectra for unlabeled and $^{13}$C labeled PS I particles from S6803 are also shown (dotted). The amide I band at 1656 cm$^{-1}$ arises mainly from the C=O stretching vibration, with minor contributions from the out-of-phase C-N stretching vibration, N-H in plane bend and CCN deformation. The amide II band at 1548 cm$^{-1}$ is due to the out-phase combination of the N-H in plane bend and the C-N stretching vibration, with smaller contributions from the C-O in plane bend and the C-C and N-C stretching vibrations [106]. Upon $^{13}$C labeling, the absorption band due to the amide I downshifts ~39 cm$^{-1}$ to 1617 cm$^{-1}$, while the absorption band due to the amide II downshifts ~14 cm$^{-1}$ to
1534 cm$^{-1}$ for PS I particles from menB mutants and S6803. These isotope shifts in Figure 3.1 indicate that these PS I particles from menB mutants and S6803 are fully $^{13}$C labeled [106].

3.3.2 The ($^{13}$C-$^{12}$C) FTIR double difference spectra

Figure 3.3 TR P700$^+$A$_1$/P700A$_1$ FTIR DS collected at 77 K for fully $^{13}$C labeled PS I particles (A solid) and fully $^{13}$C labeled PS I particles from menB mutants with unlabeled PhQ (B solid) incorporated into the A$_1$ binding site. The spectra shown are the average of 4 ($^{13}$C labeled PhQ) and 2 (unlabeled PhQ) separated experiments. The standard deviation spectra associated with the TR experiments for $^{13}$C labeled PhQ (A) and unlabeled PhQ (B) are shown (dotted). These standard deviation spectra give a true measure of the experimental variability (noise level). (C) ($^{13}$C PhQ-$^{12}$C PhQ) TR FTIR DDS obtained by subtracting spectrum B (solid) from spectrum A (solid). That is the TR P700$^+$A$_1$/P700A$_1$ FTIR DS obtained for fully $^{13}$C labeled menB PS I particles with unlabeled PhQ incorporated is subtracted from the TR P700$^+$A$_1$/P700A$_1$ FTIR DS obtained for $^{13}$C labeled PS I particles. The noise level is also shown in (C) (error bars), and is obtained by taking the square root of spectrum in (B dotted) squared plus
spectrum in (A dotted) squared. The vertical bar in (C) represents an optical density (OD) difference of ~0.1x10^{-3}.

In Figure 3.3, we present TR P700^+A_1^-/P700A_1^- FTIR DS obtained using fully $^{13}$C labeled PS I particles from menB mutants reconstituted with unlabeled ($^{12}$C) PhQ and fully $^{13}$C labeled S6803 PS I particles, and ($^{13}$C-$^{12}$C) FTIR DDS. Figure 3.3A corresponds to fully $^{13}$C labeled S6803 PS I particles. Figure 3.3B corresponds to fully $^{15}$C labeled PS I particles from menB mutants reconstituted with unlabeled ($^{12}$C) PhQ. The spectrum in Figure 3.3C is the ($^{13}$C-$^{12}$C) FTIR DDS, which is constructed by subtracting Figure 3.3B from Figure 3.3A. The standard deviations associated with time-resolved P700^+A_1^-/P700A_1^- FTIR DS obtained using fully $^{13}$C labeled PS I particles from menB mutants reconstituted with unlabeled ($^{12}$C) PhQ and fully $^{13}$C labeled S6803 PS I particles are also shown in Figure 3.3. Error bands associated with the ($^{13}$C-$^{12}$C) FTIR DDS (Figure 3.3C) present the estimated noise using equation 1.

Usually, when we use TR P700^+A_1^-/P700A_1^- FTIR DS and P700^+/P700 FTIR DS to produce A_1^-/A_1^- FTIR DDS, the feature bands of P700^+/P700 (1716(+), 1698(-), and 1687(+)) are normalized to cancel P700 and P700^+ contributions to the TR spectra. However, the difference band at 1716(+)/1698(-) cm^{-1} that is due to $^{13}$C keto C=O group of one of the Chl in P700 downshifts ~42 cm^{-1} to 1674(+)/1656(-) cm^{-1} upon $^{13}$C labeling [82, 107]. FTIR DS studies in combination with isotope labeling suggested that part of the negative band at 1654 cm^{-1} is due to the non-H bonded C_1=O mode of neutral PhQ [87]. Therefore, not only P700 but also A_1 contributes to the negative band at 1654~1656 cm^{-1} in P700^+A_1^-/P700A_1^- FTIR DS obtained using fully $^{13}$C labeled PS I particles from menB mutants reconstituted with unlabeled PhQ. To avoid losing A_1 contributions to the ($^{13}$C-$^{12}$C) FTIR DDS, we have to construct ($^{13}$C-$^{12}$C) FTIR DDS by subtracting TR P700^+A_1^-/P700A_1^- FTIR DS obtained using fully $^{13}$C labeled PS I particles from
menB mutants reconstituted with unlabeled (12C) PhQ from TR P700+A1/P700A1 FTIR DS obtained fully 13C labeled S6803 PS I particles.

We have also shown that (18O-16O) FTIR DDS, constructed by directly subtracting the TR P700+A1/P700A1 FTIR DS obtained using PS I particles with 18O labeled and unlabeled PhQ, are very similar to those constructed by subtracting A1/A1 FTIR DS obtained using PS I particles with 18O labeled and unlabeled PhQ [87].

In construction of (13C-12C) FTIR DDS, Figures 3.3 A and 3.3B were normalized so that the difference band at 1698(+)/1691(-) cm⁻¹ has a similar amplitude in both spectra. This normalization also minimizes the differences in many of the bands which are due to P700 in the spectra. The difference band at 1698(+)/1691(-) cm⁻¹ in TR P700+A1/P700A1 FTIR DS is due to the 13⁳ ester C=O group of the PsaA Chl of P700 upon 13C labeling [108].

For PhQ reconstituted PS I particles, no 3P700 features are observed in the TR FTIR DS, indicating that PhQ is incorporated into menB PS I particles at a very high level. In the (13C-12C) FTIR DDS (Figure 3.3C), several intensive bands observed at 1711 (+), 1704 (-), 1693 (+), 1677 (-), 1658(+) and 1612 (-) cm⁻¹ are larger than the estimated noise in the region from 1750–1600 cm⁻¹.

The previous FTIR DS studies have shown that, for unlabeled S6803 PS I particles, the difference band at 1754 (+)/1749 (-) cm⁻¹ downshifts 43–45 cm⁻¹ to 1711 (+)/1704 (-) cm⁻¹ upon 13C labeling, and 5–8 cm⁻¹ to 1749 (+)/1741 (-) cm⁻¹ upon deuteration in the A1/A1 FTIR DS. The isotope-induced downshifts suggests that the 1711 (+)/1704 (-) cm⁻¹ difference band is due to the 13³ ester C=O group of A0 in the A1/A1 FTIR DS [82]. Figure 3.3 A/B shows that the intensity of the difference band at 1711(+)/1704 (-) cm⁻¹ increases when unlabeled quinones are incorporated into 13C labeled PS I particles. The change of intensity may correspond to the
alteration of the long-range electrostatic effects between A1 and A0. The perturbation of A0 upon reduction of A1 was discussed previously [82].

As discussed before, for the (1^3C-1^2C) FTIR DDS, the neutral quinone spectral region (1770-1550 cm\(^{-1}\)) overlaps the downshifts of P700\(^{+}/\)P700 features caused by 1^3C labeling. This overlap makes it difficult to identify the bands in the (1^3C-1^2C) FTIR DDS. However, a positive band at 1658 cm\(^{-1}\) and a negative band at 1612 cm\(^{-1}\) are clearly observed in Figure 3.3C, which may be due to the C=O modes of PhQ. In Figure 3.3A two positive bands at 1495 and 1415 cm\(^{-1}\) decrease in intensity on 1^3C labeling, whereas two positive bands at 1451 and 1388 cm\(^{-1}\) increase in intensity. These give rise to the 1495 (+)/1451(-) cm\(^{-1}\) and 1451(+)/1388(-) cm\(^{-1}\) features in the (1^3C-1^2C) FTIR DDS. However, the noise level in Figure 3.3C in the 1530~1350 cm\(^{-1}\) region is considerable, and the spectral features mentioned are similar in amplitude to this noise level. It is therefore difficult to place any real confidence in the validity of the observed spectral features, particularly the 1495 (+)/1451(-) cm\(^{-1}\) feature. To reduce the validity of the spectral features, more experiments are needed.

3.3.3 Calculated isotope edited spectra of reduced PhQ in the A1 binding site

By comparing A1\(^{-}/\)A1 FTIR DS for PS I particles with unlabeled and 18O labeled PhQ incorporated, an (1^8O-1^6O) FTIR DDS has been produced [87]. The positive band at 1495 cm\(^{-1}\) in the A1\(^{-}/\)A1 FTIR DS was found to downshift 14 cm\(^{-1}\) and decrease in intensity upon 18O labeling. DFT based vibrational frequency calculations for isolated PhQ or PhQ with an asymmetrical H-bond indicate that the band at 1495 cm\(^{-1}\) in the A1\(^{-}/\)A1 FTIR DS is due to an antisymmetric vibration of both C=O groups of PhQ\(^{-}\). DFT based vibrational frequency calculations also predict that the band, which only downshifts 7 cm\(^{-1}\) upon 18O labeling, is due to C=C stretching
modes of both rings of PhQ, coupled to C-H bending, CH₂ wagging modes and the antisymmetric vibration of both C=O groups of PhQ⁻.

Comparisons of experimental and calculated (¹⁸O-¹⁶O) isotope edited FTIR DDS for reduced PhQ are shown in Figure 3.4. Figure 3.4A shows the experimental (¹⁸O-¹⁶O) isotope edited FTIR DDS for reduced PhQ in the region of 1530-1350 cm⁻¹, which is very similar to that produced previously [87]. Figure 3.4 B and C correspond to the vibrational mode frequency calculations for isolated PhQ (Model 1) and PhQ in the presence of a Leu residue (Model 2) based on DFT method. Figure 3.4D corresponds to the ONIOM calculation (Model 3). In Figure 3.4, bands of ¹⁶O PhQ⁻ are all negative, whereas bands of ¹⁸O PhQ⁻ are all positive. All calculated spectra in Figure 3.4 agree with the experimental results that a band at 1495 cm⁻¹ downshifts ~14 cm⁻¹ upon ¹⁸O labeling. However, the difference band at 1415 (+)/1409 (-) cm⁻¹ observed in Figure 3.4A is ~27 and 22 cm⁻¹ lower than the predictions of Model 1 and 2, respectively, but only ~10 cm⁻¹ higher than the prediction of Model 3.

The ONIOM calculated IR DS in Figure 3.4D is closed to the experimental result (Figure 3.4A). In the ONIOM calculation (Model 3), upon quinone reduction, the C₁=O stretching are coupled with C₂=O stretching at 1517 cm⁻¹ (asymmetrically) and 1495 cm⁻¹ (symmetrically). The intensive band at 1495 cm⁻¹, which is mainly due to C₁=O stretching, downshifts 13 cm⁻¹ to 1482 cm⁻¹ upon ¹⁸O labeling. The band near 1409 cm⁻¹ which is mainly due to C₄=O stretching downshifts 11 cm⁻¹ to 1398 cm⁻¹ upon ¹⁸O labeling. There are actually two bands, 1415 and 1409 cm⁻¹, which are both due to quite similar modes.
The $^{13}$C isotope edited FTIR DS is more complicated. Not only the bands due to carbonyl groups, but also all bands that correspond to carbon atoms would downshift. The noise level indicates that the spectral variability of experimental ($^{13}$C-$^{12}$C) FTIR DDS in the region from 1530-1350 cm$^{-1}$ is large and more experimental data are required to reduce noise. However, the calculated ($^{13}$C-$^{12}$C) FTIR DDS can predicate band shifts due to $^{13}$C labeled PhQ and assess the band assignments in the $A_1$/$A_1$ FTIR DS. For the calculated ($^{13}$C-$^{12}$C) FTIR DDS in Figure 3.5, bands of unlabeled ($^{12}$C) PhQ$^-$ are negative, while bands of $^{13}$C labeled PhQ$^-$ are positive.

There are two predominate difference bands in Figure 3.5B. The calculated spectrum of Model 1 suggests that the stretching of both C=O groups of PhQ$^-$ couples antisymmetrically at
1495 cm\(^{-1}\) and downshifts 47 cm\(^{-1}\) to 1448 cm\(^{-1}\) upon \(^{13}\)C labeling. The band at 1441 cm\(^{-1}\), which downshifts 36 cm\(^{-1}\) to 1405 cm\(^{-1}\), is due to the antisymmetric C\(\equiv\)O mode of PhQ\(^{-}\) coupled to the C-C mode of quinonic and aromatic ring, and C-H wagging on the aromatic ring. In Figure\(3.5\)C the intensive band at 1497 cm\(^{-1}\), which downshifts 42 cm\(^{-1}\) to 1455 cm\(^{-1}\) upon \(^{13}\)C labeling, comes from the antisymmetric C\(\equiv\)O group of PhQ\(^{-}\). The band at 1437 cm\(^{-1}\) in Figure\(3.5\)C is due to the same mode at 1441 cm\(^{-1}\) in Figure\(3.5\)B, and downshifts 34 cm\(^{-1}\) upon \(^{13}\)C labeling. For reduced PhQ, the predictions of Model 2 are very similar to Model 1, indicating that the H-bond between the backbone NH group of a Leu residue and reduced PhQ is weak. However, the advanced pulse EPR and ENDOR studies suggested the presence of a strong H-bond to the reduced quinone in the \(A_1\) binding site [69].

As shown in Figure\(3.5D\), the ONIOM calculations (Model 3) suggest that a band at 1517 cm\(^{-1}\) is due to the C\(_1\)\(\equiv\)O mode coupled with C\(_2\)=C\(_3\) mode. In Model 3, the negative band at 1495 cm\(^{-1}\) downshifts 21 cm\(^{-1}\) to 1474 cm\(^{-1}\) with decreasing intensity upon \(^{13}\)C labeling (Figure\(3.5D\)). The positive band at 1450 cm\(^{-1}\) is assigned to the antisymmetric coupling of C\(_1\)\(\equiv\)O and C\(_4\)\(\equiv\)O groups of reduced PhQ by Model 3. The negative band near 1409 cm\(^{-1}\) downshifts 29 cm\(^{-1}\) to 1380 cm\(^{-1}\) upon \(^{13}\)C labeling, and is assigned to the C\(_4\)\(\equiv\)O mode in the Model 3. The large downshift of C\(_4\)\(\equiv\)O mode of PhQ\(^{-}\) suggests a strong H-bond between the backbone NH group of a Leu residue and reduced PhQ, which confirms the previous advanced pulse EPR and ENDOR studies.
Figure 3.5 Experimental (A) and calculated ($^{13}$C-$^{12}$C) isotope edited FTIR DDS for reduced PhQ. (B) DFT calculation for isolated reduced PhQ in the gas phase. (C) DFT calculation for PhQ in the presence of a Leu residue. (D) ONIOM calculations for reduced PhQ in the A$_1$ binding site. Calculated normal mode frequencies were scaled by 0.974, 0.974 and 0.96, respectively.

### 3.3.4 Calculated isotope edited spectra of neutral PhQ in the A$_1$ binding site

The identification of bands associated with neutral PhQ in the TR FTIR DS is still questionable, because the C=O modes of PhQ occur in the region of 1660-1650 cm$^{-1}$, where the amide I also has huge absorption. However, calculated spectra can help us to identify the bands due to neutral PhQ in the A$_1$ binding site.

In the resulting isotope edited FTIR DDS of neutral PhQ, vibrational bands of unlabeled PhQ appear as positive signals, while vibrational bands of labeled PhQ appear as negative signals. Figures 3.6A and 3.7A show the experimental ($^{18}$O-$^{16}$O) and ($^{13}$C-$^{12}$C) FTIR DDS in the
neutral quinone spectral region (1700 -1550 cm \(^{-1}\)). Models 1-3 are also used to assign spectra featured to vibrational modes of neutral PhQ in Figure 3.6 and 3.7.

![Neutral Quinone Spectral Region](image)

**Figure 3.6** Experimental (A) and calculated \(^{18}\text{O}^{16}\text{O}\) isotope edited FTIR DDS for neutral PhQ. (B) DFT calculation for isolated neutral PhQ in the gas phase. (C) DFT calculation for PhQ in the presence of a Leu residue. (D) ONIOM calculations for neutral PhQ in the A\(_1\) binding site. Calculated normal mode frequencies were scaled by 0.963, 0.963 and 0.953, respectively.

Figure 3.6A and 3.7A show that the band at 1658 cm\(^{-1}\) downshifts 30/46 cm\(^{-1}\) to 1628/1612 cm\(^{-1}\) upon \(^{18}\text{O}\) and \(^{13}\text{C}\) labeling, respectively. This band is assigned to antisymmetric C=O groups of neutral PhQ in Model 1. In Model 1, the band at 1605 cm\(^{-1}\), which is due to \(\text{C}_2=\text{C}_3\) stretching, downshifts 6/57 cm\(^{-1}\) to 1599/1548 cm\(^{-1}\) upon \(^{18}\text{O}\) and \(^{13}\text{C}\) labeling, respectively. Model 1 also suggests that the band at 1580 cm\(^{-1}\), which is due to \(\text{C}=\text{C}\) mode of aromatic ring, downshifts 5/56 cm\(^{-1}\) to 1575/1544 cm\(^{-1}\) upon \(^{18}\text{O}\) and \(^{13}\text{C}\) labeling, respectively.
However, the band separation of two C=O modes caused by the H-bond is not observed in Figure 3.6A.

From DFT based vibrational frequency calculations for PhQ with the C₄=O group H-bonded to the backbone of NH of a Leu residue (Model 2), the band at 1658 cm⁻¹ is expected for a non H-bonded C₁=O mode of PhQ, and downshifts 28/42 cm⁻¹ to 1630/1616 cm⁻¹ upon ¹⁸O and ¹³C labeling, respectively. The band at 1637 cm⁻¹ comes from the H-bonded C₄=O group of PhQ and downshifts 23/43 cm⁻¹ upon ¹⁸O and ¹³C labeling, respectively. Figure 3.6C also shows that the band at 1605 cm⁻¹, which is due to C₂=C₃ stretching, downshifts 6 cm⁻¹ to 1599 upon ¹⁸O labeling. The band at 1575 cm⁻¹, which is due to C=C mode of aromatic ring, downshifts 4 cm⁻¹ to 1571 cm⁻¹ upon ¹⁸O labeling.

The ONIOM calculations of the A₁ binding site are more sophisticated and agree with experiment. The band at 1658 cm⁻¹ downshifts 28/41 cm⁻¹ to 1630/1617 cm⁻¹ upon ¹⁸O and ¹³C labeling, and is assigned to the non H-bonded C₁=O group of PhQ in Model 3. Model 3 suggests that the stretching of C₄=O group is strongly coupled to the C₂=C₃ stretching. The band at 1597 cm⁻¹ comes from the symmetric coupling of the C₄=O mode and C₂=C₃ mode, while 1586 cm⁻¹ comes from the antisymmetric coupling of the C₄=O mode and C₂=C₃ mode. The stretching of C₄=O group downshifts to 1539/1546 cm⁻¹ upon ¹⁸O and ¹³C labeling, respectively. In Model 3, the non H-bonded C₁=O mode of PhQ absorbs ~60 cm⁻¹ higher in frequency than the H-bonded C₄=O mode of PhQ. This prediction of Model 3 is much larger than that of Model 2, in which the separation of two C=O modes is only ~30 cm⁻¹, but very close to the observation for PhQ in Figure 3.6A and 3.7A. In addition, the non H-bonded C₁=O mode also absorbs ~80 cm⁻¹ higher in frequency than the H-bonded C₄=O mode of reduced PhQ. The two C=O modes are identified at 1660 and 1628 cm⁻¹ for neutral ubiquinone in the Qₐ₋/Qₐ FTIR DS, and the separations of the
two C=O modes are only ~32 cm\(^{-1}\) [109]. Therefore, the ONIOM calculated prediction could indicate that PhQ in the A\(_1\) binding site is more antisymmetrically H-bonded than ubiquinone in the Q\(_A\) binding site.

![Figure 3.7 Experimental (A) and calculated (\(^{13}\)C\(^{12}\)C) isotope edited FTIR DDS for neutral PhQ. (B) DFT calculation for isolated neutral PhQ in the gas phase. (C) DFT calculation for PhQ in the presence of a Leu residue. (D) ONIOM calculations for neutral PhQ in the A\(_1\) binding site. Calculated normal mode frequencies were scaled by 0.963, 0.963 and 0.953, respectively.]

3.4 Conclusion

We have incorporated unlabeled PhQ back into the A\(_1\) binding site of fully \(^{13}\)C labeled PS I particles from \textit{menB} mutants. Coupling this experimental work with vibrational frequency calculations, some bands associated with PhQ or PhQ\(^{-}\) in the FTIR DDS are identified. This work further supports the band assignments obtained from previous studies. The band at 1654
cm$^{-1}$, which downshifts 28 and 46 cm$^{-1}$ upon $^{18}$O and $^{13}$C labeling, is identified as C=O mode of the non H-bonded carbonyl group by OM/MM (ONIOM type) calculation. However, the assignment of 1495 cm$^{-1}$ from ONIOM calculation is different from DFT based calculations. In ONIOM calculation, the band at 1495 cm$^{-1}$ is mainly due to C=O mode of reduced PhQ. ONIOM calculations also suggest that the strong H-bond between PhQ and LeuA722 leads to C=O mode of the H-bonded carbonyl group downshifts ~60 and 80 cm$^{-1}$ for neutral and reduced PhQ, respectively.
ON THE NATURE OF THE HYDROGEN BONDS TO NEUTRAL UBQINONE IN THE QA BINDING SITE IN PURPLE BACTERIAL PHOTOSYNTHETIC REACTION CENTERS

Abstract

The nature of hydrogen bonding to pigments in protein complexes is currently a topic of some debate. The debate centers on whether hydrogen bonds can be understood on purely electrostatic grounds, or whether they need to be considered quantum mechanically. This distinction is of current relevance, primarily because of the application of QM/MM computational methods to the study of biological problems. To address this problem we have used QM/MM methods to study the neutral state of the hydrogen bonded ubiquinone molecule termed QA that functions as an electron transfer cofactor in purple bacterial photosynthetic reaction centers. In these calculations we have treated the hydrogen bonding amino acids either quantum mechanically or using molecular mechanics methods. As a specific metric for comparing the different computational methods isotope edited FTIR difference spectra are calculated. The calculated spectra are in remarkable agreement with experimental spectra, and it is found that the calculated spectra are very similar when hydrogen bonding amino acids are treated using either QM or MM methods. The latter result suggests that hydrogen bonding to neutral ubiquinone in purple bacterial reaction centers can be considered in purely electrostatic terms, which is contrary to the widely held belief that the hydrogen bonding amino acids should be treated quantum mechanically. Natural bond orbital analysis is used to further verify that the hydrogen bonds are predominantly electrostatic in nature. Calculated bond lengths and vibrational frequencies of the N-H groups involved in hydrogen bonding are used to estimate the relative strengths of the hydrogen bonds to either UQ carbonyl group.
4.1 Introduction

Quinones play an important role in biological electron and proton transfer processes that occur in both respiration and photosynthesis [110]. In type II photosynthetic reaction centers two quinone molecules are bound to the protein subunits, and act as terminal electron acceptors [51]. The two quinones are often termed QA and QB. In this manuscript, however, we will refer to the quinone binding site as QA and QB.

In Rhodobacter (Rb.) sphaeroides purple bacterial reaction centers (PBRCs), ubiquinone-10 (UQ10) molecules occupy both the QA and QB binding sites. Although the UQ10 molecules occupying the QA and QB binding sites are identical, their functions are very different. The QA ubiquinone (UQ) is an intermediary cofactor involved in transferring electrons from bacteriopheophytin to QB [111], while the QB quinone couples proton and electron transfer processes [112].

The different functionalities of the QA and QB ubiquinones must arise from different pigment protein interactions that occur in each of the binding sites. Thus the study of the properties of the quinones that occupy the QA and QB binding sites will allow an assessment of how pigment protein interactions modulate cofactor function.

Fourier transform infrared (FTIR) difference spectroscopy has been widely used to study both the neutral and radical states of cofactors in a range of protein complexes [113, 114]. In particular light induced FTIR difference spectroscopy has been widely used to study both the neutral and reduced states of quinones in PBRCs [115]. Although QA^-/QA and QB^-/QB FTIR difference spectra (DS) have been obtained, they are difficult to interpret because many bands not associated with the quinones also contributed to the spectra. Reconstitution of PBRCs with
isotope labeled quinones, however, has allowed some separation of the contributions of the quinones from those of the protein in \( Q_A^- / Q_A \) and \( Q_B^- / Q_B \) FTIR DS [115].

In this manuscript we focus specifically on the ubiquinone (UQ) molecule that occupies the \( Q_A \) binding site in \textit{Rb. sphaeroides} PBRCs. Although experimental \( Q_A^- / Q_A \) FTIR DS have been obtained under many sets of conditions, few computational studies aimed at modeling the experimental FTIR DS have been undertaken.

Calculations aimed at modeling the vibrational properties of quinones in the \( Q_A \) binding site must account for the protein environment. Quantum mechanical (QM) calculations of such a large molecular system are unfeasible. Methods have been developed, however, that allow one to separate the molecular system into distinct layers that can be treated at different levels of theory. In one layer the chemical properties of the principle species of interest (the pigment or cofactor) can be calculated using “high-level” QM methods. The surrounding protein environment is included but treated using computationally less expensive molecular mechanics (MM) methods [116].

Previously, we have undertaken QM:MM calculations for neutral UQ in the \( Q_A \) binding site using the ONIOM method [117]. ONIOM is an acronym for: our Own N-layered Integrated molecular Orbital + Molecular mechanics package [60, 118]. In these calculations only UQ was treated at the QM level, while all amino acids were treated using MM methods. Thus any QM effects of H–bonding are not considered.

Computational modeling of hydrogen bonding is a subject of much current interest [119, 120], and it is still a matter of debate as to whether H-bonds should be treated purely electrostatically or quantum mechanically [121]. In computational studies of \( UQ^- \) (singly reduced UQ) in the \( Q_A \) binding site [50, 122], it is common to consider H–bonding amino acids
at the QM level of theory. This seems appropriate since EPR data suggests the presence of spin density on (one of the) H-bonding amino acid side-chains. Little work has been undertaken to show/verify that such involved QM calculations are required for proper simulation of the EPR parameters of UQ$^-$ in the QA binding site, however.

Unlike the case for UQ$^-$, for neutral UQ in the QA binding site there is no experimental evidence indicating whether H bonding amino acids should be treated using QM or MM methods. It is therefore necessary to compare the results from calculations in which amino acids that H-bond to neutral UQ in the QA binding site are treated using both QM and MM methods.

Here we extend upon our previous QM: MM (ONIOM) calculations by including several of the amino acids surrounding the UQ in the QM part of the calculation. In this more detailed computational approach we find that the calculated isotope edited FTIR difference spectra are similar to that obtained previously, where hydrogen bonding amino acids were treated using MM methods. This suggests that hydrogen bonding to the UQ molecule in the QA binding site is well modeled without the need for a detailed QM consideration of surrounding amino acids. The H–bonding amino acids can be effectively considered using MM methods, considerably decreasing the computational cost. Following on from this natural bond orbital analysis is used to estimate to what extent the H-bonds to UQ can be considered as electrostatic. Finally, the relative strength of H-bonds to UQ in the QA binding site is calculated.

4.2 Materials and Methods

4.2.1 Model Construction

All molecular models were constructed using the crystal structure of Rb. sphaeroides PBRCs at 2.2 Å resolutions [25] (PDB file 1AIJ). The initially constructed model includes all atoms within 10 Å of both UQ carbonyl oxygen atoms. The model constructed contains 49
amino acids. Hydrogen atoms are added (using Gaussview 4.0) and then optimized (using an appropriate level of theory) with all heavy atoms fixed. The protonation state of amino acid side chains (at neutral pH and room temperature), particularly Arg and Glu residues, was checked and adjusted (if necessary) prior to calculation.

4.2.2 Calculations

All calculations described here were undertaken using Gaussian03 software [91]. In all calculations the atoms of the protein backbone were fixed in position. Calculations were undertaken with the amino acid side chains both free and fixed. The UQ hydrocarbon tail was modeled as a single prenyl unit. Inclusion of further units did not alter the calculated spectra (not shown).

In previous [117] ONIOM geometry optimizations of the QA binding site, we treated only the ubiquinone molecule at the QM level, using the B3LYP functional and the 6-31G+(d) basis set. The molecular mechanics (MM) part of the ONIOM calculation was undertaken using AMBER (Assisted Model Building with Energy Refinement) [123], and only atoms of the protein backbone were constrained. Here we treat the UQ, the hydrogen bonding amino acids (AlaM260 and HisM219), the non-heme iron atom and its ligands (HisM266, HisL190, HisM230 and GluM234) (see Figure 4.1) at the QM level, while the MM layer atoms are treated using either the UFF (Universal Force Field [88]) or AMBER force fields. Atomic charges are calculated using both Mullikan population analysis (MPA) [124] and natural population analysis (NPA) [125].

For some calculations, following geometry optimization, natural bond orbital analysis [126, 127] was undertaken within the Gaussian03 software environment. All atoms in the QM layer are included in this analysis. The charge distribution from the MM layer is also included.
4.2.3 IR Spectral Simulation

Following geometry optimization of the protein-quinone system, all atoms in the model system (QM layer) are included in vibrational frequency calculations at the same level as that considered in geometry optimization. Calculated normal mode vibrational frequencies were obtained for unlabeled and isotope labeled UQ, and isotope edited double difference spectra are constructed, as described previously [117]. In the isotope edited double difference spectra nearly all of the calculated amino acid vibrational modes subtract out, and the calculated spectra are directly comparable to experimental FTIR isotope edited double difference spectra. The calculated spectra are scaled by a factor that is estimated by comparing the frequencies of bands in the calculated and experimental spectra.

4.2.4 Harmonic Normal Mode Vibrational Frequency Assessment

Assignment of calculated vibrational frequencies to molecular groups is based on a consideration of the calculated atomic displacements (in Cartesian coordinates) associated with the normal modes. These atomic displacements can be animated using software (GaussView), and the molecular groups that most prominently contribute to the normal modes can be assessed visually. In addition potential energy distributions of the normal modes of unlabeled and isotope labeled UQ are calculated using GAR2PED [128].

4.3 Results

4.3.1 UQ structure and numbering

Figure 4.1 shows the structure and numbering scheme of the heavy atoms of the model system (atoms treated at the QM level) used in ONIOM calculations. The hydrogen atoms
involved in H–bonding are also shown. There are 99 atoms (including hydrogen atoms) treated at the QM level in this model system.

Figure 4.1 Ball and bond structural model and numbering scheme of the heavy atoms comprising the QM layer in ONIOM calculations. The hydrogen atoms of the H bonding amino acids are also shown (atoms 23 and 49). Blue/red/grey/white/purple colored balls represent nitrogen/oxygen/carbon/hydrogen/iron atoms, respectively.
Table 4.1 Details and parameters used in the different ONIOM calculations.

<table>
<thead>
<tr>
<th># Atoms</th>
<th>Fixed atoms</th>
<th>ONIOM Calculation</th>
<th>Charge Model system</th>
<th>Charge UQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model system</td>
<td>Protein backbone and Fe</td>
<td>6-31+G(d):Amber, 1,1, 0.1, 0.1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>31</td>
<td>Protein backbone and Fe</td>
<td>6-31+G(d):UFF, 1,1, 0.1, 0.1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>99</td>
<td>All heavy atoms except UQ</td>
<td>6-31G(d)/LANL2DZ:UFF, 0.2, 0.4, 0.4</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>99</td>
<td>All heavy atoms except UQ</td>
<td>6-31G(d)/LANL2DZ:UFF, 1,1, 1.5, 1.5</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>99</td>
<td>Protein backbone</td>
<td>6-31G(d)/LANL2DZ:UFF, 1,1, 1.5, 1.5</td>
<td>1</td>
</tr>
</tbody>
</table>

For the DFT part of the ONIOM calculations the B3LYP functional was used. The atomic charges (in units of e) listed were calculated using NPA. The “real system” is defined as all of the atoms in both the QM and MM layers. The “model system” is defined as only the QM layer atoms. The series of six numbers in the ONIOM calculation column refer to the charge and multiplicity of the real and model systems. For example, the series of numbers (1,1, 1.5, 1.5) in calculations 4 and 5 refer to the charge and multiplicity of: 1/ the real system at the MM level of theory (1,1); 2/ the model system at the QM level of theory (1,5); 3/ the model system at the MM level of theory (1,5).

4.3.2 Calculations Undertaken

In previous ONIOM calculations [ONIOM (B3LYP/6-31G+ (d): AMBER)] only the UQ molecule was treated using QM methods (31 atoms). Electronic embedding [118, 129, 130] was employed. This procedure is referred to as calculation 1 in Table 4.1.

To test if the type of MM layer calculation employed could impact the calculated results we have undertaken an ONIOM (B3LYP/6-31G+ (d): UFF) calculation (MM layer charges generated using the qEq method). This is calculation 2 in Table 4.1. In calculation 2, as in calculation 1, only the UQ molecule (31 atoms) is treated at the QM level.
To further develop our computational approach we treat UQ and several of the surrounding amino acids, as well as Fe, at the QM level. There are 99 atoms (including hydrogen atoms) in the model system (Figure 4.1). For this larger model system all atoms except Fe were treated using the 6-31G(d) basis set, and the Fe atom is treated separately using the LANL2DZ basis set [131]. This basis set treats the inert core electrons (of transition metals) simply as an electrostatic potential. All heavy atoms, except those of UQ, are fixed in position, and the total charge of the 99 atoms in the QM level is set to zero (calculation 3 in Table 4.1). The high spin (S=2) state of Fe is also chosen [132, 133] (multiplicity of the model system is 4).

In calculation 3 upon optimization, the NPA calculated charge on the UQ atoms is -0.874. A similar result was obtained using MPA (not shown). For the model system with a multiplicity of 2, with Fe treated using the 6-31G (d) basis set, the NPA calculated charge on the UQ is -0.865 (calculation 3A in Table 4.4). In calculations 3 and 3A UQ has significant anionic character.

Calculation 4 is similar to calculation 3 except that the total charge of the 99 atoms in the model system is set to +1. This setting is appropriate because Fe has a charge of +2 and GluM234 has a charge of -1. In calculation 4, as in calculation 3, all heavy atoms, except those of UQ, are constrained. The Fe atom is in the high spin state and is treated using the LANL2DZ basis set. In calculation 4, upon optimization, the NPA calculated charge on the UQ atoms is +0.054 (Table 4.1). If the Fe atom in the high spin/low spin state is treated using the 6-31G (d) basis set the charge on the UQ atoms is calculated to be +0.055/+0.057 (Calculation 4A/4B in Table 4.4). So the precise spin state of Fe and the use of the LANL2DZ basis set do not appear to be important, at least in terms of the NPA calculated charge on the atoms of UQ. There is some discrepancy in the MPA calculated charge on UQ in calculations 4 and 4A (Table 4.4). It
is well known that MPA calculated charges can depend on the basis set used [125]. This basis set dependence is usually less pronounced for NPA calculated charges, however.

Calculation 5 is the same as 4, except now the amino acid side chains are not constrained. Calculation 5 is computationally very expensive compared to calculation 4.

**4.3.3 Calculated Geometric Parameters**

Table 4.2 compares geometric parameters obtained from calculations 1-5 with that from various X-ray structures. For calculation 3, the C=O bonds are considerably longer than that found in the other calculations. This is consistent with the anionic character of UQ in calculation 3.
Table 4.2 Comparison of calculated and experimental bond lengths and angles

<table>
<thead>
<tr>
<th>Calculation</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>X-ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>C(_1)=O</td>
<td>1.227</td>
<td>1.225</td>
<td>1.272</td>
<td>1.229</td>
<td>1.229</td>
<td></td>
</tr>
<tr>
<td>C(_4)=O</td>
<td>1.238</td>
<td>1.235</td>
<td>1.282</td>
<td>1.238</td>
<td>1.238</td>
<td></td>
</tr>
<tr>
<td>Ala H-O(_1)</td>
<td>1.89</td>
<td>2.29</td>
<td>1.80</td>
<td>1.99</td>
<td>2.02</td>
<td>1.94±0.11</td>
</tr>
<tr>
<td>Ala N-O(_1)</td>
<td>2.84</td>
<td>3.16</td>
<td>2.81</td>
<td>2.90</td>
<td>2.93</td>
<td>2.79±0.09</td>
</tr>
<tr>
<td>∠Ala N-H-O(_1)</td>
<td>153</td>
<td>140</td>
<td>165</td>
<td>148</td>
<td>147</td>
<td>147±8</td>
</tr>
<tr>
<td>His H-O(_4)</td>
<td>1.85</td>
<td>2.37</td>
<td>1.68</td>
<td>1.89</td>
<td>1.99</td>
<td>1.79±0.11</td>
</tr>
<tr>
<td>His N-O(_4)</td>
<td>2.87</td>
<td>3.36</td>
<td>2.72</td>
<td>2.90</td>
<td>2.99</td>
<td>2.80±0.15</td>
</tr>
<tr>
<td>∠HisN-H-O(_4)</td>
<td>176</td>
<td>159</td>
<td>174</td>
<td>169</td>
<td>166</td>
<td>170±6</td>
</tr>
</tbody>
</table>

The X-ray data are averages obtained from several crystal structures [122, 134].
Figure 4.2 Experimental (red) and ONIOM calculated (black) $Q_{\lambda}/Q_{\lambda}$ isotope edited DDS for neutral UQ. UQ has been specifically (A) $^{13}C_1$, (B) $^{13}C_4$, (C) $^{13}C_4^{18}O$, (D) $^{13}C$, (E) $^{13}C^{18}O$ and (F) $^{18}O$ isotope labeled. For $^{18}O$ labeling, only the carbonyl oxygen atoms are labeled. Experimental spectra are reprinted with permission from references [47] and [109]. In calculations 1-5 spectra have been scaled by 0.9718, 0.9634, 1.0842, 0.9638 and 0.9637, respectively.
In all calculations, the C$_1$=O bond is shorter than the C$_4$=O bond. This may be a reflection of an asymmetry in the H–bonding to the UQ carbonyl groups. In calculations 1, 4 and 5 the calculated geometric parameters are in excellent agreement with that derived from a consideration of several X-ray structures. In calculation 2, however, the H–bonds to the UQ C=O groups are considerably longer than that found in calculations 1, 4 and 5. The H–bond angles are also considerably altered in calculation 2. It appears that following geometry optimization in calculation 2, the UQ is somewhat rotated in the QA binding site. Calculation 2 poorly models the crystal structure data, and is not in keeping with calculations 1, 4 and 5.

4.3.4 Calculated Isotope Edited Difference Spectra.

Figure 4.2 shows ONIOM calculated (black) isotope edited double difference spectra for neutral UQ in the QA binding site for all five calculations. Experimental spectra are also shown (red). The spectra in Figure 4.2A-F are for six different types of specific UQ isotope labeling.

Calculations 1 and 2 yield virtually identical isotope edited difference spectra. Thus the type of MM force field employed (AMBER or UFF) in the ONIOM calculations (with only UQ treated at the QM level) is not important, at least in terms of simulating isotope edited FTIR difference spectra. This is in spite of the differences in the geometric parameters found in calculations 1 and 2 (Table 4.2).

The spectra obtained from calculation 3 do not resemble the experimental spectra. The bands in the spectra from calculation 3 are roughly 180 cm$^{-1}$ lower in frequency than the bands in the spectra for the other calculations (note the differing frequency scaling factor for calculation 3). Such a large downshift is expected for a UQ anion radical, so the spectra obtained in calculation 3 also indicate a considerable negative charge on UQ.
The spectra derived in calculation 4 and 5 are very similar to that from calculations 1 and 2. Thus the additional computational expense for calculations 4 and 5 (especially for calculation 5) is unnecessary. The spectra obtained from calculation 4 are virtually identical to that obtained from calculations for both high and low spin model systems with Fe treated using the 6-31G(d) basis set (not show, but see calculation 4, 4A and 4B in Table 4.4).

4.4 Discussion

All of the calculated spectra presented here relate to the neutral state of UQ in the QA binding site. It is possible to undertake corresponding calculations for UQ\(^-\), and compare the conclusions derived from these calculations with conclusions derived from calculations that simulate the EPR properties of UQ\(^-\). Such calculations and comparisons are currently underway in our lab.

4.4.1 Assignment of Bands in the Calculated and Experimental Spectra

The positive bands in the isotope edited difference spectra in Figure 4.2 are due to vibrational modes of unlabeled UQ, while the negative bands are due to isotope labeled UQ. Figure 4.2 demonstrates that the spectra obtained for calculations 1 and 2 are very similar, the main difference being a slight shift in a positive band near 1626 cm\(^{-1}\) in calculation 1, to ~1630 cm\(^{-1}\) in calculation 2. In calculations 4 and 5 this band is upshifted further to ~1633 cm\(^{-1}\). This band frequency shift between calculations is most easily seen in Figure 4.2E, where positive bands due to modes of unlabeled UQ do not overlap with negative bands due to modes of the \(^{13}\)C\(^{18}\)O labeled UQ (\(^{13}\)C\(^{18}\)O isotope induced frequency shifts are in excess of 65/80 cm\(^{-1}\) for C=C/C=O modes, respectively).

Below we will refer to positive and negative difference bands using (+) and (-) symbols, respectively. The differences in the spectra for calculations 1, 2, 4 and 5 are best visualized in
Figure 4.2C and F, where a 1630(-)/1626(+) cm\(^{-1}\) feature in calculation 1 becomes a 1630(+)/1626(-) cm\(^{-1}\) feature in calculation 2 and the 1633(+)/1626(-) cm\(^{-1}\) feature in calculations 4 and 5. The potential energy distributions (PEDs) of the normal modes that contribute to the bands in the calculated spectra were presented previously for calculation 1 [117] and very similar results are obtained for calculation 2, 4 and 5. For calculation 1, the positive bands at ~1626 and 1663 cm\(^{-1}\) are due predominantly to C\(_4\)=O and C\(_1\)=O vibrations of unlabeled UQ, respectively [117]. In Figure 4.2C (\(^{13}\)C\(_4\)^{18}\)O labeling) the C\(_1\)=O mode at 1663 cm\(^{-1}\) downshifts 33 cm\(^{-1}\) to 1630 cm\(^{-1}\), while the C\(_4\)=O mode at 1626 cm\(^{-1}\) downshifts 78 cm\(^{-1}\) to 1548 cm\(^{-1}\). These shifts give rise to the 1630(-)/1626(+) cm\(^{-1}\) feature in the spectra for calculation 1 in Figure 4.2C. For calculation 2 the C\(_1\)=O mode is at 1661 cm\(^{-1}\) and downshifts 35 cm\(^{-1}\) to 1626 cm\(^{-1}\), while the C\(_4\)=O mode at 1630 cm\(^{-1}\) downshifts 80 cm\(^{-1}\) to 1550 cm\(^{-1}\). These shifts give rise to the 1630(+)/1626(-) cm\(^{-1}\) feature in the spectra for calculation 2 in Figure 4.2C. Thus the differences in the calculated spectra are explained in terms of small changes in band frequencies (<4 cm\(^{-1}\)) and in isotope induced frequency shifts (<2 cm\(^{-1}\)) of the same normal modes in the different calculations.

4.4.2 Comparison of spectra obtained in the different calculations

The spectra obtained in calculations 4 and 5 are very similar. If the goal is an adequate simulation of experimental isotope edited FTIR DS, then relaxing the constraints on atoms of the amino acid side chains in the molecular model does not appear to offer any advantage.

The spectra obtained in calculations 1, 2, 4 and 5 are very similar. This is in spite of the considerable additional computational expense necessary for calculations 4 and 5 (especially for calculation 5). From the similarity in the spectra in calculations 1, 2, 4 and 5, at least two points can be made:
Firstly, if the goal is an adequate simulation of experimental isotope edited FTIR DS then there is no need to consider any of the surrounding amino acids (or the Fe atom) at the QM level. This point provides a strong justification for the methodological approach taken in our previous ONIOM calculations [117]. In contrast, in previous ONIOM calculations aimed at modeling some of the magnetic spectroscopic parameters of UQ$^-$ in the Q$_A$ binding site [50], it was indicated that the metal atom should be treated using QM. No calculations were undertaken with the metal atom treated using MM methods to test this, however. In order to contrast and compare the magnetic spectroscopic computational result we are currently in the process of calculating isotope edited FTIR difference spectra for UQ$^-$ in the Q$_A$ binding site with the metal atom being treated using both QM and MM methods.

Secondly, if the goal is an adequate simulation of experimental isotope edited FTIR DS, and computational resources dictate that only the pigment of interest can be treated at the QM level of theory, then it does not appear to be important which of the MM force fields (AMBER or UFF) is chosen. However, the UFF method leads to an alteration of the structural parameters (Table 4.2) that do not appear to be in agreement with the other calculations or the X-ray data. Based on these results we suggest that if one wishes to treat only the pigment of interest at the QM level, with protein amino acids treated using MM methods, then the AMBER method is a better choice than the UFF method. However, if several amino acids are to be included in the QM treated model system, then the choice of MM force field (UFF or AMBER) is not important. In our studies the UFF approach is simpler to implement, and is thus preferred in calculations involving larger model systems.

In ONIOM calculations for the larger model system the spin state of the Fe atom appears not to be of importance, both in terms of the calculated charge on the UQ (calculation 4 and 4B
in Table 4.4), and for simulating isotope edited difference spectra. In the FTIR experiments undertaken to produce the isotope edited FTIR difference spectra the spin state of the Fe atom was not specified. It has been found recently that the Fe atom in *Rb. sphaeroides* reaction centers can exist in both the high and low spin forms [133]. Our calculations predict, however, that the spin state of the Fe atom would have little or no impact on the calculated isotope edited FTIR difference spectra.

### 4.4.3 Comparison with results obtained in different computational studies

Very recently, Chernov et al. [135] have undertaken DFT calculations using a model of the QA binding site that contained UQ, Fe and the amino acids that provide ligands (four histidines and one glutamate), and a water molecule. The peptide backbone of an alanine residue that may be involved in hydrogen bonding was not included (Chernov et al. were focused on the properties of the bidentate ligand to the Fe atom provided by glutamate, and not on quinone H-bonding). In these studies they calculate that the charge on neutral UQ is -0.19 to -0.22 (a charge of -0.09 to -0.19 was also calculated for the neutral plastoquinone in the QA site in photosystem II). If the charge on the UQ is ~ -0.2 then any calculation of isotope edited difference spectra using this model would result in spectra that do not resemble the experimental spectra. The error most probably arises because MPA rather than NPA was used to calculate the UQ atomic charges (compare MPA and NPA calculated charges on UQ in calculation 4A in Table 4.4).

Recently, computational studies of small H–bonding molecular dimers have been undertaken which show that treating one of the monomers using QM and the other using MM gave results that were the same as that found when both molecules were treated using QM [136, 137]. These studies on molecular dimers support the validity of the calculations presented here, and indicate that QM/MM potentials can be as effective as pure QM potentials.
The calculations outlined here indicate that H–bonding to neutral UQ in the QA binding site can be understood (modeled) in purely electrostatic terms, without consideration of quantum effects. Whether H–bonding needs to be treated at the QM level [138] or not [121, 139] in other systems is an area of ongoing research.

4.4.4 Electronic embedding vs. Mechanical embedding

In previous ONIOM calculations of the magnetic properties of UQ− in the QA binding site it was shown that the ONIOM calculations using mechanical embedding (ME) were just as effective (in terms of calculation of spin density distributions and hyperfine coupling constants for UQ−) as calculations undertaken using electronic embedding (EE) [50].

The differences between ME and EE have been discussed [116, 130]. Briefly, in EE the electric potential generated by the atomic charges in the MM layer are included in the QM Hamiltonian. This leads to a more realistic situation in which the MM layer charges can polarize the QM layer. The QM layer charges do not polarize the MM layer charges, however. In ME the interaction between the QM and MM layers is treated using MM. This does not allow for polarization of the QM layer, as MM methods are parameterized in terms of fixed (unpolarizable) point charges.

All five of the calculations in Table 4.2 were undertaken using EE. We have also undertaken calculation 1 using ME instead of EE, and Figure 4.3 in the supplementary information section compares isotope edited spectra obtained for calculation 1 using ME and EE. Figure 4.3 demonstrates that calculated spectra using ME poorly model the experimental spectra. In fact the spectra, the normal mode compositions, and the isotope induced frequency shifts calculated using the ME approach all resemble that calculated for UQ in the gas phase [117].
Thus it appears that the electrostatic environment of neutral UQ in the QA binding site leads to some polarization of the QM atoms, which requires an EE ONIOM approach to model correctly.

4.4.5 Quantitative measures of H-bond strength

In Table 4.2, the C<sub>4</sub>=O bond is found to be 0.01 Å longer than the C<sub>1</sub>=O bond. This could be considered to be a reflection of some asymmetry in the H–bonding to the UQ carbonyl groups. However, from studies of UQ in the gas phase, the C<sub>1</sub>=O and C<sub>4</sub>=O groups are also found to differ by ~0.01 Å [140]. So the C=O bond lengths do not provide a good measure of the strength of H–bonding to the UQ carbonyl groups. In studies of small H–bonding clusters [141] it was also found that the C=O bond length is a poor measure of H-bond strength.

For N–H - - - O type H–bonds, the H - - - O distance (also listed in Table 4.2) was also found to be a poor measure of H–bond strength [141, 142]. The N–H bond length has been found to correlate very well with H–bond strength, however [142, 143]. The N–H bond lengths of the various histidine imidazole groups, and the AlaM260 backbone, used in our model (Figure 4.1) are listed in Table 4.2.

IR spectroscopy is frequently used for testing the strength of H–bonds. In many cases, upon H–bonding the vibrational frequency of the proton donating moiety red-shifts, usually by several hundred cm<sup>-1</sup>, and the intensity of the vibration increases several fold [144]. The red-shift of the N–H vibrational stretching frequency can be correlated with other parameters such as the bond length and the strength of the H–bond [143]. For the N–H groups of HisM219 and AlaM260 the bonds lengthen and the N–H vibrational mode frequencies decrease, compared to non H–bonded imidazole N-H groups (Table 4.3). The H–bonds provided by the N–H groups of HisM219 and AlaM260 are classic “red-shifted” H–bonds [145]. The N–H mode of HisM219
downshifts more and gains considerably more in intensity that the N–H mode of AlaM260 (Table 4.3), suggesting that the HisM260 H–bond is stronger than the AlaM260 H-bond.

Table 4.3 Bond lengths, vibrational mode frequencies and intensities of the H-bonding N–H groups of histidine and alanine obtained from calculation 5.

<table>
<thead>
<tr>
<th>Bond</th>
<th>( r_{N-H} )</th>
<th>Mode Intensity</th>
<th>Mode Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>N29–H, HisM266</td>
<td>1.00691</td>
<td>75</td>
<td>3687</td>
</tr>
<tr>
<td>N41–H, HisL190</td>
<td>1.00978</td>
<td>112</td>
<td>3657</td>
</tr>
<tr>
<td>N35–H, HisM230</td>
<td>1.01076</td>
<td>83</td>
<td>3642</td>
</tr>
<tr>
<td>N48–H, AlaM260</td>
<td>1.01290</td>
<td>225</td>
<td>3583</td>
</tr>
<tr>
<td>N22–H, HisM219</td>
<td>1.01543</td>
<td>1195</td>
<td>3554</td>
</tr>
</tbody>
</table>

Atomic numbering as in Figure 4.1. Bond length in Å, intensity in km/mol, frequency in cm\(^{-1}\).

The parameter, \( \delta_{N-H} \), defined in equation 1 below, has been shown to correlate very well with H–bond strength [142, 143], where \( r_{N-H} \) is the length of the N–H bond in the H–bonded system and \( r_{N-H}^0 \) is the length of the free N–H bond, not involved in H–bonding.

\[
\delta_{N-H} = \frac{r_{N-H} - r_{N-H}^0}{r_{N-H}^0}
\]

If it is assumed that the non-ligated N-H groups of HisL230, HisM266 and HisL190 are representative of free N-H groups, then using the data in Table 4.3 with \( r_{N-H}^0 = 1.00915 \), we find \( \delta_{N-H} = 6.223 \times 10^{-3} \) and \( 3.716 \times 10^{-3} \) for the HisM219 and AlaM260 N–H groups, respectively. This suggests that the HisM219 H–bond is 1.67 times stronger than the AlaM260 H–bond. By considering a similar equation for N–H vibrational frequencies, with a free N-H vibrational frequency of 3662 cm\(^{-1}\), then using the data in Table 4.3, we find that the HisM219 H–bond is 1.37 times stronger than the AlaM260 H–bond. Averaging the results for both calculations we estimate that the HisM219 H–bond is about a factor of 1.52 stronger than the AlaM260 H–bond.
Two points should be noted in the above analysis. Firstly, in order to estimate the relative H–bond strengths from calculated vibrational frequencies, it is necessary to undertake ONIOM calculations with the H–bonding amino acids included at the QM level of theory. Thus calculations 1 and 2 could not be used for this purpose.

Secondly, the data in Table 4.3 indicate that the backbone N-H group of AlaM260 is H-bonded to UQ, albeit weakly. In IR spectroscopy the UQ C=O mode vibrational frequency is often used to give a qualitative measure of H–bond strength. Thus the UQ C₄=O group is more strongly H–bonded than the C₁=O group because it’s vibrational frequency is at 1626 cm⁻¹, compared to ~1660 cm⁻¹ for the C₁=O group [47]. However, the UQ C₁=O and C₄=O mode vibrational frequencies cannot be used to give a measure of relative H-bond strength because the vibrational frequency of the C₁=O group of UQ in the protein binding site is the same as that found for UQ in solution. This frequency similarity suggests no H–bonding to the UQ C₁=O group. So, if H-bonding is relatively weak, then properties of the N-H group involved in H-bonding, rather than the C=O group, are a better indicator of H-bond strength. Unfortunately, experimental vibrational frequencies for the His N-H groups involved in H-bonding to UQ are unavailable.

4.4.6 The electrostatic nature of the H-bonds to UQ

Many factors have been proposed to contribute to and account for H–bond stabilization energy [144, 146, 147]. The H–bond stabilization energy for the type of H–bonds studied here (red-shifted H–bonds with a proton accepting oxygen atom and proton donating N–H group) is usually dominated by electrostatics, with a smaller charge transfer (sometimes called covalent or hyperconjugative) contribution [144, 147]. The charge transfer contributions to the H–bond energy in our ONIOM calculations can be estimated using the natural bond orbital, second order
perturbation theory method [126, 127, 148]. Charge transfer interaction energies of ~3–5 kcal/mol indicate that charge transfer contributes negligibly to H–bonding [126, 127]. In calculation 5 we calculate charge transfer interaction energies of the H–bonds at O₁ and O₄ of 3.79 and 3.84 kcal/mol, respectively (see the supplementary information section for more details). Similar results are found for calculation 4. Thus charge transfer contributions to the H–bonds of UQ in the Qₐ binding site are very small, suggesting that the H–bonds to UQ in the Qₐ site are dominated by electrostatic interactions. This conclusion is in line with previous suggestions that N–H…O type H-bonds are predominantly electrostatic in nature [149].

The conclusion from natural bond orbital analysis, that the H–bonds to UQ are mainly electrostatic in nature may provide an explanation as to why the procedures outlined for calculations 1, 4 and 5 (Table 4.2) all lead to a successful description of the experimental isotope edited difference spectra.

Calculation of the vibrational properties of neutral UQ (presented here) indicates that H-bonding amino acids are adequately treated using MM methods. In contrast, calculation of the EPR properties of UQ⁻ indicates that H-bonding amino acids need to be treated using QM methods [50, 122]. Taken together these results indicate differences in the nature of H-bonding for the neutral and anion UQ species. Changes in H-bonding upon radical formation may be a mechanism for stabilizing/destabilizing cofactors to promote/inhibit/fine-tune electron transfer processes in biological systems. To investigate this intriguing topic further it will be useful to undertake calculations similar to that presented here (modeling isotope edited FTIR difference spectra) for UQ⁻ in the Qₐ binding site, and compare the findings to that obtained for calculations of the EPR properties of UQ⁻.
4.5 Conclusions

ONIOM (QM/MM) calculations, with H–bonding amino acids treated at the MM level, give calculated isotope edited difference spectra that are similar to that obtained in ONIOM (QM/MM) calculations where the H–bonding amino acids are treated at the QM level. Thus quantum effects associated with H–bonding to neutral QA are negligible.

The H–bond to the UQ C₄=O group (provided by the side chain N–H group of HisM219) is about 1.5 times stronger than the H–bond to the UQ C₁=O group (provided by the backbone N–H group of AlaM260).

For ONIOM calculations of UQ in the QA binding site, if only the cofactor is treated at the QM level, with the protein environment treated at the MM level, then the AMBER force field is preferable (to the UFF force field) for the MM part of the calculation. This seems reasonable since the AMBER force field was designed with protein systems in mind. If H–bonding amino acids are treated at the QM level then the choice of AMBER or UFF force fields is unimportant.

In the ONIOM calculations described here an electronic embedding scheme (rather than mechanical embedding) is required for accurate simulation of the experimental spectra.

The ONIOM calculated charge on UQ in the QA binding site, as well as the calculated isotope edited difference spectra, are not sensitive to the spin state of the non-heme iron atom.

In terms of simulating isotope edited difference spectra, relaxing constraints on the atoms of amino acid side chains during optimization does not appear to offer any advantage.
### 4.6 Supporting Information

Table 4.4 Charge and spin on Fe and UQ obtained from several ONIOM calculations. Atomic charges were calculated using both NPA and MPA.

<table>
<thead>
<tr>
<th>Calc</th>
<th>QM atoms</th>
<th>Fixed atoms</th>
<th>ONIOM Calculation</th>
<th>Charge Model system</th>
<th>Charge UQ NPA</th>
<th>Charge UQ MPA</th>
<th>Charge Fe NPA</th>
<th>Charge Fe MPA</th>
<th>Spin Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31</td>
<td>Protein backbone and Fe</td>
<td>6-31+G(d):Amber 1,1, 0,1, 0,1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>31</td>
<td>Protein backbone and Fe</td>
<td>6-31+G(d):UFF 1,1, 0,1, 0,1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td>0.933</td>
</tr>
<tr>
<td>3</td>
<td>99</td>
<td>All heavy atoms except UQ</td>
<td>6-31G(d)/LANL2DZ:UFF 0.2, 0.4, 0.4</td>
<td>0</td>
<td>-0.874</td>
<td>-0.790</td>
<td>1.456</td>
<td>0.581</td>
<td>3.738</td>
</tr>
<tr>
<td>3A</td>
<td>99</td>
<td>All heavy atoms except UQ</td>
<td>6-31G(d):UFF 0.2, 0.2, 0.2</td>
<td>0</td>
<td>-0.865</td>
<td>-0.799</td>
<td>1.378</td>
<td>1.053</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>99</td>
<td>All heavy atoms except UQ</td>
<td>6-31G(d)/LANL2DZ:UFF 1,1, 1,5, 1,5</td>
<td>1</td>
<td>0.054</td>
<td>0.078</td>
<td>1.393</td>
<td>0.579</td>
<td>3.740</td>
</tr>
<tr>
<td>4A</td>
<td>99</td>
<td>All heavy atoms except UQ</td>
<td>6-31G(d):UFF 1,1, 1,5, 1,5</td>
<td>1</td>
<td>0.055</td>
<td>-0.112</td>
<td>1.545</td>
<td>1.175</td>
<td>3.952</td>
</tr>
<tr>
<td>4B</td>
<td>99</td>
<td>All heavy atoms except UQ</td>
<td>6-31G(d):UFF 1,1, 1,1, 1,1</td>
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<td>0.057</td>
<td>0.074</td>
<td>1.298</td>
<td>1.000</td>
<td>0</td>
</tr>
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<td>5</td>
<td>99</td>
<td>Protein backbone</td>
<td>6-31G(d)/LANL2DZ:UFF 1,1, 1,5, 1,5</td>
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<td>0.047</td>
<td>0.077</td>
<td>1.449</td>
<td>0.634</td>
<td>3.740</td>
</tr>
</tbody>
</table>
4.6.1 Comparison of isotope edited difference spectra obtained from ONIOM calculations employing mechanical and electronic embedding

Figure 4.3 Experimental (red) and ONIOM calculated (black) isotope edited DDS for neutral UQ. UQ has been specifically (A) $^{13}C_4$, (B) $^{18}O$ and (C) $^{13}C^{18}O$ isotope labeled (only the carbonyl oxygen atoms are $^{18}O$ labeled). Experimental spectra are reprinted with permission from [47] and [109].

Figure 4.3 compares isotope edited difference spectra obtained from ONIOM calculations employing ME and EE (using the same approach as calculation 1 in Table 4.2). The spectra
obtained using ME clearly differ from that obtained using EE, and from that obtained experimentally. For example, in Figure 4.3A, the separation between the positive and negative bands is 17 and 23 cm$^{-1}$ for EE, compared to 28 and 11 cm$^{-1}$ for ME. The spectra calculated using the ME ONIOM approach appears to be very similar to the spectra calculated for UQ in the gas phase (see Table 1 in reference 19).

The composition of the normal modes that are associated with the bands in the spectra in Figure 4.3, obtained using the ME and EE approaches, are listed in Table 4.5, for unlabeled and $^{13}$C$_4$ labeled UQ in the QA binding site. For the ONIOM approach employing ME, the composition of the normal, and the isotope induced frequency shifts of the modes (Table 4.5), are very similar to that found in calculations of UQ in the gas phase (see Table 1 in (19)) and, as was pointed out previously, calculated spectra for UQ in the gas phase do not resemble the experimental spectra.

In summary, the ONIOM approach employing ME gives results that are essentially the same as that found for calculations of UQ in the gas phase, and the calculated spectra poorly resemble the experimental spectra. These observations suggest that calculations employing ME are not well suited, for modeling isotope edited difference spectra associated with UQ in the QA binding site, and the ONIOM calculations employing ME are clearly inferior to calculations employing EE.
Table 4.5 Normal mode frequencies, intensities, and potential energy distributions (PEDs) obtained from ONIOM calculations employing ME and EE, for unlabeled and $^{13}$C$_4$ labeled neutral UQ$_1$.

<table>
<thead>
<tr>
<th>ONIOM-EE</th>
<th></th>
<th></th>
<th>ONIOM-ME</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>v</td>
<td>Intensity</td>
<td>Potential energy distribution</td>
<td>v</td>
<td>Intensity</td>
</tr>
<tr>
<td></td>
<td>ν</td>
<td>ν</td>
<td></td>
<td>ν</td>
<td>ν</td>
</tr>
<tr>
<td>1679</td>
<td>12</td>
<td>C=C$_1$ (66%)</td>
<td>1679</td>
<td>11</td>
<td>C=C$_1$ (66%)</td>
</tr>
<tr>
<td>1663</td>
<td>185</td>
<td>C$_1$=O (81%)</td>
<td>1663</td>
<td>200</td>
<td>C$_1$=O (82%)</td>
</tr>
<tr>
<td>1653</td>
<td>26</td>
<td>C$_5$=C$_6$ (45%), C$_2$=C$_3$ (19%)</td>
<td>1653</td>
<td>23</td>
<td>C$_3$=C$_6$ (45%), C$_2$=C$_3$ (19%)</td>
</tr>
<tr>
<td>1626</td>
<td>305</td>
<td>C$_4$=O (68%), C$_2$=C$_3$ (9%)</td>
<td>1579</td>
<td>258</td>
<td>C$_4$=O (71%), C$_2$=C$_3$ (6%)</td>
</tr>
<tr>
<td>1601</td>
<td>275</td>
<td>C$_2$=C$_3$ (35%), C$_5$=C$_6$ (18%)</td>
<td>1609</td>
<td>276</td>
<td>C$_2$=C$_3$ (38%), C$_5$=C$_6$ (19%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C$_4$=O (14%), C$_2$-O (7%)</td>
<td></td>
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<td>C$_4$=O (9%), C$_2$-O (10%)</td>
</tr>
<tr>
<td>1671</td>
<td>19</td>
<td>C=C$_1$ (65%)</td>
<td>1671</td>
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<td>C=C$_1$ (65%)</td>
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<tr>
<td>1661</td>
<td>177</td>
<td>C$_1$=O (80%)</td>
<td>1661</td>
<td>188</td>
<td>C$_1$=O (80%)</td>
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<tr>
<td>1640</td>
<td>37</td>
<td>C$_3$=C$_6$ (39%), C$_2$=C$_3$ (26%)</td>
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<td>C$_3$=C$_6$ (39%), C$_2$=C$_3$ (27%)</td>
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<td>264</td>
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<td>276</td>
<td>C$_4$=O (53%), C$_2$=C$_3$ (16%)</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>C$_5$=C$_6$ (9%)</td>
</tr>
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<td>1594</td>
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<td>C$_2$=C$_3$ (36%), C$_5$=C$_6$ (26%)</td>
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<td>223</td>
<td>C$_4$=O (28%), C$_2$=C$_3$ (23%)</td>
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<td></td>
<td></td>
<td>C$_2$-O (7%), C$_4$=O (6%)</td>
<td></td>
<td></td>
<td>C$_5$=C$_6$ (20%), C$_2$-O (6%)</td>
</tr>
</tbody>
</table>

Frequency in cm$^{-1}$ and intensity in km/mol.
4.6.2 Charge transfer contributions to H–bond energy

The natural bond orbital (NBO) second order perturbation theory method can provide information on donor-acceptor orbital interaction energies [126]. The charge transfer interaction energy can be expressed as $E^{(2)} = \Delta E_{ij} = -n^\sigma F_{ij}^2 / (E_j - E_i)$, where $n^\sigma$ is the donor orbital occupancy, $F_{ij}$ is the off-diagonal NBO Fock matrix element, and $E_i$ and $E_j$ are the donor and acceptor orbital energies [126, 127].

To gain a more detailed understanding of the origins of the red-shifted N$_{48}$-H···O and N$_{22}$-H···O H-bonds, NBO analysis has been carried out at the B3LYP/6-31G(d) level for calculation 5.

In the following BD* denotes an $\sigma^*$ antibonding orbital; LP (1) and LP (2) denotes the two lone pair electrons.

For the AlaM260 (N$_{48}$-H) H-bond, there is an increase in the antibonding orbital occupancy $n^\sigma^*$, mainly caused by the two pairs of intermolecular donor-acceptor orbital interactions: LP(1)O$_1$→BD*(N$_{48}$-H) and LP(2)O$_1$→BD*(N$_{48}$-H). These interaction energies are 2.06 and 1.73 kcal/mol, respectively. Thus, in calculation 5, the overall charge transfer interaction energy of the H–bond at O$_1$ is 3.79 kcal/mol.

For the HisM219 (N$_{22}$-H) H-bond there is an increase in the $\sigma^*$ antibonding orbital occupancy, that arises primarily from LP(1)O$_4$→BD*(N$_{22}$-H) and LP(2)O$_4$→BD*(N$_{22}$-H). The charge transfer interaction energies are 3.62 and 0.22 kcal/mol, respectively, and the total charge transfer interaction energies of the H–bond to O$_4$ is 3.84 kcal/mol.

As indicated in the text, an orbital interaction energies of 3-4 kcal/mol is considered very small, and UQ H-bonds are negligibly covalent.
COMPARISON OF CALCULATED AND EXPERIMENTAL ISOTOPE EDITED FTIR DIFFERENCE SPECTRA OBTAINED USING PURPLE BACTERIAL PHOTOSYNTHETIC REACTION CENTERS WITH DIFFERENT QUINONES INCORPORATED INTO THE QA BINDING SITE

Abstract

Previously we have shown that ONIOM type (QM/MM) calculations can be used to simulate isotope edited FTIR difference spectra for neutral ubiquinone in the QA binding site in *Rhodobacter sphaeroides* photosynthetic reaction centers. Here we considerably extend upon this previous work by calculating isotope edited FTIR difference spectra for reaction centers with a variety of unlabeled and $^{18}$O labeled foreign quinones incorporated into the QA binding site. Isotope edited spectra were calculated for reaction centers with 2,3-dimethoxy-5,6-dimethyl-1,4-benzoquinone (MQ$_0$), 2,3,5,6-tetramethyl-1,4-benzoquinone (duroquinone, DQ), and 2,3-dimethyl-1,4-naphthoquinone (DMNQ) incorporated, and compared to corresponding experimental spectra. The calculated and experimental spectra agree well, further demonstrating the utility and applicability of our ONIOM approach for calculating the vibrational properties of pigments in protein binding sites.

The normal modes that contribute to the bands in the calculated spectra, their composition, frequency and intensity, and how these quantities are modified upon $^{18}$O labeling, are presented. This computed information leads to a new and more detailed understanding/interpretation of the experimental FTIR difference spectra.

Hydrogen bonding to the carbonyl groups of the incorporated quinones is shown to be relatively weak. It is also shown that there is some asymmetry in hydrogen bonding, accounting for 10-13 cm$^{-1}$ separation in the frequencies of the carbonyl vibrational modes of the
incorporated quinones. The extent of asymmetry H-bonding could only be established by considering the spectra for various types of quinones incorporated into the QA binding site.

The quinones listed above are “tail-less”. Spectra were also calculated for reaction centers with corresponding “tail” containing quinones incorporated, and it is found that replacement of the quinone methyl group by a phytyl or prenyl chain does not alter ONIOM calculated spectra.

5.1 Introduction

Quinones play an important role in biological proton and electron transfer processes that occur in both respiration and photosynthesis [110]. In type II photosynthetic reaction centers two quinone molecules act as terminal electron acceptors [150, 151]. The two quinones are often termed QA and QB. In this manuscript we will refer to the quinone binding site as QA and QB, however. The quinones that occupy the QA and QB binding sites have very different functions. The QA quinone is an intermediary cofactor involved in transferring electrons from (bacterio)pheophytin to QB, while the QB quinone couples proton and electron transfer processes [111, 112, 151].

In this chapter we focus on the QA binding site. The quinone occupying the QA binding site is species dependent. In Rhodobacter (Rb.) sphaeroides purple bacterial reaction centers (PBRCs) a ubiquinone (UQ) molecule occupies the QA binding site. In PBRCs from Blastochloris Viridis [152] and Chloroflexus aurantiacus [153] a menaquinone occupies the QA binding site. In photosystem II reaction centers from oxygen evolving organisms, a plastoquinone (PQ) molecule occupies the QA binding site. In photosystem I the secondary electron acceptor, termed A1, is a vitamin K1 (VK) molecule (also called phylloquinone).
Menaquinone and VK are both naphthoquinone (NQ) moieties that differ only in the degree of saturation of the tail at C₆.

Figure 5.1 shows the structure, numbering and abbreviations we will use for the various quinones discussed in this manuscript. MQ₀ and DMNQ are UQ and VK analogues, respectively, in which the hydrocarbon tail has been replaced with a methyl group. DQ is a PQ analogue in which the hydrocarbon chain at C₆ is replaced with a methyl group.

![Figure 5.1 Structure and numbering of ubiquinone (2,3-dimethoxy, 5-methyl,6-prenyl benzoquinone) (UQₙ), 2,3-dimethoxy, 5,6-methyl benzoquinone (MQ₀), 2,3,5,6-methyl benzoquinone ( duroquinone, DQ), 2,3-dimethyl, 1,4-naphthoquinone (DMNQ) and 2-methyl, 3-phytyl 1,4-naphthoquinone (VK). The numbering scheme employed here for the naphthoquinone structures is nonstandard, and was chosen to facilitate comparison between naphthoquinone and ubiquinone structures.

It has been suggested, at least for the UQ that occupies the QA site in PBRCs, that the role of the hydrocarbon chain at C₆ is to anchor and orient the quinone head-group in a specific way [154]. Data is available that may argue against this proposal, however [68, 134, 155].

Comparison of the properties of PBRCs with MQ₀ and UQₙ, or VK and DMNQ, incorporated into the QA binding site will allow one to assess how or if the hydrocarbon chain at
C₆ modifies the quinones functional properties. Similarly, comparison of the properties of PBRCs with MQ₀ and DQ incorporated into the Qₐ binding site will allow one to assess how or if the methoxy groups at C₂ and C₃ modifies the quinones functional properties. Calculated spectra for *Rb. sphaeroides* PBRCs with VK in the Qₐ binding site can be compared to experimental spectra. These calculated spectra may also serve as a useful model for *B. viridis* PBRCs that naturally have VK incorporated into the Qₐ binding site.

Fourier transform infrared (FTIR) difference spectroscopy (DS) is a sensitive molecular-level probe of pigment-protein interactions, and it is widely used to study both the neutral and reduced states of quinones in PBRCs [115] and in photosystem II [156]. In this manuscript we focus on Qₐ⁻/Qₐ FTIR DS. Many molecular species contribute to Qₐ⁻/Qₐ FTIR DS, and in the past it has been difficult to identify which bands are associated specifically with UQ in the Qₐ site. However, fully functional quinones can be incorporated into Qₐ depleted PBRCs, and by collecting Qₐ⁻/Qₐ FTIR DS using PBRCs with unlabeled and isotopically labeled quinones incorporated, so called isotope edited FTIR difference spectra can be constructed, and from these spectra it has proven possible to separate contributions of the quinones from those of the protein in Qₐ⁻/Qₐ FTIR DS [115]. Previously, a variety of unlabeled and ¹⁸O labeled quinones have been incorporated into the Qₐ binding site in PBRC’s, and ¹⁸O isotope edited FTIR DS have been obtained [157]. The goal in this manuscript is the simulation of these experimental ¹⁸O isotope edited FTIR DS associated with the neutral state of the quinone in the Qₐ binding site. Calculated IR spectra associated with the quinone anion state are considerably more complicated [158] and are currently being undertaken.

Although experimental Qₐ⁻/Qₐ FTIR DS have been obtained using PBRCs with various unlabeled and isotope labeled quinones incorporated, virtually no computational work aimed at
modeling the experimental FTIR DS have been undertaken. Calculations aimed at modeling the vibrational properties of quinones in the QA binding site must account for the protein environment. Quantum mechanical (QM) calculations of such a large molecular system (pigment plus protein environment) are unfeasible. To circumnavigate this problem methods have been developed that allow one to separate the molecular system into distinct layers that can be treated at different levels of theory. In one layer the chemical properties of the principle species of interest (the pigment) can be calculated using “high-level” QM methods. The surrounding protein environment is included in the calculation but it is treated using computationally less expensive molecular mechanics (MM) methods.

Recently we have undertaken QM: MM calculations for UQ in the QA binding site using the ONIOM method [118]. ONIOM is an acronym for: our Own N-layered Integrated molecular Orbital + Molecular mechanics package. In these calculations we showed that we could simulate experimental isotope edited FTIR difference spectra obtained using PBRCs with neutral UQ in the QA binding site. Here we extend upon these previous studies by attempting to simulate experimental isotope edited FTIR difference spectra obtained using PBRCs with symmetric tail-less and corresponding tail containing quinones incorporated into the QA binding site. We show that the calculated spectra agree well with the experimental spectra, further supporting the notion that the ONIOM method is a useful approach for understanding complex FTIR difference spectra associated with pigments in protein binding sites. We are also able to assess to what extent the quinone hydrocarbon chain may influence the calculated spectra.
5.2 Materials and Methods

5.2.1 Structural Model Used in Calculations

The molecular model used in ONIOM calculations was generated from the crystal structure of *Rb. sphaeroides* PBRCs at 2.2 Å resolution [25] (PDB file 1AIJ). From the PDB file all atoms within 10 Å of either carbonyl oxygen atom of UQ were selected. This subset of atoms formed the basis of the QA binding site structural model. Hydrogen atoms (not included in the PDB file) were added to the model using the software Gaussview4, resulting in a final structural model consisting of 1024 atoms. Following the addition of hydrogen atoms the structural model was optimized (energy minimized) using ONIOM methods with all atoms associated with the protein backbone, and the non-heme iron atom, being held fixed. All atoms of the amino acid side chains and the incorporated quinone are unconstrained. For calculations of UQ/VK the hydrocarbon tail was modeled as a single prenyl/phytyl unit, respectively. Inclusion of further prenyl/phytyl units did not alter the calculated spectra (not shown).

The structural models for the different incorporated quinones are initially set up by simply replacing the molecular substituents of the originally incorporated UQ species. So, the C=O groups of the different quinones incorporated will initially have the same orientation and position to that found for UQ in the QA binding site. DMNQ and VK structures were constructed starting from the UQ structure, by replacing the methoxy groups with the NQ aromatic ring, without alteration of the quinone ring (Figure 5.2F). This orientation of the NQ ring (of DMNQ and VK) was chosen as previous docking calculations have suggested it is the most favorable [159].
5.2.2 Calculations

All calculations were undertaken using Gaussian 03 [91] software. For calculation of UQ molecules in the gas phase, and for the QM part of ONIOM calculations, molecular geometry optimizations and harmonic vibrational frequency calculations were undertaken using hybrid DFT methods, employing the B3LYP functional and the 6-31+G(d) basis set. This choice of functional and basis set are appropriate for calculation of the vibrational properties of quinones [160, 161]. The MM part of the ONIOM calculation is undertaken using the AMBER force field [123]. Following ONIOM geometry optimization of the structural model, the optimized quinone molecule from the model is considered separately for vibrational frequency calculations.

5.2.3 Normal Mode Assessment

Assignment of calculated vibrational frequencies to molecular groups is based on a consideration of the calculated atomic displacements (in Cartesian coordinates) associated with the normal modes. These atomic displacements can be animated using software (GaussView4), and the molecular groups that most prominently contribute to the normal modes can be assessed visually (for example, see Figure 5.2 in reference [160]). In addition, potential energy distributions of the normal modes are calculated using the freeware GAR2PED [128]. For the various quinones in the QA binding site we calculate both vibrational mode frequencies and intensities. With both the frequency and intensity information “stick spectra” can be constructed. These stick spectra are representative of IR absorption spectra, as described previously [90, 140, 162]. The calculated stick spectra are convolved with a Gaussian function with half-width of 4 cm$^{-1}$ to produce more realistic looking IR absorption spectra [90, 140, 162].
5.3 Results

5.3.1 UQ structure and numbering

Figure 5.1 shows the structure and numbering scheme used here for UQ$_{n}$, MQ$_0$, DQ, DMNQ and VK. Naphthoquinones generally have a different numbering scheme. We have applied the UQ numbering scheme to DMNQ and VK for the sake of easy comparison. Figure 5.2 shows a picture of (A) DMNQ, (B) VK, (C) MQ$_0$ and (D) UQ$_1$ in the Q$_A$ binding site along with the two H-bonding amino acids. The structures shown are after geometry optimization using ONIOM methods. Possible hydrogen bonds (or ligand to the non-heme iron atom) are indicated by dotted lines.

To gain a better sense of the relative orientation of the different quinones in the Q$_A$ binding site Figure 5.2 also shows the (E) DMNQ/DQ and (F) DMNQ/UQ structures from two ONIOM calculations overlapped. These overlapped structures are created by considering the (fixed) atoms of the protein backbone. Figure 5.2E/F indicates that the side chains of HisM219 and AlaM260 are unaltered when a different quinone is incorporated into the binding site.

Table 5.1 lists several bond lengths and bond angles derived from our ONIOM calculated optimized geometries of the various quinones in the Q$_A$ binding site. For comparison, Table 5.1 also lists corresponding bond lengths and angles derived from our DFT calculated optimized geometries of the various quinones in the gas phase. Table 5.1 also list results obtained from previous QM/MM calculations [122], and data taken from the 1AIJ crystal structure [25].

Table 5.1 list the three distances associated with the peptide or imidazole H-bond to the carbonyl oxygen atoms of the quinone (N-H, NH - - O and N - - O distances). These distances completely determine the N-H - - O H-bond geometry. These angles are listed in Table 5.1.
Table 5.1 Comparison of bond lengths and angles derived from the ONIOM calculated (O) and gas phase calculated (GP) optimized geometry of neutral UQ₁₀, MQ₀, DQ, VK and DMNQ. Bond lengths and angles from the 1AIJ crystal structure [25] are also listed. Distances are in Å and angles are in degrees. The C₂ and C₃ methoxy group dihedral angles are defined as the C₃-C₂-O-CH₃ and C₂-C₃-O-CH₃ dihedral angles.

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|                  |          |      |     |    |     |      |          |
|                  | O        | GP   | O   | GP | O   | GP   |          |
|                  | 1.232     | 1.238| 1.231| 1.238| 1.231| 1.236| 1.229    |
|                  | 1.404     | 1.366| 1.364| 1.367| 1.355| 1.355| 1.405    |
|                  | 1.419     | 1.354| 1.354| 1.354| 1.354| 1.357| 1.355    |
|                  |           |      |     |    |     |      | 1.363    |
|                  |           |      |     |    |     |      | 1.362    |
|                  |           |      |     |    |     |      | 1.360    |
|                  |           |      |     |    |     |      | 1.360    |

For UQ₁₀ in the QA site the 1AIJ crystal structure [25] indicates that the C₁=O bond is marginally longer than the C₄=O bond. (1.234 versus 1.232 Å). In contrast, from ONIOM calculations of all the quinones listed in Table 5.1 the C₁=O bond is shorter than the C₄=O bond.

In gas phase calculations the C₁=O and C₄=O bond lengths are shorter than that found in ONIOM calculations (except the C₁=O of DQ). This lengthening of the C=O bonds of the quinones in the QA binding site is related to hydrogen bonding and other electrostatic interactions of the pigment with the protein environment.

For UQ₁ and MQ₀ the C₁=O bond is shorter than the C₄=O bond in both ONIOM and gas phase calculations. In gas phase calculations this difference in C₁=O and C₄=O bond lengths of UQ₁ and MQ₀ must relate to the differing orientations of the C₂ and C₃ methoxy groups. The
ONIOM calculated $C_2$ and $C_3$ methoxy group dihedral angles for UQ$_1$ are -25.3 and 150.5° (Table 5.1). Similar angles are calculated for MQ$_0$. The calculated dihedral angles for UQ$_1$ in the gas phase, and the observed angles for UQ$_{10}$ in the Q$_A$ binding site (from the crystal structure) are within 32 degrees of that calculated for UQ$_1$ using ONIOM methods.

For UQ$_{10}$ in the Q$_A$ site the crystal structure indicates that the $C_2$-$C_3$ bond is shorter than the $C_5$-$C_6$ bond. (1.404 versus 1.419 Å). In contrast, for all quinones except DQ, in both ONIOM and gas phase calculations the $C_2$-$C_3$ bond is longer than the $C_5$-$C_6$ bond. For VK and DMNQ the calculated $C_2$-$C_3$ and $C_5$-$C_6$ bond lengths are considerably different.

![Figure 5.2 Ball and stick representation of the calculated structure of (A) DMNQ, (B) VK, (C) MQ$_0$ and (D) UQ$_1$ in the Q$_A$ binding site in PBRCs from Rb. sphaeroides. Structure shown is after geometry](image)

Figure 5.2 Ball and stick representation of the calculated structure of (A) DMNQ, (B) VK, (C) MQ$_0$ and (D) UQ$_1$ in the Q$_A$ binding site in PBRCs from Rb. sphaeroides. Structure shown is after geometry.
optimization using ONIOM methods. Possible H-bonds are shown (*dotted*). Hydrogen atoms, except the ones involved in H-bonding, have been omitted. Distances quoted are in Å. (E, F) Overlap of structures obtained from ONIOM calculations for (E) DMNQ and DQ and (F) DMNQ and UQ\textsubscript{1}. Overlap is based on using the (fixed) backbone atoms of HisM219 and AlaM260. The amino acid side chains are virtually unaltered in the structures shown.

For UQ\textsubscript{1} and VK the hydrocarbon chain attached at C\textsubscript{6} makes a distinct “kink” after the first carbon atom (Figure 5.2B, D). The C-C-C bond angle is 112-115\textdegree for both quinones in both the ONIOM and gas phase calculations. The calculated angles are virtually the same as that found in the crystal structure. Given these similarities (between the ONIOM and gas phase calculations for both UQ\textsubscript{1} and VK, as well as between calculation and experiment) the suggestion is that the protein environment does not constrain the orientation of the quinone ring relative to the C\textsubscript{6} hydrocarbon chain.

Figure 5.3A shows ONIOM calculated \textsuperscript{18}O isotope edited difference spectra for neutral VK and DMNQ. Figure 5.3D shows corresponding DFT calculated spectra for VK and DMNQ in the gas phase. Experimental spectra are also shown (Figure 5.3B and C) for comparison. Positive/negative bands in the isotope edited spectra are due to the unlabeled/\textsuperscript{18}O labeled quinone species, respectively. The ONIOM calculated spectra clearly better describe the experimental spectra. Calculations including the protein environment appear to be necessary in order to adequately simulate the experimental spectra.
Figure 5.3 (A) ONIOM calculated $^{18}$O isotope edited DDS for neutral VK (dotted) and DMNQ (solid) in the QA binding site. Experimental spectra for VK (B) and DMNQ (C) are also shown, and were taken from reference [157], with permission. (D) DFT calculated $^{18}$O isotope edited DDS for neutral VK (dotted) and DMNQ (solid) are also shown. ONIOM/gas phase calculated spectra were scaled by 0.9718/0.9608, respectively.

In the DFT calculated $^{18}$O isotope edited spectrum for DMNQ/VK in the gas phase (Figure 5.3D) the antisymmetric vibration of both C=O groups gives rise to the band at ~1654 cm\(^{-1}\) (Figure 5.3D), which downshifts 30 cm\(^{-1}\) upon $^{18}$O labeling [160]. The calculated isotope-edited gas phase spectrum is in excellent agreement with the experimental spectrum for DMNQ in solution [157].

Figure 5.3 shows that except for a small frequency shift in some of the modes, the calculated spectra for DMNQ and VK are virtually the same. Replacement of the methyl group at C\(_{6}\) with an isoprene unit therefore has no influence on the calculated spectra.
The normal modes (frequencies and intensities) that give rise to the various bands in the ONIOM calculated $^{18}$O isotope edited spectra of DMNQ and VK are listed in Table 5.2. The potential energy distributions (PEDs), which quantify to what extent various internal coordinates contribute to the normal modes, are also listed in Table 5.2. Results for DMNQ and VK are very similar. Below we will discuss calculated data obtained for DMNQ with the recognition that very similar results and conclusions also apply to VK.

Table 5.2 Normal mode frequencies (in cm$^{-1}$), intensities (in km/mol) and PEDs (in %) calculated using ONIOM methods for unlabeled and $^{18}$O labeled neutral DMNQ, VK, DQ, MQ$_0$, and UQ$_1$. Frequency shifts upon $^{18}$O labeling are also listed. Negative signs in the PEDs refer to the relative phase of vibration of the internal coordinates. Only internal coordinates that contribute at least 5 % are shown. Mode frequencies were scaled by 0.9718.
In the ONIOM calculated $^{18}$O isotope edited spectra for DMNQ the two bands at 1654 and 1644 cm$^{-1}$ are due to C$_1$=O and C$_4$=O stretching vibrations, respectively (Table 5.2). These bands almost certainly correspond to the at 1653 and 1643 cm$^{-1}$ bands in the experimental spectrum (Figure 5.3C). So our calculations *predict* that the 1653 and 1643 cm$^{-1}$ bands in the experimental spectrum are due to C$_1$=O and C$_4$=O stretching vibrations, respectively. This is in fact the first direct evidence that the 1653 and 1643 cm$^{-1}$ bands in the experimental spectrum are due to C$_1$=O and C$_4$=O stretching vibrations. A direct assignment has never been made because specific $^{13}$C$_1$ and $^{13}$C$_4$ isotopic labeled VK or DMNQ has never been incorporated into the Q$_A$ binding site in PBRCs.

In contrast to the observation of two separate C=O modes in ONIOM calculations, in gas phase calculations the two C=O modes of DMNQ are anti-symmetrically coupled [90], giving rise to a single intense band at 1654 cm$^{-1}$ (Figure 5.3D).

In ONIOM calculations it is found that upon $^{18}$O labeling the C$_1$=O and C$_4$=O modes of DMNQ downshift 23 and 19 cm$^{-1}$, to 1631 and 1625 cm$^{-1}$, respectively (Table 5.2). Upon $^{18}$O labeling the 1625 cm$^{-1}$ mode is more than six times more intense than the 1631 cm$^{-1}$ mode. The 1625 cm$^{-1}$ mode in $^{18}$O labeled DMNQ is due mainly to the antisymmetric coupled vibration of both C=O groups. That is, two separate C=O modes of unlabeled DMNQ couple upon $^{18}$O labeling. This behavior is not predicted based upon consideration of the experimental spectra, where it is “assumed” that the two C=O modes remain separate upon $^{18}$O labeling [109, 163].

A C=C mode of the quinone ring of DMNQ is found at 1617 cm$^{-1}$. This quinonic C=C mode downshifts 13 cm$^{-1}$, to 1604 cm$^{-1}$, upon $^{18}$O labeling, with little change in intensity. The 1604 cm$^{-1}$ mode composition in $^{18}$O labeled DMNQ displays considerable mixing of the C=O
and C=C modes (the C=O modes account for 39% of the PED). This behavior might be expected given that the C=O and C=C modes are closer in frequency upon $^{18}$O labeling.

A C=C mode of the aromatic ring of DMNQ occurs at 1591 cm$^{-1}$. This aromatic C=C mode downshifts 5 cm$^{-1}$ to 1586 cm$^{-1}$ upon $^{18}$O labeling. The 1586 cm$^{-1}$ mode in $^{18}$O labeled DMNQ displays some mixing with C=O modes (23%), and the intensity of the aromatic C=C mode nearly doubles upon $^{18}$O labeling. The calculated C=C normal modes and their interpretation in terms of internal coordinates, as well as the calculated $^{18}$O induced frequency shifts are similar to that suggested on the basis of the experimental spectra [157].

Figure 5.4A shows ONIOM calculated $^{18}$O isotope edited IR difference spectra for neutral DQ in the QA binding site. Figure 5.4C shows the corresponding DFT calculated spectrum for DQ in the gas phase. The experimental spectrum is shown in Figure 5.4B. Again, the ONIOM calculated spectrum agrees well with the experimental spectrum while the calculated gas phase spectrum does not. The ONIOM calculated normal modes (frequencies and intensities) that give rise to the bands in the $^{18}$O isotope edited spectrum for DQ, as well as the PEDs, are listed in Table 5.2.
Figure 5.4 (A) ONIOM calculated $^{18}$O isotope edited DDS for neutral DQ in the QA binding site. Experimental spectra are shown in (B), and were taken from reference [157] with permission. (C) DFT calculated $^{18}$O isotope edited DDS for neutral DQ. ONIOM and gas phase calculated spectra were scaled by 0.9718 and 0.9608, respectively.

In the ONIOM calculated $^{18}$O isotope edited spectrum for DQ the two bands at 1646 and 1632 cm$^{-1}$ are due to C$_1$=O and C$_4$=O stretching vibrations, respectively (Table 5.2). Upon $^{18}$O labeling the C$_4$=O and C$_1$=O modes both downshift 33 cm$^{-1}$ with little change in mode intensities (Table 5.2). This 33 cm$^{-1}$ downshift is large compared to that calculated for DMNQ (19-23 cm$^{-1}$). For DQ, the ONIOM calculated mode composition is virtually unchanged upon $^{18}$O labeling. This is also markedly different to that calculated for DMNQ. The normal modes that give rise to the isotope edited spectra of DQ and DMNQ in the gas phase are very similar, so replacing the methyl groups of DQ with the aromatic ring of DMNQ in the QA binding site leads to an alteration in the electronic structure of the quinone ring. This modification is not obvious given the similar orientation of DQ and DMNQ in the QA binding site (Figure 5.2E).
In the DFT calculated $^{18}$O isotope edited spectrum for DQ in the gas phase, the two C=O modes are strongly coupled, and give rise to the band at 1639 cm$^{-1}$ in Figure 5.4C. The calculated gas phase spectrum is in line with the experimental FTIR spectrum for DQ in solution [157].

From ONIOM calculations for DQ, C=C modes do not couple with the C=O modes. The C$_2$=C$_3$ and C$_5$=C$_6$ groups couple to produce in phase and out of phase vibrational modes. The in phase mode has negligible IR intensity. The out of phase C=C mode is calculated to be at 1620 cm$^{-1}$. This C=C mode is virtually unaltered in frequency, intensity and mode composition upon $^{18}$O labeling (Table 5.2).

Figure 5.5A shows ONIOM calculated $^{18}$O isotope edited IR spectra for neutral MQ$_0$ (solid) and UQ$_1$ (dotted) in the Q$_A$ binding site. Figure 5.5D shows DFT calculated spectra for MQ$_0$ and UQ$_1$ in the gas phase. The experimental spectra for UQ$_1$ and MQ$_0$ are shown in Figure 5.5B and C, respectively. The normal modes (frequencies and intensities) that give rise to the various bands in the ONIOM calculated spectra, as well as the PEDs, are listed in Table 5.2. The data for UQ$_1$ has been presented previously [117], and we show here that very similar spectra are calculated for both MQ$_0$ and UQ$_1$. Replacement of an isoprene unit at C$_6$ with a methyl group does not greatly alter the calculated spectra.
Figure 5.5 (A) ONIOM calculated $^{18}$O isotope edited DDS for neutral MQ$_0$ (solid) and UQ$_1$ (dotted) in the QA binding site. Experimental spectrum for (B) MQ$_0$ and (C) UQ$_1$ are also shown, and were taken from reference [157] with permission. (D) DFT calculated $^{18}$O isotope edited DDS for neutral MQ$_0$ (solid) and UQ$_1$ (dotted). ONIOM and gas phase calculated spectra were scaled by 0.9718 and 0.9608, respectively.

In the ONIOM calculated $^{18}$O isotope edited spectra for neutral MQ$_0$ the two bands at 1666 and 1627 cm$^{-1}$ (Figure 5.5C) are due to C$_1$=O and C$_4$=O stretching vibrations, respectively (Table 5.2). Upon $^{18}$O labeling the C$_1$=O and C$_4$=O modes downshift 35 and 40 cm$^{-1}$, respectively (Table 5.2). The mode intensities and composition are little altered by $^{18}$O labeling. The C=O mode of MQ$_0$/UQ$_1$ at 1601 cm$^{-1}$ up-shifts 8/7 cm$^{-1}$ upon $^{18}$O labeling (Table 5.2). An explanation for this $^{18}$O induced frequency upshift has been presented [117].

In the DFT calculated $^{18}$O isotope edited spectra for UQ$_1$/MQ$_0$ in the gas phase, the two C=O modes are well separated, and give rise to bands at ~1665 and ~1635 cm$^{-1}$ (Figure 5.5D), which downshift 36 and 27 cm$^{-1}$, respectively, upon $^{18}$O labeling, as described previously [140].
5.4 Discussion

Previously we have shown that ONIOM methods can be used to calculate isotope edited difference spectra for UQ₁ in the QA binding site, and that these calculated spectra model very well the corresponding experimental spectra [117]. Here we considerably extend these studies, and show that ONIOM calculated isotope edited spectra for different quinones in the QA binding site model very well the corresponding experimental spectra. We further show that the calculated spectra for quinones in the gas phase are totally inappropriate for modeling the vibrational properties of quinones in the QA binding site. This is also very likely to be the case for modeling the properties of any protein bound pigment.

Without normal mode vibrational frequency calculations interpretation of experimental spectra is limited, and here we clearly show that our computational methods lead to a greatly increased understanding of the normal modes that contribute to the bands in the experimental spectra.

In our ONIOM calculations for neutral UQ₁ in the QA binding site we considered all amino acids included in the model only at the molecular mechanics level of computation. Previously, ONIOM calculations have been undertaken in order to model EPR data associated with the UQ anion in the QA binding site [50]. In these calculations key amino acids, such as HisM219 and AlaM260, were considered at the higher quantum mechanical level of calculation. Taken together these results may indicate differences in the nature of H-bonding for the neutral and anion UQ species. Changes in H-bonding upon radical formation may be a mechanism for (de)stabilizing cofactors to fine-tune electron transfer processes in biological systems. Clearly it will be useful to undertake calculations similar to that presented here (modeling isotope edited FTIR difference spectra) for the UQ anion in the QA binding site, and such calculations are
underway in our lab. Based on the above one could argue that the methods used here, with only the quinone treated at the QM level, will be inadequate to simulate the experimental spectra associated with quinone anions in the QA binding site. Or, for simulating the vibrational properties of quinone anions in the QA binding site it will be necessary to treat key amino acids at a quantum mechanical level. Again, calculations are underway in our lab to test this proposal.

For the neutral state of quinones occupying the QA binding site, calculations with the H-bonding amino acids treated at the MM level lead to calculated spectra that are in excellent agreement with experimental spectra (Figures 5.3, 5.4 and 5.5). Clearly, treating H-bonding amino acids quantum mechanically will not lead to improved modeling of the experimental spectra. We have in fact undertaken calculations in which neutral UQ and the H-bonding amino acids are treated using QM, and we have found that the calculated spectra are very similar to that obtained when only neutral UQ is treated using QM (and the surrounding amino acids are treated using MM) [63]. Thus it is very clear that, at least for the case of neutral quinones occupying the QA binding site, and as far as modeling isotope edited FTIR spectra is concerned, QM/MM calculations with only the quinone treated at the QM level need to be considered.

An experimental $^{18}$O isotope edited FTIR difference spectrum for UQ in the QA binding site is shown in Figure 5.5B. Three positive bands at 1660, 1629 and 1601 cm$^{-1}$ are observed. By considering FTIR difference spectra obtained using PBRCs with unlabeled and specifically $^{13}$C$_1$ and $^{13}$C$_4$ labeled UQ occupying the QA binding site, it was concluded that the 1660 and 1601 cm$^{-1}$ bands are due to the C$_1$=O and C$_4$=O vibrations of unlabeled neutral UQ, respectively. It was also concluded that the 1628 cm$^{-1}$ band is due to a UQ C=C vibration [47]. Since the C$_4$=O mode was so massively downshifted (from ~1660 cm$^{-1}$ for UQ in solvent to 1601 cm$^{-1}$ for UQ in the QA binding site) it was suggested that this group must be engaged in very strong
hydrogen bonding, presumably with HisM219 (Figure 5.2) [47]. This conclusion is difficult to rationalize based on the crystal structural data and other experimental data (see [134] for a review). Such a conclusion is also not supported by the data presented here. Specifically, the C_1=O and C_4=O modes of DMNQ and VK are found at 1653 and 1643 cm$^{-1}$ (Table 5.2), respectively, compared to ~1662 cm$^{-1}$ for the coupled C=O vibration in solution [90]. Thus the C_1=O/C_4=O mode of DMNQ or VK in the QA site is downshifted 9/19 cm$^{-1}$, respectively, compared to that found in solution. Such shifts suggest that both C=O modes of DMNQ or VK are H-bonded in the QA site, albeit quite weakly.

From the experimental spectrum of VK (or DMNQ) in Figure 5.3B two positive bands are observed at 1651 and 1640 cm$^{-1}$ and one negative band at 1620 cm$^{-1}$. The two C=O modes of unlabeled VK give rise to the positive bands at 1651 and 1640 cm$^{-1}$, but only a single band is observed at 1620 cm$^{-1}$ upon $^{18}$O labeling. Two interpretations for these observations have been proposed [109]. One suggestion is that upon $^{18}$O labeling the 1640 cm$^{-1}$ band downshifts to ~1620 cm$^{-1}$, while the 1651 cm$^{-1}$ band downshifts to near 1640 cm$^{-1}$ and decreases in intensity. The negative band near 1640 cm$^{-1}$ due to a C=O group of VK is then masked by the positive band (also at 1640 cm$^{-1}$) due to the unlabeled C=O group. A second hypothesis is that the two C=O modes of unlabeled VK (at 1651 and 1640 cm$^{-1}$) both downshift to ~1620 cm$^{-1}$ upon $^{18}$O labeling. The different $^{18}$O induced shifts of the two C=O modes results from differential coupling to C=C modes.

The calculated data presented here allow us to address which of these interpretations could be appropriate, or if either is appropriate. The ONIOM calculations show that the C_1=O and C_4=O modes of unlabeled VK occur at 1652 and 1642 cm$^{-1}$, and that neither of these modes are coupled to C=C modes (Table 5.2). Upon $^{18}$O labeling the C_1=O/C_4=O mode downshifts
The modes of $^{18}$O labeled VK also display considerable coupling with C=C modes. Upon $^{18}$O labeling the C$_1$=O/C$_4$=O group couples with C=C$_{\text{ring}}$ in-phase/out-of-phase vibrations, respectively. Coupling of the C$_4$=O group to the out of phase C=C vibration leads to a large intensity enhancement, while coupling of the C$_1$=O group to the in-phase C=C vibration leads to a large intensity decrease (Table 5.2). So, the calculations indicate that two separate uncoupled C=O modes in unlabeled VK give rise to predominantly a single mixed mode (that carries most of the intensity) in $^{18}$O labeled VK. These calculated results indicate that neither of the two previously proposed interpretations of the experimental spectra is correct. Clearly, the calculations presented here allow a more detailed insight into the nature of the bands in the experimental isotope edited FTIR difference spectra.

Experimentally, the vibrational modes of DMNQ are at a slightly higher frequency (~3 cm$^{-1}$) than corresponding modes of VK. Presumably replacing the C$_6$ methyl group with a phytol unit causes this difference. Interestingly, this small frequency difference in the modes of DMNQ and VK is also found in our ONIOM calculated spectra (compare spectra in Figure 5.5C and B). This result is not entirely specific to the ONIOM method, however, as a small shift is also found in the gas phase calculations (Figure 5.3D).

The C$_1$=O and C$_4$=O modes of DMNQ and VK are calculated to be separated by 10 cm$^{-1}$. This separation cannot be due to differences in the molecular group attached at C$_6$. It must be due to differences in how the two C=O groups interact with the protein. Similarly, the two C=O modes of DQ are calculated to be separated by 13 cm$^{-1}$, and this separation is also likely due to differences in how the two C=O groups of DQ interact with the protein.

For UQ$_1$ (and MQ$_0$) the separation of the C=O modes is ~32 cm$^{-1}$ (1660-1628). Some of the differences in frequency of the C=O modes of UQ are due to the different orientation of the
methoxy groups. If we assume that protein interactions with the C=O groups gives rise to a 13 cm\(^{-1}\) separation in the frequencies of the two C=O modes then this would indicate that the difference in the orientation of the methoxy groups of UQ (or MQ\(_0\)) gives rise to a frequency difference of 19 cm\(^{-1}\) for the two C=O groups. This result is in quite good agreement with results from experimental spectra of UQ in solution, which show that the two C=O modes are separated by \(\sim 16\) cm\(^{-1}\) [46, 47].

Normal mode vibrational frequencies are governed by molecular bonding force constants. These force constants relate to the electronic structure of the molecule. Since the calculated and experimental spectra for DMNQ and VK are virtually the same it is concluded that the replacing the phytanyl unit at C\(_6\) of VK with a methyl group does not appreciably perturb the electronic structure of the naphthoquinone ring. In addition, the tail does not perturb the protein in a way that significantly modifies any pigment protein interactions.

In VK and UQ\(_1\), the “kink” in the hydrocarbon chain after the first carbon atom is 3.1-3.2 degrees higher in ONIOM calculations compared to gas phase calculations. It seems therefore that the hydrocarbon chain is somewhat constrained relative to the quinone ring when incorporated into the Q\(_A\) binding site. It is not clear if this is a significant constraint, however. The C\(_1\)=O and C\(_4\)=O bonds of MQ\(_0\) and UQ\(_1\) (and of DMNQ and VK) are virtually unaltered in ONIOM calculations (Table 5.1). The hydrogen bond lengths for the C=O groups are also little altered (Table 5.1). The distance of the C\(_4\)=O oxygen to the non-heme iron atom is 0.029/0.055 Å longer for UQ\(_1\)/VK compared to MQ\(_0\)/DMNQ, respectively, suggesting a very small change in orientation of the UQ\(_1\)/VK head-group (since the iron atom is fixed) compared to MQ\(_0\)/DMNQ in the Q\(_A\) binding site. The hydrocarbon chain may therefore lead to a very slight change in the
orientation of the quinone ring in the QA binding site. Figure 5.2F shows that there is only a very small difference in the orientation of DMNQ relative to UQ1.

The experimental $^{18}$O isotope edited spectra for MQ0 and UQ1 are quite different (compare Figure 5.5B and C). This difference cannot be modeled computationally (Figure 5.5A). The experimental isotope edited spectrum for MQ0 is considerably noisier than the spectrum for UQ [157]. As far as we are aware the QA$^{-}$/QA FTIR difference spectrum for RCs with MQ0 in the binding site have never been reproduced, so the accuracy of the spectrum may be somewhat questionable. On the other hand MQ0 may be able to incorporate into the QA binding site with the methoxy groups oriented in several different ways. As described previously, each of these methoxy group conformers will have slightly different spectra [140]. This heterogeneity in orientation of MQ0 in the QA binding site may be a factor that contributes to differences in the experimental spectra for MQ0 and UQ, as demonstrated in Figure 5.5B and C. In spite of this, there are some overall similarities in the MQ0 and UQ1 experimental spectra in Figure 5.5B and C. For the MQ0 spectrum positive bands are found at 1665, 1631 and 1608 cm$^{-1}$. For UQ1 the bands are at 1660, 1628 and 1601 cm$^{-1}$. For the MQ0 spectrum negative bands are found at 1616 and 1602 cm$^{-1}$. For UQ the bands are at 1613 and 1586 cm$^{-1}$.

The ONIOM calculated and experimental isotope edited spectra for VK are very similar, although the intensity ratios of the different bands do not appear to match well. For example, the intensity ratio of 1652 and 1644 cm$^{-1}$ bands in the calculated spectrum (Figure 5.3A, dotted) is ~2.1, compared to a ratio of ~0.95 in the experimental spectrum. To investigate this further we have also calculated the $^{13}$C isotope edited spectrum for VK in the QA binding site (Figure 5.6A) (global $^{13}$C labeling of VK), and compared it to the corresponding experimental spectrum (Figure 6B). For completeness the calculated $^{13}$C isotope edited spectrum for VK in the gas phase is
shown in Figure 5.6C. Again, it is evident that the calculated gas phase spectrum in no way resembles the experimental spectrum (compare Figure 5.6B and 5.6C). The normal modes (frequencies, intensities and PEDs) that give rise to the various bands in the ONIOM calculated $^{13}\text{C}$ isotope edited spectra of VK in Figure 5.6A are listed in Table 5.3.

![Graph of spectra](image)

Figure 5.6 (A) ONIOM calculated $^{13}\text{C}$ isotope edited DDS for neutral VK in the Q$_A$ binding site. Experimental spectrum is also shown (B), taken from [163] (with permission). (C) DFT calculated $^{13}\text{C}$ isotope edited DDS for neutral VK in the gas phase. ONIOM and gas phase calculated spectra were scaled by 0.9718 and 0.9608, respectively.

Notice that the ONIOM calculation predicts that the two C=O modes remain completely separate (do not mix) upon $^{13}\text{C}$ labeling (Table 5.3), which is unlike the behavior observed for the C=O modes upon $^{18}\text{O}$ labeling (see above). Also notice that in the experimental isotope edited spectrum (Figure 5.6B) the 1640 cm$^{-1}$ band is now considerably more intense than the 1651 cm$^{-1}$ band, whereas in the calculated spectrum the higher frequency band is considerably more intense. The origin of these mode intensity differences are not entirely clear and are currently being investigated by considering calculations associated with VK in the presence of various types of H-bonding molecules.
Table 5.3 Normal mode frequencies (in cm$^{-1}$), intensities (in km/mol) and PEDs (in %) calculated using ONIOM methods for unlabeled and $^{13}$C labeled neutral VK. Frequency shifts upon $^{13}$C labeling are also listed. Negative signs in the PEDs refer to the relative phase of vibration of the internal coordinates. Only internal coordinates that contribute at least 5 % are shown. Mode frequencies were scaled by 0.9718.

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<td>$C=C_{arom}$ (54), $-C_4=O$ (5)</td>
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5.5 Conclusions

We have shown that ONIOM type QM/MM calculations can be used to model experimental isotope edited FTIR difference spectra obtained using purple bacterial reaction centers that have had several different quinones incorporated into the QA binding site. The fact that the many different spectra can all be modeled is a clear indicator of the appropriateness of the approach.

The calculated spectra appear not to depend on whether the quinone incorporated has a prenyl/phytyl unit or a methyl group attached at C$_6$. The electronic structure of the quinone ring is therefore not sensitive to the presence or absence of a hydrocarbon side chain at C$_6$. This suggests that the hydrocarbon side chain does not significantly constrain the quinone ring in the QA binding site.

Comparison of the calculated and experimental spectra, in combination with a consideration of the calculated potential energy distributions of the normal modes, allows a direct assessment of the appropriateness of previous suggestions as to the origin of the bands in the experimental spectra.
6 CONCLUSIONS AND FUTURE WORK

6.1 Dissertation conclusions

This dissertation presents studies of the vibrational properties of quinones in photosynthetic reaction centers (RCs) using FTIR DS in combination with ONIOM type QM/MM vibrational frequency calculations. In particular, quinones in the A1 binding site in PS I, and in the QA binding site in purple bacterial RCs were studied.

PhQ has a long hydrocarbon (phytyl) chain. 2MNQ is a PhQ analogue in which the hydrocarbon chain is replaced with a hydrogen atom. To evaluate if the hydrocarbon chain of PhQ influences FTIR difference spectra, we compared spectra obtained using PS I particles with PhQ and 2MNQ incorporated into the A1 binding site. ONIOM type QM/MM calculations aimed at modeling the experimental (2MNQ-PhQ) A1/A1 FTIR DS were also undertaken. The calculated spectrum agrees well with the experimental spectrum. The calculations indicate that the hydrocarbon chain of PhQ does not significantly modify the orientation of PhQ or PhQ' in the A1 binding site, compared to 2MNQ.

To test the appropriateness of the computational methods, and to further investigate whether the presence of the hydrocarbon chain constrains the quinone ring, calculations were undertaken for several different quinones in the QA binding site. In particular chain containing and corresponding chain-less UQ and PhQ species were studies. The calculated spectra are very similar for incorporated quinones with and without a hydrocarbon chain, again suggesting that the hydrocarbon chain does not constrain the quinone ring in the protein binding site.

Our studies help in better understanding the role of hydrocarbon chain in the QA binding site. The available literature indicates that the hydrocarbon chain in the QA binding site plays an important role in the binding free energies for UQ and menaquinones. It was also found that
competitive interference of quinone function can be effectively inhibited by in vivo tail-protein interaction by amphiphilic species present in the native membrane [154].

ONIOM type QM/MM calculations were an essential aid in assigning bands to the vibrational modes of PhQ and PhQ\(^-\) (and 2MNQ and 2MNQ\(^-\)) in TRSS A\(_1\)/A\(_1\) FTIR DS. In experimental spectra, a band at 1494 cm\(^{-1}\) was observed and assigned (based on computational modeling) to a C\(_1\)=O stretching vibrational mode of PhQ\(^-\). The corresponding mode of 2MNQ\(^-\) was found at 1505 cm\(^{-1}\) and assigned similarly. A band at 1415 cm\(^{-1}\) was observed and assigned to a C\(_4\)=O stretching vibrational mode of PhQ\(^-\). The corresponding mode appears at 1427 cm\(^{-1}\) for 2MNQ\(^-\).

Based on the accumulated results from several sets of experiments bands of neutral PhQ were identified at 1656 and 1596 cm\(^{-1}\) and assigned (via calculation) to C\(_1\)=O and C\(_4\)=O modes of neutral PhQ, respectively. ONIOM calculations predict that upon binding at the A\(_1\) site, the C\(_4\)=O mode of PhQ and PhQ\(^-\) are downshifted ~60 and 80 cm\(^{-1}\) relative to the C\(_1\)=O mode, respectively. The C\(_1\)=O group is essentially free from hydrogen bonding while the C\(_4\)=O group is very strongly hydrogen bonded. Such strong hydrogen bonding has been observed in other systems. For example, intramolecular hydrogen bonding interactions in \(\beta\)-hydroxylated naphthoquinones and anthraquinones cause downshifts of C=O modes by 30–80 cm\(^{-1}\) [164, 165]. For Lewis acids interacting with carbonyl groups, notably with phenyl ketones [166] C=O mode downshifts of 70–180 cm\(^{-1}\) have been documented. Hence, a 60–80 cm\(^{-1}\) downshift of the C\(_4\)=O mode for PhQ or PhQ\(^-\) observed in our studies is not totally unprecedented.

We also studied isotope edited Q\(_A\)/Q\(_A\) FTIR DS, by comparing ONIOM based calculations to experimental spectra. For neutral UQ in the Q\(_A\) binding site, the C\(_4\)=O mode of UQ downshifted ~32 cm\(^{-1}\) due to the H-bonding. This downshift indicated that the formed H-
bond of C₄=O group of UQ with the QA binding site was not strong. Isotope edited difference spectra calculated with ONIOM methods were similar when H-bonding amino acids were treated at the MM level and at the QM level. This result further supports that the H-bonding to neutral UQ in the QA binding site is relatively weak and can be considered in purely electrostatic terms.

The differences in H-bonding to two C=O groups of UQ would cause separation of two C=O modes. Our studies showed that the H-bond to the C₄=O group (provided by the side chain NH group of HisM219) was stronger than the H-bond to the C₁=O group (provided by the backbone NH group of AlaM260).

Previous studies show that the reduction potential for PhQ in the A₁ binding site was -800 mV [167], compared to -190 mV for UQ or menaquinone in the QA binding site [168], and the difference could be due to their different structures of the hydrocarbon chain. Another study suggested that the strong hydrogen bonds, possibly from the enveloping proteins, make quinones more reducible [169]. In our study with quinones in the PS I and purple bacteria RCs, time-resolved (TR) FTIR DS in combination with ONIOM calculations suggests that the single H-bonding to quinone is very strong in the A₁ binding site, while the H-bonding to quinone is relatively weak and asymmetric in the QA binding site. Therefore, the work presented here suggests that the reduction potential of quinone is more negative in the A₁ binding site than in QA binding site, because of the stronger H-bond.

6.2 Future work

The work presented here has shown that ONIOM type QM/MM vibrational frequency calculations are an essential tool for assigning bands in FTIR DS associated with cofactors in protein binding sites.
TR A₁₁/A₁ FTIR DS obtained using PS I particles with supposedly plastoquinone incorporated (from menB mutants) is dominated by bands associated with ³P700, indicating that, under our conditions, the A₁₁ bind site is empty, or the quinine in the binding site does not support forward electron transfer, in a large fraction of the PS I particles [83]. However, EPR studies of menB mutant PS I showed that PQ9 is present in the A₁₁ site, and it functions as an efficient cofactor in electron transfer [78]. How or whether the hypotheses proposed from EPR studies are compatible with FTIR DS studies is still an open question. ONIOM calculations of plastoquinone incorporated into the A₁₁ binding site could be used to interpret these experimental results.

We have undertaken ONIOM calculations for the neutral state of UQ in the QA binding site. However, ONIOM calculations for UQ⁻ in the QA binding site have yet to be presented.

Experimental Q₆/Q₆ isotope edited FTIR DS have been obtained. Although the reconstitution of purple bacterial RCs with isotope labeled quinones allowed separation of quinone bands from those of the protein, the interpretation of the spectra is still purely qualitative. No computational studies have been undertaken in the attempt to model the Q₆/Q₆ isotope edited FTIR DS.

The X-ray crystal structures of the mutant RCs Pro-L209→ Tyr, Pro-L209→ Phe, and Pro-L209→ Glu have revealed that Q₆ occupies a proximal, intermediate, and distal position in these three mutants, respectively. However, all Q₆/Q₆ FTIR DS obtained using the above mutants are similar to wild type. ONIOM type calculations may be a useful tool to address this issue. The various locations and orientations of Q₆ observed in the different crystallographic structures of the RC can be explained by the Q₆ model whose ONIOM calculated frequencies agree with experimental measurements. In addition, comparison of vibrational modes of UQ in
Q_A and Q_B binding sites would enable the comparison of the interaction between UQ and protein in different binding sites.

We have shown that TR FTIR DS is a useful tool for probing the substituents of quinones in protein binding sites. Similar experiments for different quinones incorporated into A_1 binding site can be designed to investigate the role of other quinine functional groups, such as the methyl group of the quinone ring. In addition, more experimental data (specific isotope labeling of incorporated quinones, in combination with computational work, are required to establish band assignments unambiguously.
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