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Transient Raman spectroscopy of ^{15}N -substituted bacteriochlorophyll a. An empirical assignment of T_1 Raman lines

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Abstract

^{15}N -substituted bacteriochlorophyll a (BChl a) was extracted from the cells of *Rhodobacter sphaeroides* 2.4.1 grown in a medium containing ^{15}N -ammonium sulfate and yeast concentrate. The T_1 Raman spectra of ^{14}N - and ^{15}N -BChl a were obtained as the difference spectra of high-power minus low-power of one-color, pump-and-probe measurements using 420 nm, 5 ns pulses. A set of empirical assignments of the T_1 Raman lines was made, based on shifts upon $^{14}\text{N} \rightarrow ^{15}\text{N}$ substitution. The S_0 Raman spectra of the two BChls were also obtained by using the 457.9 nm cw beam, and a set of assignments of the S_0 Raman lines was given for comparison.

1. Introduction

Bacteriochlorophylls (BChl) in excited states play important roles in bacterial photosynthesis: The S_1 state is responsible for singlet energy transfer in light-harvesting complexes (LHC) and for charge separation at the special pair in the reaction center (RC). On the other hand, the T_1 state is generated at the special pair by charge recombination under reducing conditions, and the triplet energy is transferred, via one of the accessory BChls, to the carotenoid (Car) to be dissipated [1,2]. In the triplet energy transfer reaction to the Car, the electronic and molecular structure of T_1 state BChl must be most important, since the overlap of the LUMOs and the HOMOs is a crucial factor for the reaction to take place.

Changes in the bond order in the macrocycle of BChl a, upon excitation, have been shown by transient Raman spectroscopy, a decrease (increase) in

the bond order for a bond with a double-bond (single-bond) character has been predicted based on changes in Raman frequencies upon excitation to both the T_1 [3] and S_1 [4] states. Here, comparison of the Raman frequencies was based on the assumption that no drastic changes should take place in the bond order. Thus, a pair of Raman lines with the nearest frequencies were correlated between the ground state and the excited state in question.

Since BChl molecules with exactly the same structural formula play different roles depending on the binding site in pigment-protein complexes, the excited-state structures and properties must be controlled by intermolecular interaction with apo-protein(s) and/or nearby pigment(s). From this viewpoint, solvent effects on T_1 state BChl a have been examined by transient Raman spectroscopy [5,6], and the penta- and hexa-coordinated monomeric states as well as the penta-coordinated aggre-

gated state were differentiated by the use of 'the ring-breathing mode' in the T_1 state.

The above two sets of conclusions critically depend on the assignment of the excited-state Raman lines. The assumption of no drastic changes in the bond order upon triplet excitation was not warranted in linear polyenes (retinoids and carotenoids). Upon excitation to the triplet state, large changes in the bond order, toward inversion, take place in the central part of a conjugated chain, which we call 'the triplet-excited region', although the bond order in the S_0 state is conserved at both ends [7,8]. Such drastic changes in the electronic and molecular structure may take place in BChl **a** as well.

In order to examine this issue by characterizing each Raman line, the most powerful technique is isotope substitution which was successfully applied to S_0 state BChl **a** by Lutz [9]. In the present investigation, we have attempted to record the T_1 and S_0 Raman spectra of ^{14}N - and ^{15}N -BChl **a** in order to answer the following two questions. (1) How can the T_1 and S_0 Raman lines be assigned empirically based on isotope substitution? (2) How does the T_1 Raman spectrum compare with, or contrast to, the S_0 Raman spectrum?

2. Experimental

Cells of *Rhodobacter sphaeroides* 2.4.1 were grown in the rhodospirillaceae medium [10], in which 0.1 g/l $^{14}\text{NH}_4\text{Cl}$ was replaced by 0.2 g/l $(^{15}\text{NH}_4)_2\text{SO}_4$ (Sigma-Aldrich, 98 at%) and yeast extract was replaced by yeast concentrate (Sigma) [11]. ^{15}N -substituted bacteriochlorophyll **a** (^{15}N -BChl **a**) was extracted from the cells with methanol in the dark under nitrogen atmosphere. It was transferred to the mixed ether layer by partitioning between petroleum ether/diethyl ether (1:2 v/v) and water. After drying, it was purified by column chromatography using Sepharose CL-6B as the stationary phase, and 2-propanol/*n*-hexane (1:20 v/v) as the eluent. Analysis by HPLC of ^{15}N -BChl **a** thus obtained showed a single peak (detection at both 355 and 435 nm). ^{14}N -BChl **a** was obtained as described previously [3].

The T_1 Raman spectrum was obtained in acetone solution (3×10^{-3} M, sealed under nitrogen atmo-

sphere in an ampule and rotated) by a one-color experiment using the 420 nm pulses (duration 5 ns and repetition 10 Hz) as the difference spectrum which was obtained by subtracting a low-power spectrum (0.3 mJ/pulse) from a high-power spectrum (2.0–2.4 mJ/pulse). The authentic S_0 Raman spectrum was obtained in acetone solution (9×10^{-3} M) by the use of the cw 457.9 nm beam of an Ar^+ -ion laser (17 mW). The details were described previously [3,6]. Spectral smoothing was performed for both the T_1 and S_0 Raman spectra.

The substitution of ^{15}N at each nitrogen site, i.e. $x = [^{15}\text{N}] / ([^{15}\text{N}] + [^{14}\text{N}])$, was determined as follows. (1) Four ^{15}N peaks in the NMR spectrum of ^{15}N -BChl **a** showed equal intensity, a fact which indicates equal substitution at the four nitrogen sites in BChl **a**. (2) A mass spectrum of ^{14}N -BChl **a** showed a series of peaks with the interval of one mass unit originating from the molecular ion of BChl **a**, M^+ , and those of $(M-1)^+$, $(M-2)^+$, ... and $(M+1)^+$, $(M+2)^+$, ... due to the abstraction and addition of hydrogen by the solvent, *m*-nitro-benzyl-alcohol. (3) A mass spectrum of ^{15}N -BChl **a** showed a series of peaks, the changes in the relative intensity of which were ascribed to the generation of a series of isotope species in the ratio, $^{15}\text{N}_4: ^{15}\text{N}_3^{14}\text{N}_1: ^{15}\text{N}_2^{14}\text{N}_2: ^{15}\text{N}_1^{14}\text{N}_3: ^{14}\text{N}_4 = 0.09: 0.24: 0.32: 0.22: 0.13$, which lead to a value of x of approximately 0.55. The distribution of various molecular ions was assumed to be the same between ^{14}N -BChl **a** and ^{15}N -BChl **a**.

3. Results and discussion

3.1. Efficient preparation of ^{15}N -BChl **a**

Growth conductions (complete consumption of oxygen in the medium before starting irradiation, moderate light intensity and a temperature of 30°C) to keep the cells of *Rhodobacter sphaeroides* active turned out to be most important in ^{15}N incorporation; much better results were obtained for the wild type 2.4.1 than for a carotenoidless mutant R26.1. The cells were adapted for a couple of transfers (5–7 days of incubation each time) to the medium containing ammonium sulfate and yeast concentrate. In order to enhance the ^{15}N enrichment, the amount of

the nitrogen source was reduced to 40% before culturing the cells in the medium containing $(^{15}\text{NH}_4)_2\text{SO}_4$.

In order to increase the yield in the purification procedure of ^{15}N -BChl a, the conditions in the column chromatography were carefully controlled so that pure ^{15}N -BChl a could be obtained without further purification by HPLC. A typical extraction and purification procedure to obtain 150–200 mg of ^{15}N -BChl a from 40 g cells took less than 5 h; this rapid procedure strongly prevented degradation of BChl a.

3.2. Isotope shifts and assignment of Raman lines in the S_0 state

Fig. 1 shows the chemical structure of BChl a together with the atom typification used. The macrocycle has the bacteriochlorine skeleton containing two unsaturated rings (rings I and III) and two saturated rings (rings II and IV); an additional saturated ring (ring V) is attached to ring III. All the C–C and C–N stretchings in the macrocycle are expected to be coupled with one another to form a set of normal modes.

Nishizawa and Koyama [3] attempted to estimate the π -bond order of each bond in the bacteriochlorine skeleton based on a set of resonance structures,

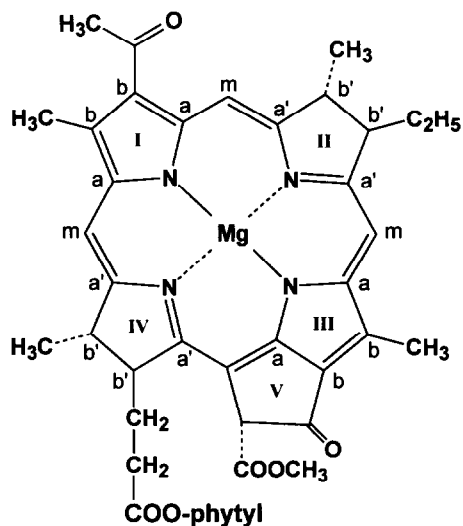


Fig. 1. The chemical structure of bacteriochlorophyll a (BChl a) and typification of atoms.

and predicted the intrinsic frequencies of the stretching vibrations in the following order: $C_{a'}-C_m > C_b-C_b = C_a-C_b > C_a-C_m = C_{a'}-N > C_a-N$. Donohoe et al. [12] calculated the normal vibrations of the BChl a model by the QCFF/PI method. Here, the differentiation between the $C_{a'}-C_m$ and C_a-C_m ($C_{a'}-N$ and C_a-N) stretchings turned out to be of no practical significance because of strong coupling between them. The coupled stretching vibrations appeared in the following order: the C_a-C_m stretchings ($1650-1540\text{ cm}^{-1}$) $>$ the C_b-C_b stretchings ($1620-1520\text{ cm}^{-1}$) $>$ the C_a-C_b stretchings ($1530-1430\text{ cm}^{-1}$) $>$ the C_a-N stretchings ($1390-1280\text{ cm}^{-1}$) $>$ the C_m-H deformations ($1280-1200\text{ cm}^{-1}$) $>$ the C_a-N stretchings ($1200-1100\text{ cm}^{-1}$). (The C_a-N stretchings were split into two separate regions.)

The Raman spectra of monomeric and oligomeric BChl a at 30 K probed at 363.8 nm have been reported by Lutz and Robert [13] and Lutz [9], and a set of empirical assignment of the Raman lines for the entire spectral region was proposed on the basis of the $^{14}\text{N} \rightarrow ^{15}\text{N}$ and $^{24}\text{Mg} \rightarrow ^{26}\text{Mg}$ substitutions [9].

The above theoretical and experimental results obtained so far, together with the shifts upon the $^{14}\text{N} \rightarrow ^{15}\text{N}$, will be used in the following empirical assignments of the S_0 and T_1 Raman lines.

Fig. 2 shows the S_0 Raman spectra of (1) ^{14}N - and (2) ^{15}N -BChl a. The pattern of the present spectrum

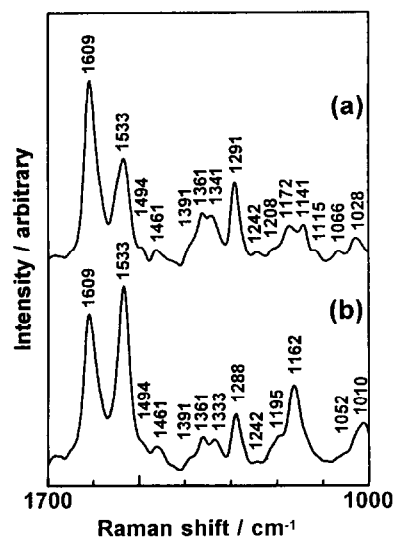


Fig. 2. The S_0 Raman spectra of (a) ^{14}N - and (b) ^{15}N -BChl a.

of ^{14}N -BChl a (457.9 nm excitation, in acetone solution, and at room temperature) is slightly different from that reported by Lutz and Robert [13] (363.8 nm excitation, in methylimidazole, and at 30 K), although major Raman lines are observed in common in these spectra. The difference must originate from the different wavelengths of probing (supported by the measurement of an excitation profile), the amount of substitution, and from the spectral resolution which depends also on the temperature. (The Raman spectra of ^{14}N - and ^{15}N -BChl a probed by the 420 nm pulses with low photon density (low lasing power and defocused beam) should represent the S_0 Raman spectra. The spectral patterns (data not shown) are similar to, but definitely different from, those of Fig. 2. This is due to the different wavelength of probing, and also due to some contribution of the T_1 species generated by the pulsed excitation.)

Fig. 3a compares schematically the authentic S_0 Raman lines (probed by the cw 457.9 nm beam) between the ^{14}N - and ^{15}N -BChl a. The S_0 Raman lines of ^{14}N -BChl a can be classified into two groups based on the shifts upon $^{14}\text{N} \rightarrow ^{15}\text{N}$ -substitution and assigned as follows.

(a) Raman lines which are not affected by the isotope substitution. The line at 1609 cm^{-1} should be definitely assigned to the $\text{C}_a\text{-C}_m$ stretching, while the 1533 cm^{-1} line can be assigned to the $\text{C}_b\text{-C}_b$ (probably coupled with $\text{C}_a\text{-C}_b$) stretching. The 1494 and 1461 cm^{-1} lines can be assigned to the $\text{C}_a\text{-C}_b$ (coupled with $\text{C}_b\text{-C}_b$) stretchings. Finally, the 1391 , 1361 and 1242 cm^{-1} bands may be assigned to the $\text{C}_m\text{-H}$ deformations.

(b) Raman lines which are shifted by the isotope substitution. A shoulder at 1549 cm^{-1} and the lines at 1341 and 1291 cm^{-1} , all of which are shifted to the lower frequencies by the isotope substitution, are to be related to the $\text{C}_a\text{-N}$ stretchings. Medium and weak Raman lines in the $1230\text{--}1000\text{ cm}^{-1}$ are strongly affected by the isotope substitution, which is probably due to the presence of variously ^{15}N -substituted species. It is almost impossible to correlate any pair of the Raman lines between ^{14}N - and ^{15}N -BChl a, and to define 'the isotope shifts' as has been done by Lutz [9].

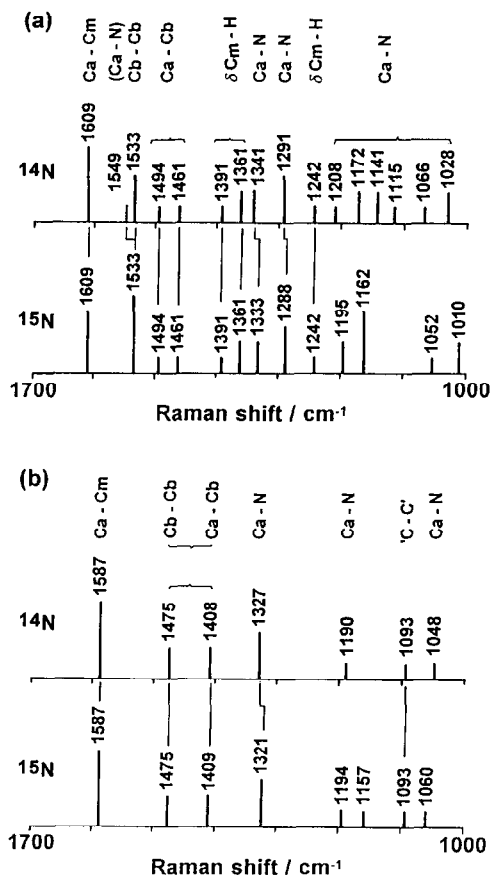


Fig. 3. A schematic presentation of (a) the S_0 and (b) the T_1 Raman lines of ^{14}N - and ^{15}N -BChl a. A pair of empirical sets of assignments are also given.

3.3. Isotope shifts and assignment of Raman lines in the T_1 state

Fig. 4 shows the T_1 Raman spectra of ^{14}N - and ^{15}N -BChl a. Fig. 3b compares schematically their Raman lines. The T_1 Raman lines of ^{14}N -BChl a also can be classified into two groups based on the isotope shifts and assigned as follows.

(a) Raman lines which are not affected by the isotope substitution. The line at 1587 cm^{-1} should be definitely assigned to the $\text{C}_a\text{-C}_m$ stretching which we referred to as the ring-breathing mode [5]. It is not shifted by the $^{14}\text{N} \rightarrow ^{15}\text{N}$ substitution, and the in-phase stretching of the $\text{C}_a\text{-C}_m$ (and $\text{C}_a'\text{-C}_m$) bonds is expected to give rise to this high Raman intensity. The 1475 and 1408 cm^{-1} lines can be assigned to the $\text{C}_b\text{-}$

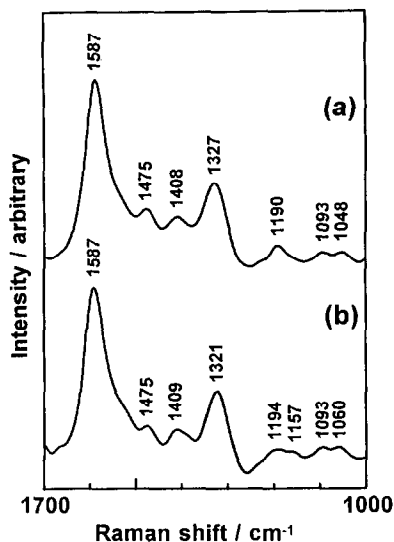


Fig. 4. The T_1 Raman spectra of (a) ^{14}N - and (b) ^{15}N -BChl a.

C_b and C_a-C_b stretchings, which may be coupled with one another. The Raman line at 1093 cm^{-1} is assigned to some 'C-C' single-bond ($C_{b'}$ - $C_{b'}$ and/or $C_{a'}$ - $C_{b'}$) stretching.

(b) Raman lines which are shifted by the isotope substitution. The Raman line at 1327 cm^{-1} , which shifts to lower frequency upon the isotope substitution, can be assigned to one of the C_a-N stretchings. The 1190 and 1048 cm^{-1} lines are related to the C_a-N stretchings. Large changes in the spectral pattern in the region below 1200 cm^{-1} (except for the 1093 cm^{-1} line) prevents the correlation of the Raman lines between ^{14}N - and ^{15}N -BChl a and also the definition of the isotope shifts; this is probably due to the presence of variously ^{15}N -substituted species as in the case of the S_0 state.

Thus, two sets of empirical assignments have been given for the S_0 and T_1 Raman lines to answer the first question addressed in Section 1. The Raman lines in the highest frequency region have been characterized as the C_a-C_m , C_b-C_b , and C_a-C_b stretchings. The present results support the previous conclusion: (1) that a decrease in the bond order takes place, upon triplet excitation, for the C-C bonds with a double-bond character [3], and (2) that the ring-breathing mode reflects the states of coordination and aggregation in T_1 state BChl a [5]. However, the Raman lines in the region below 1200 cm^{-1} could not be characterized. Therefore, the conclusion that an increase in

the bond order takes place for a C-C or C-N bond with a single-bond character awaits a final proof.

As for the spectral comparison between the S_0 and T_1 states to answer the second question in Section 1, it has been found that the spectral patterns of T_1 state BChl a (Fig. 3b) are much simpler than those of S_0 state BChl a (Fig. 3a). The situation is similar to the case of retinal, which was analyzed in great detail by combination of specific deuterium substitutions and the calculation of normal vibrations (unpublished results). Only selected vibrational modes appear in the T_1 Raman spectrum of retinal; those vibrational modes which take place in 'the central, triplet-excited region' gave rise to high Raman intensity, while those vibrational modes taking place at the peripheral parts did not appear in the T_1 spectrum. The present T_1 Raman spectrum (with fewer Raman lines and the large low frequency-shifts of the carbon-carbon double-bond stretchings) suggests the presence of 'a triplet-excited region' in BChl a as well, although the final conclusion should wait for a detailed analysis by the calculation of normal vibrations for the completely isotope substituted species.

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