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Resonance Raman Evidence That the Thioester-Linked 4-Hydroxycinnamyl Chromophore of Photoactive Yellow Protein Is Deprotonated†

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ABSTRACT: Resonance Raman spectra of the ground state of photoactive yellow protein (PYP), a photoactive pigment found in Ectothiorhodospira halophila, have been obtained with excitation at 413.1 nm using a microspinning sample cell. The resonance Raman spectra of the thioester-linked 4-hydroxycinnamyl chromophore in the protein are compared with the preresonance Raman spectra of the 4-hydroxycinnamyl phenyl thioester and 4-hydroxycinnamic acid model compounds at various pH values. Bands at 1568, 1542, 1500, 1434, and 1166 cm⁻¹ in the Raman spectrum of the anionic form of the 4-hydroxycinnamyl phenyl thioester are shown to be characteristic for the deprotonation of the chromophore. The observation of bands in PYP exhibiting very similar frequency and intensity patterns provides strong evidence that the chromophore in PYP is stabilized as a phenolate anion at pH 7.4, in support of conclusions from crystallographic studies. Furthermore, the insensitivity of the PYP Raman spectrum to placement of the protein in D₂O buffer is consistent with the absence of the exchangeable phenolic proton on the cinnamyl chromophore. These results establish the feasibility of elucidating the molecular mechanism of light-to-information transduction by this new photosensory pigment with resonance Raman spectroscopy.

Photoactive yellow protein (PYP), a water-soluble yellow-colored protein with a visible absorption maximum at 446 nm, is found in several halophilic phototrophic bacteria including Ectothiorhodospira halophila (Meyer, 1985; Meyer et al., 1990; Hoff et al., 1994a). E. halophila exhibits a negative phototactic reaction or repellent response to physiological intensities of blue light (Sprenger et al., 1993). The wavelength dependence of this photosponse matches the absorption spectrum of PYP, leading to the hypothesis that PYP functions as the photoreceptor in E. halophila (Sprenger et al., 1993). Absorption of a photon by PYP initiates a cyclic photochemical reaction with at least two photointermediates (Meyer et al., 1987; Hoff et al., 1994a). The photocycle of PYP is similar to those of membrane-bound rhodopsins isolated from Halobacterium salinarium (Meyer et al., 1987; Hoff et al., 1994a). However, the protein structure of PYP is very different from that of bacteriorhodopsin (McRee et al., 1989; Van Beeumen et al., 1993); PYP has an α/β-fold characterized by a central, twisted, six-stranded, antiparallel β-sheet flanked on both sides by loops and helices (Borgstahl et al., 1995), while bacteriorhodopsin contains seven closely packed α-helices (Henderson et al., 1990). In addition, while the chromophore of PYP is a 4-hydroxycinnamyl group covalently bound to a cysteine via a thioester linkage (Hoff et al., 1994b; Baca et al., 1994), all rhodopsins contain a Schiff base-linked retinal chromophore. PYP therefore exemplifies a new class of photoreceptor proteins whose protein structure is now well known (Hoff et al., 1994b; Baca et al., 1994; Borgstahl et al., 1995). However, little is known about the structure of the chromophore and especially the light-induced structural changes in the chromoprotein that lead to the signaling state of this photoreceptor.

We report here the first resonance Raman vibrational spectra of PYP. Resonance Raman spectroscopy provides a sensitive and selective probe for monitoring the structure and structural changes of chromophores embedded in proteins [for example, see Mathies et al. (1987)]. Interestingly, X-ray crystallographic data suggest that the chromophore in the ground state of PYP is stabilized within the folded protein as a phenolate anion (Baca et al., 1994; Borgstahl et al., 1995). This suggestion encouraged us to examine the ionization state of the chromophore using resonance Raman spectroscopy. To interpret the basic vibrational characteristics of the PYP chromophore, preresonance Raman spectra of the 4-hydroxycinnamyl phenyl thioester and 4-hydroxycinnamic acid model compounds were also obtained at various pH values. Comparison of PYP and model compound Raman data provides strong evidence that the chromophore in native PYP is deprotonated at the phenolic hydroxyl group at pH 7.4 and also gives new insight into how the chromophore interacts with the encompassing protein. This work establishes the feasibility of studying the various PYP photointermediates to elucidate its mechanism of phototransduction.

MATERIALS AND METHODS

Photoactive yellow protein from E. halophila was isolated by a modification of Meyer’s method (1985) as described by Hoff et al. (1992). Typically, 200 μg of freeze-dried...
FIGURE 1: Microspinning sample cell for resonance Raman spectroscopy. Typically, ~80 \mu L of aqueous protein solution was secured into a shallow circular chamber (18 mm diameter) in a stainless steel block that was formed by clamping a thin circular cover glass (18 mm diameter, 150 \mu m thick) on a 360 \mu m thick Teflon spacer using a threaded ring. The resonance Raman scattering was collected at about 90° to the incident laser beam.

The model compound, 4-hydroxycinnamyl phenyl thioester (HCPT), was prepared by the reaction of thiophenol with acyloxyppyridinium salt formed from free 4-hydroxycinnamic acid and 2-fluoro-1-methylpyridinium p-toluenesulfonate, as described previously (Duran et al., 1987). The final purification of the model compound was performed with a Rainin HPLC, which was equipped with a C18 reverse phase column (25 mm x 500 mm) run with a linear gradient from 60% acetonitrile in water to 100% acetonitrile over 40 min at 4.0 mL min\(^{-1}\). The eluted solution was then vacuum evaporated.

A microspinning sampling system, consisting of a thin (150-\mu m) circular cover glass (18 mm diameter) and a 360-\mu m Teflon spacer, was developed for resonance Raman studies on PYP. The sample spinning system, which is shown in Figure 1, allows us to record resonance Raman spectra from as little as 80 \mu L of colored-protein solution at any rotation speed from 1 to 30 Hz. This minimized the contamination of spectra with scattering from photoproducts that might build up using stationary cell formats. For presereresonance Raman spectra, a rectangular Suprasil cell was used in the 90° geometry. The Raman spectra, excited by the 413.1- and 647.1-nm lines from a Spectra Physics 2025-11 Kr\(^{+}\) laser and by the 488.0-nm line of a Spectra Physics 2020 Ar\(^{+}\) laser, were measured using a modified Spex 1400 polychromater (Mathies and Yu, 1978) equipped with a Princeton Instruments Model LN-CCD with a UV-coated EEV Model 88130 (298 x 1152 pixel) array. The spectral slit width was 10, 8, and 6 cm\(^{-1}\) for 413.1-, 488.0-, and 647.1-nm excitations, respectively. Typical data acquisition times were 45 and 10 min for the protein and model compounds, respectively. The data were collected with the use of CSMA software (Princeton Instruments) on a PC and processed by Igor Pro version 2.03 (WaveMetrics) on a Macintosh Quadra 700. The spectra were calibrated by comparison to the Raman bands of cyclohexanone for 647.1- and 488.0-nm excitation and to those of 25% acetone/water for 413.1-nm excitation.

RESULTS AND DISCUSSION

The 413.1-nm excited resonance Raman spectra of PYP in H\(_2\)O and D\(_2\)O in the 1750–1000 cm\(^{-1}\) region are compared in Figure 2 with the 488.0-nm excited presereresonance Raman spectrum of the neutral form of 4-hydroxycinnamyl phenyl thioester (HCPT), at pH 6.0 and further with the 647.1-nm excited presereresonance Raman spectrum of the anionic form of HCPT at pH 9.5. At a glance, the resonance Raman spectrum of PYP in H\(_2\)O in Figure 2A is more similar to the Raman spectrum of the neutral form of HCPT in Figure 2D than to the spectrum of its neutral form in Figure 2C. Specifically, the bands at 1558, 1534, 1498, 1439, 1288, and 1165 cm\(^{-1}\) in Figure 2A exhibit a similar intensity and frequency pattern to those at 1568, 1542, 1500, 1434, 1306, and 1166 cm\(^{-1}\) in Figure 2D.

Before examining the details of the protein spectra, the effect of deprotonation on the molecular vibrations of HCPT...
must be examined to determine the proper chemical structure
to be discussed. Upon deprotonation, the most intense
doublet band centered at 1600/1587 cm⁻¹ in Figure 2C
downshifts to 1568/1542 cm⁻¹. The two bands at 1600 and
1587 cm⁻¹ are analogous to the Y8a and Y8b modes of
tyrosine, respectively (Harada & Takeuchi, 1986). The deprotonation of tyrosine to form tyrosinate
is known to shift the Y8a and Y8b modes from 1617 to 1603
cm⁻¹ and from 1601 to 1558 cm⁻¹, respectively. The
latter large 43-cm⁻¹ downshift is partially due to the involvement
of phenolic hydrogen motions in the corresponding mode of
tyrosine (Harada & Takeuchi, 1986). Thus, it is reasonable
that the bands at 1600 and 1587 cm⁻¹ for the neutral
form of HCPT would be very sensitive to deprotonation.
Second, in the spectrum of the anionic form, two distinctive
bands show up at 1500 and 1434 cm⁻¹, that can be ascribed
to the Y19a and Y19b modes of tyrosine, respectively.
Third, the band at 1176 cm⁻¹ in Figure 2C downshifts by
10 cm⁻¹ to 1166 cm⁻¹ in Figure 2D. Thus, there are a variety
of distinctive marker bands for the deprotonation of the PYP
cromophore.

The above three spectral characteristics accompanying
deprotonation are also confirmed in the protein spectrum in
Figure 2A. In particular, the low frequencies of the 1558/
1534-cm⁻¹ doublet, the presence of the characteristic modes
at 1498 and 1439 cm⁻¹, and the excellent frequency
correspondence of the 1165-cm⁻¹ mode all argue that the
chromophore in the ground state of PYP is deprotonated.
Thus, the resonance Raman spectrum of PYP at pH 7.4 can
be understood in terms of the deprotonation of the 4-hy-
droxyxynamyl chromophore at the hydroxyl group.

An additional line of evidence that the chromophore in
PYP is deprotonated is obtained by examining spectra in
D₂O. Solvent replacement by D₂O does not cause any
significant change in the spectrum of the protein, as shown
in panels A and B of Figure 2. There is only a small
difference in peak position and relative intensity between
the protein spectra in H₂O and D₂O. For example, the
prominent bands at 1558, 1498, 1439, and 1165 cm⁻¹ in H₂O
shift by only 3–4 cm⁻¹, and the band near 1290 cm⁻¹ is
somewhat weaker in D₂O than in H₂O. The slight spectral
differences between H₂O and D₂O might suggest that some
perturbation is imposed on the deprotonated chromophore,
e.g., by hydrogen-bonding donors in the protein and/or
internal water molecules vibrationally coupled to the chro-
mophore. It is important to note that the spectrum of neutral
HCPT is sensitive to D₂O exchange as expected, while that
of anionic HCPT is not (data not shown).

Two broad bands are seen near 1670 and 1720 cm⁻¹ in
the protein spectrum of Figure 2A. The intensity of these
bands increases when the spinning speed of the Raman
sample cell is slowed from 20 to 1 Hz (data not shown).
Upon speeding up the rotation rate, the intensity of both
bands immediately drop, demonstrating that they are due to
transient intermediates rather than permanent photodegrada-
tion. A more detailed characterization of these intermedi-
ate spectra and comparison with model compounds will be
presented elsewhere.

There are two other interesting features to be noted in the
resonance Raman spectrum of PYP. First, there is an intense
band at 1288 cm⁻¹ that is probably due to stretching
vibrations delocalized over the 4-hydroxyxynamyl skelton,
mainly ascribable to tyrosinate C=O and C–C stretching

![Figure 3: Raman spectra of 5 mM 4-hydroxycinnamic acid in the
1500–1800 cm⁻¹ region at various pH values: (A) pH 1.4; (B) pH 7.2; (C) pH 13.0. The laser power at 488.0 nm was 200 mW.](image)
and 1592 cm$^{-1}$ in this region for 4-hydroxycinnamic acid in the diaionic form. Based on analogy with tyrosine (Harada & Takeuchi, 1986) and also with the HCPT results discussed above, the bands near 1610 and 1594 cm$^{-1}$ seen in Figure 3, panels A and B, are assigned to vibrational modes analogous to Y8a and Y8b of tyrosine, respectively; the bands at 1592 and 1546 cm$^{-1}$ in Figure 3C can be assigned to vibrational modes equivalent to Y8a and Y8b of tyrosinate, respectively. An important common feature for the above three forms of 4-hydroxycinnamic acid is that a distinctive band is seen in the 1630$-$1640 cm$^{-1}$ range. A semiempirical calculation for 4-hydroxycinnamic acid using PM3 indicates that a stretching vibration of the central C=C double bond makes a significant contribution to the 1635 cm$^{-1}$ mode. Recently, D’Ordine et al. (1994) found drastic changes in the Raman features for cinnamyl-coenzyme A, when the acryloyl portion of the cinnamyl chromophore upon binding to crotonase. There is, however, no evidence that a similar effect is occurring on the acryloyl portion of the chromophore in PYP, since the C=C double bond stretching vibration of the chromophore is seen at 1633 cm$^{-1}$ in the encompassing protein, close to the frequency observed in the model compounds. The appearance of this band at 1633 cm$^{-1}$ in the protein spectrum of Figure 2A is quite interesting, because it provides a way to probe the structure of the central C=C double bond in the ground state and in the various photointermediates. Further experimental and theoretical work on the model compounds closer to the exact structure of the chromophore in PYP is in progress.

An important outcome of the present work is that comparative Raman studies on PYP in H$_2$O and D$_2$O and on its model compounds provide the unequivocal conclusion that the 4-hydroxycinnamyl chromophore in PYP at pH 7.4 is deprotonated in the ground state. The full crystallographic atomic model of PYP proposes that the deprotonated chromophore is stabilized by hydrogen bonds from the side chains of Tyr42 and Glu46 to the phenolic oxygen atom and by electrostatic complementarity with the positively charged Arg52. These three amino acids are interlocked by Thr50 through a network of hydrogen bonds (Borgstahl et al., 1995). All structural information available now on PYP, including this Raman study, leads to a model of the binding pocket of PYP in the ground state, as shown in Figure 4. The 4-hydroxycinnamyl chromophore is deprotonated to form a phenolate anion. The three-center hydrogen-bonding interactions with the side chains of Tyr42 and Glu46, in concert with the positively charged side chain of Arg52, are presumably used to stabilize the phenolate anion, resulting in a lowering the pK$_a$ of the PYP chromophore by 2 or more units. It is estimated that the pK$_a$ of the chromophore in the unfolded holoprotein is 9.0 $\pm$ 0.5 (Baca et al., 1994). Resonance Raman studies on photointermediates of PYP are in progress and will provide dynamical information on the structure of the chromophore and its interactions with apoprotein during its progression through the photocyte. In particular, it will be important and interesting to determine if light absorption produces changes in C=C configuration, C=C conformation, and/or protonation state.

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