Infrared and EPR Spectroscopic Characterization of a Ni(I) Species Formed by Photolysis of a Catalytically Competent Ni(I)-CO Intermediate in the Acetyl-CoA Synthase Reaction†

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ABSTRACT: Acetyl-CoA synthase (ACS) catalyzes the synthesis of acetyl-CoA from CO, coenzyme A (CoA), and a methyl group from the CH₃-Co³⁺ site in the corrinoid iron–sulfur protein (FeSP). These are the key steps in the Wood–Ljungdahl pathway of anaerobic CO₂ fixation. The active site of ACS is the A-cluster, which is an unusual nickel–iron–sulfur cluster. There is significant evidence for the catalytic intermediacy of a CO-bound paramagnetic Ni species, with an electronic configuration of [Fe₂S₄]³⁺-(Ni₁⁻ CO)²⁺Ni₂⁰, where Nip and Niₙd represent the Ni centers in the A-cluster that are proximal and distal to the [Fe₂S₄]²⁺ cluster, respectively. This well-characterized Ni₁⁻ CO intermediate is often called the NiFe₃C species. The substrate binding to the Ni₁⁻ CO state generates a novel Ni₁⁺ species (Ared⁰) with a rhombic electron paramagnetic resonance (g values of 2.56, 2.10, and 2.01) and an extremely low (1 kJ/mol) barrier for recombination with CO. We suggest that the photolytically generated Ared⁰ species is (or is similar to) the Niᵢ⁺ species that binds CO (to form the Niᵢ⁺ CO species) and the methyl group (to form Niᵢ⁻ CH₃) in the ACS catalytic mechanism. The results provide support for a binding site (an "alcove") for CO near Nip, indicated by X-ray crystallographic studies of the Xe-incubated enzyme. We propose that, during catalysis, a resting Niᵢ⁺ CO species is trapped by the coupling of a one-electron transfer step to the binding of CO, which pulls the equilibrium toward Niᵢ⁻ CO formation.

Carbon monoxide dehydrogenase/acetyl-CoA synthase (CODH/ACS) catalyzes the key steps in the Wood–Ljungdahl pathway of anaerobic CO₂ fixation, which provides carbon and energy for a variety of anaerobic microbes (1–4). This bifunctional enzyme consists of two central CODH subunits, each of which is attached to an ACS subunit, forming an α₂β₂ complex (5, 6). In the CODH subunit, CO₂ is reduced to CO, which then travels through a 70 Å tunnel to the A-cluster of ACS (7). Here, CO, a methyl group from the CH₃-Co³⁺ cofactor in the corrinoid iron–sulfur protein (FeSP), and coenzyme A (CoA) (1) are converted to acetyl-CoA. On the basis of the results of X-ray crystallographic (5, 8) and biochemical (9, 10) studies, the active A-cluster is known to be composed of a [Fe₂S₄] cluster bridged through cysteine to the proximal Ni (Nip) of a dinuclear Ni site (Figure 1), an arrangement similar to that for the Fe-only hydrogenases in which a [Fe₂S₄] cluster and a binuclear Fe site are bridged by a Cys residue (11, 12). The substrate binding site is ambiguous; however, computational results (13) combined with biochemical and spectroscopic experiments (10, 14–16) and studies of model complexes (17, 18) suggest that Nip is the binding site. Therefore, for the purpose of discussion, we will refer to the CO complex as involving Nip-Co₃⁺, as shown in the mechanism in Figure 2. Nip changes ligation and oxidation states during catalysis, whereas the distal Ni (Niₙd), which is ligated by two deprotonated amides and two cysteine thiolates in a Cys-Gly-Cys motif, appears to remain square planar in the +2 oxidation state (17). Various details of the mechanism of acetyl-CoA synthesis have not yet been established; for example, whether Nip forms paramagnetic or diamagnetic intermediates during the reaction is debated (1, 19–21). The paramagnetic mechanism, which is so-called because it includes a paramagnetic Ni(I)-CO species, is outlined in Figure 2. For the sake of simplicity, the ACS mechanism is described as an ordered reaction; however, recent isotope trapping experiments demonstrate that CO and the methyl group bind randomly to ACS, forming a ternary CH₃-Ni-Co₃⁺ (or binary acetyl) intermediate that reacts with Co₃⁺ to form acetyl-Co₃⁺ (20).

Because binding of CO is not a redox reaction, the Nip center in Ared⁰ (prior to binding substrates, CO, or CH₃) should have the same redox state as Nip⁻ CO, namely Nip⁺, as shown in Figure 2. However, it is a conundrum that ACS lacks an electron paramagnetic resonance (EPR) signal before binding CO and becomes EPR-active afterward, because this would indicate that CO binding converts the enzyme from a diamagnetic to a paramagnetic state. Ironically, the best-characterized intermediate in
the ACS mechanism is the most controversial one; this is the paramagnetic CO-bound Ni₆ species (Ni₆⁺-CO) (called A_red･CO or the “NiFeC species”), which has been trapped, spectroscopically characterized, and shown to be catalytically competent in acetyl-CoA synthesis (22). On the basis of density functional theory (DFT) computations that incorporate the results of EPR (15), Mössbauer (23, 24), electron nuclear double resonance (ENDOR) (25), infrared (26, 27), and X-ray crystallographic experiments (11, 12), the electronic configuration of A_red･CO has been described as [Fe₅S₄]⁺⁺-(Ni₆⁺-CO)-(Ni₆⁺⁺⁺) (13). The assignment of this as a catalytically competent intermediate is based on its formation and decay rates being faster than the overall rate of acetyl-CoA formation (22, 27, 28). Furthermore, the results of combined freeze quench EPR and stopped-flow Fourier transform infrared (FTIR) experiments demonstrate that the NiFeC species is the sole metal-carboxyl species formed upon reaction of ACS with CO (27).

Besides Ni₆⁺-CO, both methyl-ACS (14, 22) and acetyl-ACS (5, 29) species have been trapped, and these forms of the enzyme are EPR-silent and likely diamagnetic. The diamagnetic nature of methyl-ACS represents a challenge for the paramagnetic mechanism because rapid kinetic studies indicate that methyl transfer is an Sₐ2 reaction in which the methyl group is transferred formally as a cation; thus, nucleophilic attack of Ni₆⁺ or Ni₆⁺⁺-CO on a methyl cation should generate a paramagnetic methyl-Ni₆⁺⁺⁺ (or acetyl-Ni₆⁺⁺⁺) state. However, it is recognized that such a species would be highly oxidizing, possessing a Ni₆⁺⁺⁺ state that accepts an electron to generate the stable methyl-Ni₆⁺⁺⁺ intermediate, which undergoes carbonyl insertion to generate an acetyl-Ni₆⁺⁺⁺ intermediate. As the acetyl group undergoes thiolysis by the nucleophilic attack of CoA, two electrons bifurcate: one goes into the internal electron transfer pathway and the other is used to regenerate Ni⁺. In the diamagnetic mechanism, so-called because none of the proposed intermediates are paramagnetic, the substrates bind to a diamagnetic “Ni(0)⁺” state to generate a diamagnetic methyl-Ni(II) or Ni(II)-CO species. The intramolecular electron transfer step would not be required in the “diamagnetic mechanism”.

See the text for details.

Characterization of the photolysis of M-CO complexes, e.g., of the Fe⁺⁺･-CO state of heme in myoglobin or hemoglobin (30, 31), has yielded important insights into protein structure, function, and dynamics. Detailed analysis of CO rebinding kinetics can provide information about different ligand binding sites and mechanisms (32). Here, we show that photolysis of the catalytically competent Ni₆⁺･CO species at low temperatures generates a novel paramagnetic Ni₆⁺ species with an extremely low barrier for recombination with CO. The photolysis and recombination have been characterized by EPR and IR measurements. The photolysis and spectroscopic studies described here provide significant novel insights into the mechanism of binding of CO to ACS and into the electronic structure of the A-cluster.

MATERIALS AND METHODS

Protein Purification. The His-tagged α-subunit (ACS) of the Moorella thermoacetica CODH/ACS was prepared, purified, and Ni-reconstituted under strictly anaerobic conditions with <1 ppm of O₂ as described previously (20). For some ACS samples, Ni reconstitution was conducted for longer periods (2–3 days) and at a higher temperature (45 °C), which gave a higher NiFeC EPR spin quantity (60–75%).

FTIR Spectroscopy. The FTIR cell consisted of a 50 μm thick, airtight, transparent sample compartment and an outside metal frame. We prepared the samples used for FTIR by
incubating 100 μL of dithionite-reduced ACS (609 μM) with CO for 5 min, filling the FTIR cell in the anaerobic chamber using a blunt-ended syringe, removing the cell from the chamber, and freezing the sample immediately in liquid nitrogen. Then, the FTIR cell was transferred into a liquid helium cooling cryostat to start the experiment. Identical samples were prepared in H2O and D2O. Similar results were obtained with the H2O- and D2O-prepared samples; however, having D2O as the solvent provided better access to the 1800–1600 cm⁻¹ region of the spectrum, which includes the so-called “amide I region” where conformational changes in the polypeptide are observed.

**EPR Spectroscopy.** For the EPR-based detection of the photolysis reaction, we formed the Ni²⁺-CO intermediate by incubating 50–150 μM ACS with 2 mM dithionite and then purging the mixture with 100% CO for 15 min in an EPR tube. The spin concentration of the resultant Ared-CO, measured by double integration relative to a Cu perchlorate standard, was between 30 and 75% in different samples. Dithionite-reduced and methylated ACS samples were similarly prepared, but not treated with CO. Methylated ACS was prepared by incubation of 65 μM ACS with 2.5 equiv of methylcobinamide and 4 mM Ti(III) citrate at 45°C for 2.5 h and removal of excess methylcobinamide by ultrasfiltration. Acetylated ACS was prepared by purging the methylated ACS sample with 100% CO for 15 min in the EPR tube. X-Band (9.4 GHz) continuous-wave EPR spectra were recorded under nonsaturating, slow-passage conditions using a Bruker ECS106 spectrometer equipped with a TE_{102} cavity. Cryogenic temperatures were achieved and controlled using an Oxford Instruments ESR900 liquid helium cryostat in conjunction with an Oxford Instruments ITC503 temperature and gas flow controller.

Spectrometer settings for the data presented in Figure 6 included the following: temperature, 4.7 K; excitation frequency, 9.480 GHz; microwave power, 20 mW; modulation amplitude, 0.5 mT; modulation frequency, 100 kHz; sweep rate, 4.1 mT/s. The microwave power had to be reduced to 320 nW to give the NiFeC signal shown in the inset under nonsaturating conditions.

**Photolysis and Recombination Experiments.** For the FTIR experiments, sample photolysis was conducted in an Oxford cryostat with CaF₂ external windows, ZnSe intermediate windows, and ZnS windows for the IR cell. Spectra were recorded at 4 cm⁻¹ resolution with a Bruker V-70 FT-IR spectrometer using a TE_{102} cavity. For photolysis, a 100 W XENOPHOT lamp (OSRAM HLX) source was located at the alternate source position of the Bruker spectrometer, and the sample was irradiated by turning the spectrometer mirrors to illuminate the sample with the alternative source. The estimated power on the sample was approximately 100 mW. The FTIR cell was irradiated at 4.7 K for different amounts of time as indicated in the legend of Figure 3. We observed the recombination after turning off the lamp, adjusting the temperature to one of the higher points indicated in Figure 4, and recording the kinetics at which the FTIR difference peak disappeared after the new temperature stabilized (within 90 s).

For the EPR experiments, photolysis was performed by focusing the 1R-filtered [10 cm of an aqueous 10 mM Cu(II)SO₄ solution] light from a 300 W halogen incandescent lamp into the light port of the EPR cavity. The sample was rotated four times in 90° intervals each followed by continuous illumination for 15 min to maximize photolysis. No further intensity changes in the NiFeC signal were observed after illumination for this 1 h. The addition of 50% glycerol (v/v) to samples of Ared-CO led to a significant increase in the efficacy of the photolysis. Without glycerol, we observed an only 20% decrease in the magnitude of the NiFeC signal upon illumination. We attribute this change in yield to an increase in the optical quality of the frozen glass upon addition of glycerol. This has the effect of decreasing light scattering and allowing the incident light to penetrate more deeply into the 3 mm diameter EPR sample. For all reported data, a spectrum of the buffer collected under identical spectrometer conditions was subtracted. Data manipulations and spectral simulations were performed in MatLab using EasySpin 3.1 (33, 34). Parameters used for the EPR spectral simulation presented in Figure 6 included the following: $S = 1/2$, $g = [2.56, 2.10, 2.01]$, $g$ strain = [0.06, 0.015, 0.015], line width = 7 mT.

The recombination kinetics data obtained via FTIR spectroscopy were supported by analogous EPR experiments that
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RESULTS

FTIR Studies of the Photolysis of Ared-CO and Recombination of CO with Ared\(^+\). Low-temperature (4.5 K) photolysis of Ared-CO generates a negative band at 1998 cm\(^{-1}\) in the difference FTIR spectrum (Figure 3). This is the first observation of any effect of photolysis on the FTIR (or EPR) spectra of Ared\(^+\)-CO. This feature shifts to a lower frequency (1953 cm\(^{-1}\)) when ACS is treated with \(^{13}\)CO. This band and a similar isotope shift were first observed in FTIR studies of CO binding to CODH/ACS and assigned as a terminal carbonyl bound to the Ni center in ACS\(^2\) (26). We attribute this loss of the ν(C=O) stretching mode intensity to photoinduced breaking of the Ni–CO bond to generate CO and an Ared\(^+\) species. Indeed, upon photolysis, a small positive band appears at 2129 cm\(^{-1}\) (2081 cm\(^{-1}\) when prepared with \(^{13}\)CO) that is associated with unbound CO. When the temperature is increased, the negative CO bands disappear as the original Ni\(^+\)-CO species reappears (Figure 4); thus, photolysis must be conducted at low temperatures for Ared\(^+\) to accumulate. Studies of the temperature dependence of the recombination rate reveal an exceptionally low activation energy (E\(_a\)) of 1 kJ/mol (Figure 5). For comparison, CO recombination to the Fe\(^{2+}\)-heme in myoglobin has an E\(_a\) of 8.4 kJ/mol (35).

EPR Studies of the Photolysis of Ared-CO and Recombination of CO with Ared\(^+\). The prephotolysis spectrum of Ared\(^+\)-CO (black trace, inset of Figure 6) is identical to that previously observed for the NiFeC signal (15). After continuous white-light illumination for 1 h at 4.7 K, the NiFeC signal intensity diminishes by 66% (red trace, inset of Figure 6) as a new set of resonances at ca. 260, 310, and 325 mT appear (Figure 6A). After subtraction of residual NiFeC contributions, the resultant Ared\(^+\) signal is well-simulated as an S = 1/2 spin system with g values of 2.56, 2.10, and 2.01 (Figure 6B). These signals are absent from the spectra of pre- or postphotolyzed ACS samples (Ared, Ared-CH\(_3\), or Ared-COCH\(_3\)) lacking CO (Figure 7).

As in the FTIR experiment, photolysis of Ared-CO is only observed at low temperatures, and after photolysis, the NiFeC signal returns at a rate consistent with that measured by FTIR (cf. Figures 4 and 8). Thus, the formation of the paramagnetic photoproduc (Ared\(^\ast\)) observed by EPR spectroscopy appears to be correlated with loss of the CO ligand in Ared-CO, observed by IR.

Other minor features at g values of 2.40 and 2.20 are observed in the difference EPR spectrum. These minor signals may arise from a slightly altered Ared\(^+\) state, which is consistent with the appearance, in some samples of CO-treated ACS, of an altered form of the NiFeC signal with g values of 2.05 and 2.028 (15). It is also possible that these low-intensity resonances represent a small amount of Nid reduction; however, this is unlikely because spectroscopic and electrochemical studies of the Ni\(^{2+}/^{3+}\) couple in model complexes with an N\(_2\)S\(_2\) thiolato and carboxamido coordination environment reveal a very low midpoint potential (approximately −1.26 V vs the normal hydrogen electrode) that would not be accessible in aqueous solution with biological reductants (18, 36). Thus, we suggest that the existence of these low-intensity features in the EPR spectra for the Nip center indicates variations in electronic and geometric environments, which has been observed after low-temperature photolysis of Mb-CO (37).

In this citation, the M-CO band was assigned to CODH because it was not known until later (64) that CO oxidation and acetyl-CoA synthesis occur at separate sites.
center in ACS. The 1953 cm$^{-1}$ IR band of A$_{\text{red}}$-CO exhibits an isotope shift when the $^{13}$CO-incubated enzyme is reacted with natural abundance acetyl-CoA, indicating that the CO group of A$_{\text{red}}$-CO undergoes isotope exchange with the carbonyl group of acetyl-CoA (26). Furthermore, this IR band develops at catalytically relevant rates upon incubation of ACS with CO (27). These isotopic exchange experiments indicate that A$_{\text{red}}$-CO is a catalytically relevant intermediate in the mechanism of acetyl-CoA synthesis (26, 27).

The IR band associated with A$_{\text{red}}$-CO forms at the same rate as an EPR signal with g values of 2.074 and 2.028 (27). This EPR signal has been called the NiFeC signal because it undergoes hyperfine-induced broadening when the metal centers in ACS are isotopically substituted with $^{61}$Ni or $^{57}$Fe and when ACS is incubated with $^{13}$CO versus $^{12}$CO (15). Here we describe EPR spectroscopic studies of the photolysis of A$_{\text{red}}$-CO. When we had earlier irradiated samples of CO-incubated CODH/ACS at 77 K in EPR tubes that were transferred into the EPR cavity for analysis, we did not observe any effects of photolysis on the NiFeC EPR signal (unpublished results). We now recognize that, as seen in the IR experiment, to observe photolysis, the experiment must be performed at low temperatures; for example, after continuous white-light illumination for 1 h at 4.7 K, the EPR signal intensity of A$_{\text{red}}$-CO is diminished by 66%.

These photolysis results have important implications for the structure of the CO binding site in ACS. We attribute the loss of the ν(C=O) stretching mode intensity to photoinduced breaking of the Ni$^{2+}$-CO bond to generate CO and a Ni$^{3+}$ species (designated A$_{\text{red}*}$), a concept that is supported by the g values in the EPR experiments being similar to those of other Ni$^{3+}$ complexes (see below) and by the appearance of a small positive IR band (at 2129 cm$^{-1}$) when ACS is reacted with $^{13}$CO and 2081 cm$^{-1}$ with $^{12}$CO) that is associated with unbound CO. Such low temperatures are required to observe photolysis because recombination of CO with A$_{\text{red}*}$ to generate the original Ni$^{2+}$-CO species has an activation energy ($E_a$) of only 1 kJ/mol. The minimal $E_a$ for recombination of CO with A$_{\text{red}*}$ suggests that the nascent CO molecule cannot diffuse far from the Ni$_p$ site. For comparison, CO recombination with the Fe$^{2+}$-heme in myoglobin has an $E_a$ of 8.4 kJ/mol (35). FTIR (38, 39) and X-ray crystallographic (40) studies of these heme-based systems indicate that, after photolysis, CO exits the active site and recombination kinetics depend on CO migration inside the protein as well as on protein dynamics accompanying the movement of CO. As shown in Figure 1B, a hydrophobic pocket located by crystallographic studies of Xe-incubated CODH/ACS is only 3.9 Å from Ni$_p$ and has been proposed to represent the point of entry of CO into the A-cluster (7). Assuming a Ni$_p$-CO bond distance of 1.8 Å (41), CO would travel $\approx$2 Å to reach this hydrophobic binding pocket after the bond is broken. We propose that photolysis of A$_{\text{red}}$-CO could relocate CO into this alcove, a position from where it can rebind to Ni$_p$ with a minimal $E_a$. The low $E_a$ for CO recombination also implies that the photolysis and rebinding of CO at liquid He temperatures are not accompanied by any major reorganization of the active site conformation.

The photolysis results also have important implications with respect to the electronic and electrochemical properties of the A-cluster of ACS. Coupled to photoinduced loss of the Ni$^{2+}$-CO species is the formation of a novel S = $\frac{1}{2}$ species with g values of 2.56, 2.10, and 2.01, which are appropriate for assignment of the
photolyzed state as a Ni(I) species (42–44). The unusually large g anisotropy found for Ared* indicates that the unpaired electron is almost wholly localized on Ni\(_p\) with very little spin density on the adjacent metal centers. Complexes that exhibit similar EPR spectra include a three-coordinate bispiphosphate diethyl ether Ni complex (\(g = 2.45, 2.11, and 2.11\)) (42) and a tetrahedral tris-thioether Ni complex with bound CO (\(g = 2.64, 2.02, and 1.95\)) (45). The Ni-L form of [NiFe] hydrogenase (\(g = 2.3, 2.12, and 2.05\)), which is formed by photolysis of the \(\text{H}_2\)-reduced enzyme at 40 K (46), has much less g anisotropy because of the near square-pyramidal geometry of the Ni site and because exchange interactions with a neighboring Fe delocalize the electron density (47).

We do not observe any indication of the reduced [Fe\(_2\)S\(_4\)] cluster (\(g\) values of 2.06, 1.92, and 1.80) (48) or of a Ti(III) citrate-reduced form of ACS that exhibits an axial EPR signal (\(g = 2.10 and 2.03\)) (21). There also is no evidence of the reduction of the Ni\(_d\) site. As described above, reduction of Ni\(_d\) would be highly unlikely on the basis of the very low midpoint potential of the Ni\(_{2+/+}\) couple in model complexes with a similar coordination environment (18, 36). Because an electron from the photolytically generated Ni\(_p^+\) species could potentially transfer to either of the metal centers to which it is bridged, the predominance of the Ni\(_p^+\) state suggests that, even though the redox potential for the Ni\(_{2+/+}\) couple of Ni\(_p\) must be extremely low, those for the [Fe\(_2\)S\(_4\)]\(^{2+/+}\) cluster and for Ni\(_d^2+/+\) must be even lower (or their reductions are kinetically disfavored).

Importantly, the photolysis experiments allow the observation of a novel EPR active form of the A-cluster of ACS that is generated when CO is released; thus, this is the state that binds CO. As shown in Figure 2, we suggest that Ared* is a thermodynamically unfavorable Ni\(_p^+\) state. The EPR signal of Ared* is not observed when ACS treated with reductants like Ti(III) citrate or dithionite because, in the absence of CO, the Ni\(_{2+/+}\) equilibrium strongly favors Ni(II) (eq 1). In the presence of CO, the equilibrium shifts to favor the formation of Ni(I)-CO because CO tends to bind strongly to the low-valent states of metal centers [the \(K_m\) for CO in the CO-acetyl-CoA exchange is 10 \(\mu\)M (49)] and because there is a gas-binding pocket near Ni\(_p\) (7). Thus, it appears that, even in the presence of low-potential reductants with midpoint potentials below \(-500\) mV, there is too little accumulation of the Ni\(_p^+\) state for observation; however, by kinetically coupling the reduction (eq 1) and CO binding (eq 2) processes, formation of a low-valent Ni\(_{2+/+}\) -CO complex becomes favorable. In a similar fashion, it was observed by cyclic voltammetry that the midpoint redox potentials of nickel(I) macrocyclic complexes shifted to a more positive value under 1 atm of CO (50).

\[
\text{Ni(II)} + e^- \leftrightarrow \text{Ni(I)} \tag{1}
\]

\[
\text{Ni(I)} + \text{CO} \leftrightarrow \text{Ni(I)}-\text{CO} \tag{2}
\]

Figure 2 shows two one-electron transfer steps that occur during the catalytic cycle. One is used to reductively activate Ni\(_z^+\) to Ni\(_z^-\) in the one-electron coupled CO binding step, and the other electron is used in the internal one-electron transfer associated with the methylation of ACS by the methylated CFeSP. These electrons ultimately come from CoA-dependent thiolysis of the acetyl-ACS intermediate to generate acetyl-CoA; thus, the overall reaction cycle does not involve net electron transfer. There is ample evidence of cryptic redox chemistry during acetyl-CoA synthesis; in fact, an unknown factor that was isolated on the basis of its ability to stimulate the CO/acetyl-CoA exchange reaction turned out to be ferredoxin, but it could be replaced by other mediators (51). Although CoA is the ultimate electron donor, the immediate donor(s) of the reducing equivalents involved in conversion of Ni\(_z^+\) to Ni\(_z^-\)CO and of methyl-Ni\(_z^+\) to methyl-Ni\(_z^-\) during the transmethylation reaction is unknown. Because the [Fe\(_2\)S\(_4\)] cluster that is attached to Ni\(_p\) is a low-potential center, we speculate that it could act as a conduit in the formation of Ared*-CO. Although the transfer of electrons to and from the [Fe\(_2\)S\(_4\)]\(^{2+/+}\) cluster has been shown to be 200-fold slower than the rate of methyl group transfer (52), coupling the electron transfer step to carboxylation in a so-called “EC reaction”, i.e. electrochemical followed by chemical, would significantly enhance the rate because the thermodynamic driving force would be greater. We speculate that Ni\(_d\) may be involved in the redox-coupled methyl transfer reaction. Like other cobalamin-dependent transmethylation processes (53), this is a nucleophile SN2-type reaction (54, 55) that would initially generate a methyl-Ni\(_{2+/+}\) intermediate; however, unlike methyl-Co\(_{2+/+}\), methyl-Ni\(_{2+/+}\) is expected to be highly oxidizing and to undergo reduction to the methyl-Ni\(_{2+/+}\) state in the presence of even moderate reducing agents. The coordination environment of Ni\(_d\) resembles that of Ni-superoxide dismutase (Ni-SOD) (56, 57), which accesses both the Ni\(_{2+/+}\) and Ni\(_{2+/+}\) states during the catalytic cycle (56, 58). Furthermore, model studies have shown that Ni\(_{3+/+}\) is stabilized by the anionic amidate ligands found in Ni\(_d\) (59, 60). Regardless, the paramagnetic pathway and the internal electron transfer loop in Figure 2 describe a speculative, but testable, working hypothesis that would include roles for all three components of the A-cluster.

In summary, we have demonstrated the photodissociation of CO from the Ni\(_p\) site in Ared*-CO, which is a catalytically competent intermediate in acetyl-CoA synthesis (22, 27, 28). This is the first time a photolysis event has been observed on a catalytically competent metal-carbonyl intermediate on an enzyme. Though, CO photodissociation was observed in Ni-based inorganic compounds (61) and in Mo- and Ni-dependent nitrogenase and hydrogenase, respectively, for which CO acts as an inhibitor rather than a substrate (62, 63). The other photoproduc (Ared*) is a Ni\(_z^+\) species that is only long-lived at low temperatures (\(t_{1/2} = 24.8\) min at \(18\) °C) and has EPR properties similar to those of Ni\(_z^+\) compounds with trigonal planar or tetrahedral geometries. The facile recombination of CO with Ared* can be attributed to the capture of photolyzed CO in a gas-binding pocket near Ni\(_p\) that has been observed in the crystal structure (7). The Ni\(_p^+/+\) couple must have a sufficiently low redox potential that the Ni\(_p^+/+\) photoprod got trapped in this study at low temperatures does not accumulate during catalysis. We propose that, during the ACS catalytic mechanism, binding of CO traps this unstable Ni\(_p^+/+\) species in a coupled one-electron transfer step, pulling the redox equilibrium toward formation of Ni\(_z^+\)-CO. Further spectroscopic and computational studies of Ared* are underway and are expected to yield essential insight into changes in the electronic and geometric structures of the A-cluster that occur upon substrate binding.

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