Electron bifurcation arises from emergent features of multicofactor enzymes

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Abstract

Quinone-based electron bifurcation (EB) catalyzed by cytochrome bc_1 (cytbc_1) plays a critical role in maximizing efficiency of biological energy conversion. The canonical EB model (CEB), grounded in equilibrium redox potentials, dictates the order of EB steps with initial endergonic reduction of high-potential iron-sulfur cluster (2Fe2S) by quinol followed by exergonic reduction of low-potential heme b_L (b_L) by semiquinone (SQ). However, this concept falls short in explaining several experimental observations, including intermediate semiquinone spin-coupled to 2Fe2S (SQ-2Fe2S^{red}) and the absence of short-circuiting. Presented here DFT calculations on large cluster models of cytbc_1, encompassing both 2Fe2S and b_L, identified location of donor (HOMO) and acceptor (LUMO) orbitals along with the previously not considered microstates to reveal that EB is an emergent property of an integrated system of redox cofactors where transient charge separations dynamically modulate electron affinities. In this system, electron transfer initiates preferentially toward b_L, indicating a departure from the conventional sequence proposed by CEB. Based on this finding, we introduce an EMBER (EMergent B_L-first Electron Routing) model of EB and demonstrate that its assumptions are supported by electron paramagnetic resonance spectroscopy data. Unlike CEB, EMBER proposes a relatively flat energy profile for EB that accommodates stable SQ-2Fe2S^{red} and explains suppression of short-circuits without additional assumptions. It highlights the importance of dynamic electrostatic interactions in shaping electron transfer pathways. In general, the concept of emergence inherent to EMBER offers a mechanistic framework applicable to a broad range of multi-cofactor redox enzymes beyond cytbc_1.

Introduction

The quinone-based electronic bifurcation (EB) is a crucial process that maximizes the efficiency of energy conversion during respiration and photosynthesis[1–5]. Although flavin-based EB has also been identified in some enzymes, the present work focuses on the mechanism of EB catalyzed by cytochromes (cyt) *bc* of the Rieske/*b* family, including cytochrome bc_1 (cytbc_1) in bacteria, mitochondrial complex III, and cytb_6f in plants[2,6,7]. These enzymes share a similar homodimeric structure across all organisms, exhibiting nearly identical core compositions (Fig. 1A) and spatial arrangements of redox cofactors (Fig. 1B) as well as catalytic sites for quinol (QH_2) oxidation (Q_o) and quinone (Q) reduction (Q_i)[2,8,9]. In each monomer, the cofactors are branched into two chains: low- and high-potential, with Q_o located between them (Fig. 1C). Upon binding to this site, QH_2 becomes flanked by two redox cofactors: the Rieske iron–sulfur cluster (2Fe2S) from the high-potential chain and heme b_L (b_L) from the low-potential chain.

In cytbc_1, EB relies on the two-electron oxidation of QH_2, with each electron diverging into a different direction by transfer to distinct electron acceptors, b_L and 2Fe2S:

$$b_L \leftarrow QH_2 \rightarrow 2Fe2S$$

A one-to-one correlation between the number of electrons transferred from QH_2 to b_L and to 2Fe2S is expected to ensure maximal energy conservation efficiency, while preventing direct electron exchange between b_L and 2Fe2S. Although this process appears conceptually simple, it has never been reproduced in synthetic systems[10].

The general framework for EB mechanism, originally proposed by Mitchell, was based on the formalism of equilibrium electrochemistry[11,12]. It describes EB as two consecutive one-electron steps, with the Q/QH_2 redox reaction divided into two half-reactions involving the SQ/QH_2 and Q/SQ redox couples (where SQ and Q denote semiquinone and quinone, respectively). These couples are proposed to differ significantly in their redox midpoint potentials (E_m), with the SQ/QH_2 couple being very high-potential (>400 mV) and the Q/SQ couple being very low-potential (~−200 mV)[13,14]. This suggests that EB is driven by large (more than 600 mV) differences between these couples. Accordingly, EB is assumed to begin with an uphill oxidation of QH_2 to SQ by 2Fe2S (E_m^{2Fe2S} ~300 mV), followed by downhill oxidation of SQ to Q by b_L (E_m^{bL} ~−120 mV). This specific sequence of QH_2 oxidation, first by 2Fe2S and then by b_L, derived from consideration of E_m values for the immediate acceptors (i.e. 2Fe2S and b_L) and the Q/SQ/QH_2 triad, has become the canonical EB mechanism and the basis for interpreting both experimental and computational studies. Hereafter, this model is referred to as the canonical EB mechanism (CEB).

Several important consequences follow from CEB. First, SQ is expected to be very unstable and transient, as the first step (oxidation of QH_2 to SQ by 2Fe2S) is endoergic, while the second (oxidation of SQ to Q by b_L) is exoergic. Consequently, SQ is presumed to be highly unstable and potentially a substrate for superoxide radical formation due to low E_m of Q/SQ couple[15]. This inherent instability may explain the long-standing challenges associated with the direct detection of SQ at the Q_o site. Second, considering the E_m values of b_L, 2Fe2S, and the Q/SQ/QH_2 triad, the overall reaction should, under certain conditions, be susceptible to internal electron exchange between the chains, that is, quinone-mediated electron transfer from b_L to 2Fe2S[2,4]. This issue becomes especially problematic in understanding the inhibition of cytbc_1 by antimycin[16,17]. According to CEB, inhibition by antimycin should result in the reduction of both b_H and b_L. Subsequent oxidation of QH_2 by 2Fe2S would then be followed by favorable reduction of SQ back to QH_2 by b_L. As a consequence, EB would be bypassed, with both electrons from QH_2 flowing exclusively through the high-potential chain. This possible reaction is referred to as short circuit[4,14]. However, so far such events have remained experimentally undetectable. On the other hand, under non-equilibrium conditions in the presence of antimycin, relatively large amounts of SQ spin-coupled to $2Fe2S^{red}$ (SQ–$2Fe2S^{red}$) and small amounts of SQ free radical signal have been detected[18–22]. Yet, the roles of these species in EB remain poorly understood. While the presence of the SQ signal can still be explained within the framework of CEB, the problem arises when considering the substantial population of SQ spin-coupled to reduced 2Fe2S (SQ–$2Fe2S^{red}$). These unresolved observations have long hindered full mechanistic understanding of EB in cytbc_1.

The issue associated with the inhibitory effect of antimycin is particularly important, considering the fact that this inhibitor has been widely used for years in experiments performed to understand the mechanism of EB. Simple models based solely on E_ms face problems in explaining the inhibition of QH_2 oxidation and the lack of internal short circuits. Over the years, various models have been proposed to overcome these problems, yet the aforementioned issues have never been satisfactorily addressed[2]. Consequently, several, often mutually exclusive, gating mechanisms of EB coexist[14,23–29], raising the concern that a fundamental principle underlying efficient QH_2 oxidation by cytbc_1 might still be missing and that a complete description of Q_o catalysis has yet to be formulated.

Here, we employed quantum mechanical (QM) calculations to analyze EB in cytbc_1 at the level of the electronic function, allowing us to follow the progress of the key steps of the reaction. We also aimed to clarify the role of SQ–$2Fe2S^{red}$ in suppressing short circuits and the mechanism of antimycin inhibition of QH_2 oxidation at the Q_o site of cytbc_1 from *Rhodobacter capsulatus*. To this end, we performed density functional theory (DFT) analyses on models containing both b_L and 2Fe2S cofactors as inseparable components of the EB reaction. To the best of our knowledge, this

approach has not been previously applied in studies of EB mechanism in cytbc_1 and was chosen to avoid or at least minimize the artificial selection of reaction sequence inherent in models that isolate individual one-electron reactions. Our *ab initio* approach lead us to demonstration that all redox-active elements act as an integrated system of cofactors, whose behavior cannot be reproduced by two separate models comprising the quinone molecule and either b_L or 2Fe2S. In particular, we show that the initiation of EB deviates significantly from CEB and proceeds through previously unconsidered states. Based on the calculations, we developed a model of EB and analyzed its predictions with existing data and the results of newly performed experiments. We believe that these results help reconcile the apparent discrepancies between reports detecting semiquinone intermediates within the Q_o site of cytbc_1 and cytb_6f, while also explaining the absence of short circuiting and the mechanism of antimycin inhibition. If our model correctly describes the EB mechanism, it also underscores the potential limitations of using equilibrium-determined E_m values to construct each step of the reaction. Charge separations, resulting from eTs and pTs within the protein interior, can modify interactions (Coulombic, for example) between cofactors, leading to transient changes in their electron affinities.

Although our proposition represents a new hypothesis that requires extensive future validation, it offers a unified explanation for several long-standing challenges. We propose that this model provides mechanistic insight into the efficiency of EB and may guide the design of synthetic systems.

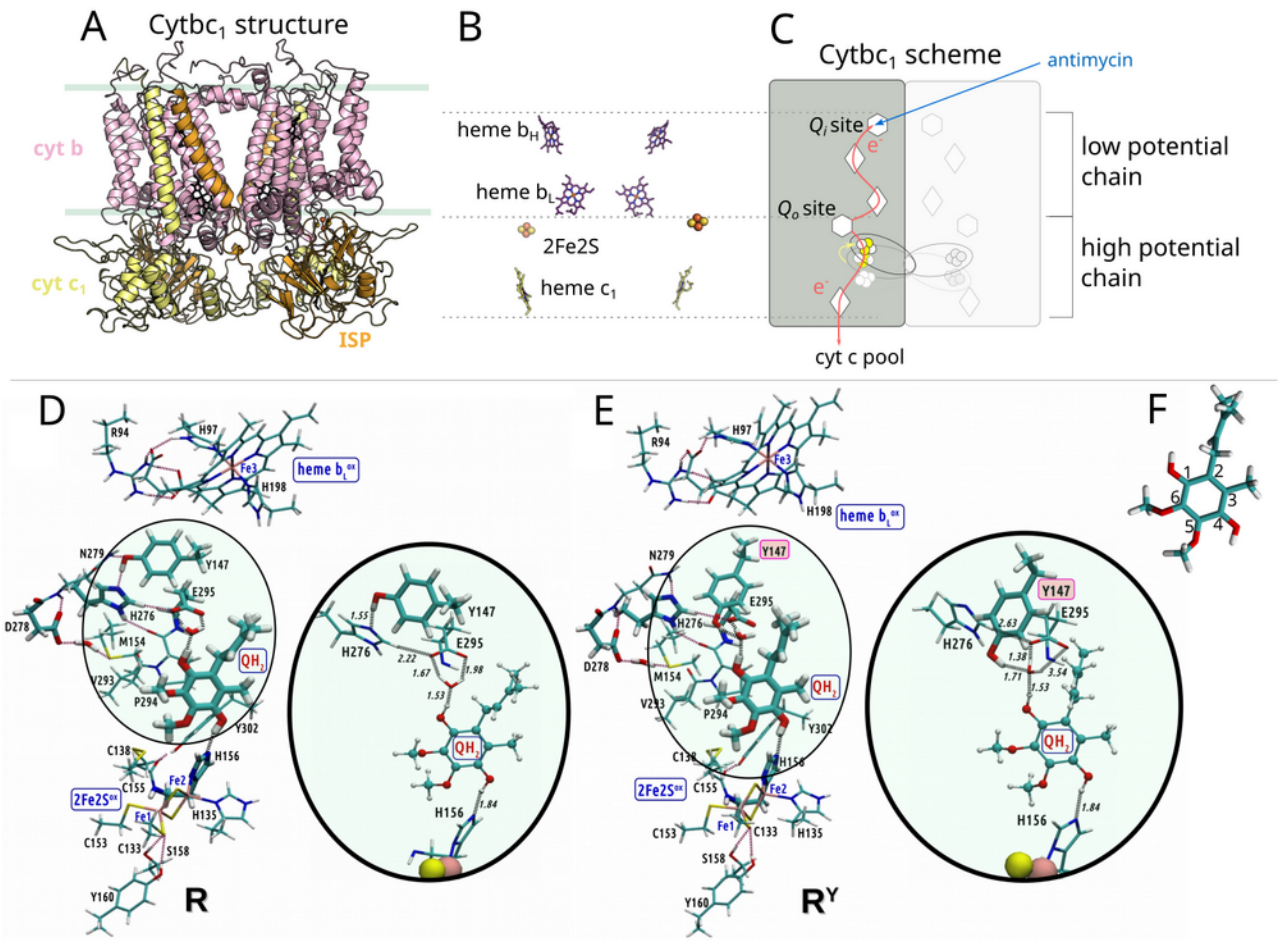

Figure 1. Overview of the structural elements of cyt*bc*$_1$. A) The crystallographic model of the cyt*bc*$_1$ dimer from *Rhodobacter capsulatus* (PDB ID: 1ZRT). Each monomer consists of 3 catalytic subunits: cytochrome *b* (cyt*b*), cytochrome (cyt*c*$_1$) and iron-sulfur protein (ISP). B) The spatial arrangement of redox-active cofactors: hemes b_L, b_H of cyt*b*, 2FeS of ISP, heme c_1 of cyt*c*$_1$. C) General pathways for electrons (*red arrows*) released upon oxidation of QH_2 at Q_o (*white hexagon*). EB directs one electron to high potential chain (consisting of 2Fe2S, c_1 and *c*) and one electron to the low potential chain (consisting of b_L, b_H and Q_i). *White diamonds* denote hemes, *circles* denote 2Fe2S. Yellow arrow indicates movement of the head domain of ISP (ISP-HD) containing 2Fe2S between cyt*b* and cyt*c*$_1$. The blue arrow shows where inhibitor antimycin binds. For simplicity, the scheme shows eT in one monomer. D) and E) show optimized initial structures of QM model with two possible conformations of cyt*b*:Y147: (D) **R** with Y147 directed toward cyt*b*:H276, and (E) $\mathbf{R^Y}$ with Y147 directed toward the bound QH_2. Fragments of the models, highlighting the different conformations of the Y147 side chain, are magnified. F) The quinone moiety with the carbon atom numbering of the ring indicated.

Materials and Methods

<u>Specific assumptions for EB modeling</u>

The cluster model of the Q_o active site was constructed based on the crystallographic structure of cyt*bc*$_1$ from *R. capsulatus* (PDB code: 1ZRT)[30]. In the model, stigmatellin bound at the Q_o site was replaced with ubiquinol, preserving the position of the isoprene chain, and two water molecules were added based on molecular dynamics simulations[31]. The structure containing stigmatellin was selected as the model for constructing the active state **R**, following suggestions that stigmatellin at Q_o mimics the enzyme–substrate complex between quinol and $2Fe2S^{ox}$ [32].

In our work, we did not calculate TSs and therefore did not estimate rates for eT and pT. This is because the large size of the cluster models (~400 atoms) made such calculations unfeasible. However, comparing the geometries of the **R**, **I1**, **I2**, and **P3** structures, we did not observe any significant nuclear rearrangements. Thus, we assume *a posteriori* that the eT and pT rates should not be higher than estimated in previous studies (5-12 kcal/mol)[33,34].

QM model of the Q_o active site

The QM model applied in this study consisted of 399 atoms and included the following elements: b_L, ubiquinol (with its hydrophobic tail truncated to one isoprene unit), two water molecules, the 2Fe2S cluster, eight residues from chain E (C133, H135, C138, C153, C155, H156, S158, Y160), and twelve residues from chain P (R94, H97, Y147, M154, H198, H276, D278, N279, V293, P294, E295, Y302). The residues from chain E (C133, H135, C138, C153, S158, Y160) and chain P (R94, H97, Y147, M154, H198, H276, Y302) were included with their amino and carbonyl moieties of the protein backbone replaced by hydrogen atoms. The protein fragments C155–H156 (chain E) and D278–N279, V293–P294–E295 (chain P) were included along with the peptide bonds connecting them, with the corresponding CO and NH groups of the protein backbone substituted by hydrogen atoms (i.e., for C155, D278, and V293 the NH groups were replaced, and for H156, N279, and E295 the CO groups were replaced).

Protonation states of the residues were assigned using program Propka 3.1 [35,36], validated by PypKa 2.10.0 [37]. For the H156 residue, which coordinates the 2Fe2S cluster and is hypothesized to act as a direct proton acceptor during QH_2 oxidation, two protonation states were tested. In the first state, the H156 ligand was deprotonated and ready to accept a proton, while in the second state, H156 was protonated at the N_τ atom. To maintain the rigidity of the protein backbone, geometry optimizations of all structures considered in the present study were performed with constraints imposed on the hydrogen atoms replacing protein backbone moieties and on the carbon atoms that are part of the protein backbone.

QM model of the active Q_i active site

The QM models of the Q_i site were constructed based on the crystallographic structure of cytbc_1 from *Bos taurus* with ubiquinone bound at the Q_i site (PDB code: 1NTZ)[38]. This structure was chosen for several reasons. It includes the substrate bound at the Q_i site and its quality is sufficient for geometry optimization of large models using QM methods. Also it contains resolved positions of water molecules which, according to the literature, directly participate in the ubiquinone reduction reaction; and its Q_i site shows high structural similarity[39]. When comparing the Q_i sites from *B. taurus* and *R. capsulatus*, subtle differences can be observed, but they do not involve the residues directly participating in the reaction. The cluster model of the Q_i site consisted

of 334 atoms and included the following components: heme b_H, ubiquinone with its hydrophobic tail truncated to one isoprene unit (as in the model of the Q_o site), four water molecules (in the same positions as in the 1NTZ structure), and thirteen protein residues: I27^{Bt}/L41^{Rc} (*Bt* and *Rc* in superscript denote *Bos taurus* or *R. capsulatus,* respectively), W31^{Bt}/W45^{Rc}, H97^{Bt}/H111^{Rc}, R100^{Bt}/R114^{Rc}, H196^{Bt}/H212^{Rc}), L200^{Bt}/F216^{Rc}), H201^{Bt}/H217^{Rc}, S205^{Bt}/N221^{Rc}, N206^{Bt}/N222^{Rc}, F220^{Bt}/F244^{Rc}, Y224^{Bt}/F248^{Rc}, K227^{Bt}/K251^{Rc}, D228^{Bt}/D252^{Rc}. In the QM model of the Q_i site, the amino and carbonyl groups of the protein backbone were replaced by hydrogen atoms in the following residues: I27, W31, H97, R100, H196, L200, H201, and Y224. In F220, the Cβ carbon was replaced by a hydrogen atom. The fragments S205–N206 and K227–D228 were included in the model with their peptide bonds preserved. Accordingly, only the NH backbone moieties of S205 and K227, and the CO backbone moieties of N206 and D228 were substituted with hydrogen atoms.

Protonation states of the residues were assigned using program Propka 3.1[35,36] and validated by PypKa 2.10.0[37]. The geometry optimization of intermediates involved in the ubiquinone reduction was perfomed with the constraints imposed on atoms derived from protein backbone, including hydrogen atoms replacing any moieties present in the whole protein structure.

QM methods

Due to the very large cluster models used in this study, QM calculations were limited to the geometry optimization of intermediates involved in the studied reactions, i.e., the oxidation of ubiquinol at the Q_o site and the reduction of ubiquinone at the Q_i site. Computational limitations made vibrational analysis and the related optimization of TSs unfeasible; therefore, the final conclusions were based on the relative energies and electronic structures of the optimized reaction intermediates, as well as on available experimental data. All QM computations were performed using the Gaussian 16 program[40]. The geometries of all stationary points were optimized using DFT with the B3LYP hybrid exchange–correlation functional and Grimme's D3 dispersion correction with Becke–Johnson damping[41,42]. Geometry optimizations were performed with the double-ζ basis set def2-SVP, while the final energies of the intermediates were computed with the triple-ζ basis set def2-TZVP, within a polarizable continuum model (PCM) characterized by a dielectric constant of 4.0 and a probe radius of 1.4 Å, to mimic the electrostatic effects of the protein environment[43]. These methods have been previously validated for computational studies of active sites involving iron–sulfur clusters and hemes[44,45].

Since the **P3** structure relaxed to **I2** during geometry optimization with doublet multiplicity, its geometry was optimized in the quartet multiplicity state, and the final energy was computed for the doublet state. QM calculations using the triple-ζ basis set def2-TZVP and the PCM model showed that the doublet and quartet states of P3 are degenerate. Thus, the orientation of the spin of

the electron on b_L^{ox} does not affect the ferromagnetic coupling between the semiquinone and the reduced 2Fe2S cluster in **P3**.

Material used for experimental sample preparation

Equine cytochrome *c* (cyt*c*), 2,3-dimethoxy-5-decyl-6-methyl-1,2-benzoquinone (DB), and antimycin were purchased from Sigma-Aldrich (St. Louis, MO, USA). Cytbc_1 was isolated from *Rhodobacter capsulatus* grown under semiaerobic conditions, as described previously [46]. The isolated cytbc_1 solution was dialyzed against reaction buffer composed of 50 mM bicine (pH 8.0), 100 mM NaCl, and 0.01% (w/w) dodecylmaltoside (DDM). DB was reduced to its hydroquinone form (DBH_2) using sodium borohydride. Iron(III) citrate, used as an internal standard for sample packing efficiency, was prepared immediately before the experiment by adding $FeCl_3$ to a tenfold molar excess of citric acid.

Freeze-quench experiments

Non-equilibrium samples of cytbc_1 were prepared as described previously[47]. Briefly, freeze-quenched samples were generated using a Biologic SFM-300 stopped-flow mixer equipped with an MPS-70 programmable syringe controller and electron paramagnetic resonance (EPR) freeze–quench accessories. One syringe contained a mixture of cytbc_1 (50 μM), antimycin (250 μM), cyt*c* (370 μM), and Fe^{3+} citrate (10 μM). The second syringe contained a solution of DBH_2 (390 μM) in bicine buffer. The reaction was initiated by mixing the contents of the two syringes in a 1:1 volume ratio. The mixture was incubated in a delay line for a programmed period and then injected into an isopentane bath cooled to 170 K. The frozen droplets were collected in an EPR tube and measured immediately after preparation. Different occupancies of the Q_o site by quinone radical states were achieved by modulating the sample incubation time.

Double mixing experiments

For the double mixing experiments shown in Fig. 5D, we used our home-built multichannel pulse high-current drivers and a custom mixer with a rotary valve, as described previously[48,49]. Cytbc_1 was prepared at a concentration of 80 μM in bicine buffer (as described above) and supplemented with 100 μM antimycin. Prior to mixing, portions of potassium ferricyanide were added, and the oxidation level of cytc_1 was continuously monitored spectrophotometrically. Addition of the oxidant was continued until 90% of heme c_1 was oxidized. Synthetic ubiquinol (DBH_2) and equine cyt*c* were prepared in bicine buffer at concentrations of 180 μM and 300 μM, respectively. Syringes 1 and 2 contained 125 μL of cytbc_1 solution and 125 μL of DBH_2 solution, respectively. The solutions were mixed and incubated for 500 ms in syringe 3 to allow the enzyme to reach state P3. Then, 250 μL of the cytbc_1 + DBH_2 mixture was combined with 250 μL of cyt*c*

solution and aged for an additional 200 ms. Finally, the mixture containing cytbc_1, DBH_2, and cyt*c* was injected into cold isopentane to stop the reaction. This procedure was repeated twice using independently isolated cytbc_1 preparations, and each experiment was performed in triplicate.

The table below shows the pattern used for the multichannel pulse high-current drivers.

Start [ms]	0	500	700	705	800
Duration [ms]	35	70	60	1	120
Piston	P1,P3	P1,P2	P4		
Channel				4	
Power	100%	100%	70%	25%	30%

EPR measurements

All EPR measurements were performed using a Bruker Elexsys E580 spectrometer (Bruker, Billerica, MA, USA). X-band continuous wave EPR spectra were measured using a SHQE0511 resonator and an ESR900 cryostat (Oxford Instruments, Abingdon, UK). The helium temperature was maintained using a closed-cycle Stinger cryocooler (ColdEdge, Allentown, USA). The parameters for reduced 2Fe2S (corresponding to states P3 and P1) and Fe^{3+} citrate measurements were as follows: temperature 20 K, microwave power 2 mW, modulation amplitude 14.36 G, conversion time 40.96 ms, time constant 81.92 ms, sweep time 83.89 s, and the number of scans was 1–3, depending on the signal-to-noise ratio. For the free radical signal (corresponding to states I1 and I2), the following parameters differed: temperature 200 K, microwave power 80 mW, modulation amplitude 6 G, and the number of scans was 1–12, depending on the signal-to-noise ratio. All amplitudes of the recorded EPR spectra were normalized using the amplitude of the Fe^{3+} citrate spectra as the internal standard.

Results

To understand how nature realizes EB at a fundamental level, we conducted QM calculations of possible enzyme-catalyzed reactions using multiple models, with different electron/proton configuration, based on cytbc_1 crystallographic structures from *R. capsulatus*. For clarity, we define what we consider as the EB reaction. In this work, EB is viewed as a minimal cascade of reactions leading to a stable, low-energy state containing the product Q, which corresponds to a state that can be detected experimentally as the dominant one under equilibrium conditions, i.e., upon depletion of reaction substrates. In this respect, we consider only the primary EB steps, rather than the entire catalytic Q cycle. For the first time, and unlike as in previous studies[33,34,50,51], the QM model of Q_o included both acceptors of electrons from QH_2: 2Fe2S and b_L

(Fig. 1D, E). In the starting state, QH_2 forms a hydrogen bond to deprotonated H156 of iron-sulfur protein (*R. capsulatus* numbering) and *via* water molecule to E295 of cyt*b*, at the time when immediate electron acceptors 2Fe2S and b_L are oxidized. Y147 of cyt*b* adopts two conformations: away from or close to E295 (**R** in Fig. 1D or $\mathbf{R^Y}$ in Fig. 1E, respectively and Fig. S1). We tested effect of protonation of H156 but in that case no reaction was observed. The rationale behind selection of the starting state is explained in SI (Section „Selection of the starting model").

Initially, following the assumptions of CEB, we tested the scenario in which the reaction is expected to start from **R** or $\mathbf{R^Y}$ with protonation of H156 by C4-OH of QH_2 (atom numbering in Fig. 1F), followed by eT to 2Fe2S. Neither of expected structures containing b_L^{ox}, QH^-, protonated H156 and oxidized 2Fe2S ($2Fe2S^{ox}$), nor those with b_L^{ox}, SQH/SQ^- and reduced 2Fe2S ($2Fe2S^{red}$) could be obtained in our QM models. Instead, relocation of proton from C4-OH to H156 is accompanied by both: pT from C1-OH to E295 and simultaneous eT from QH_2 to b_L. This led to the intermediate containing SQ^-, b_L^{red}, and $2Fe2S^{ox}$ (**I2** in Fig. 2A and **I2** or $\mathbf{I2^Y}$ in Fig. S2), which appeared in a clear contradiction with predictions based on CEB, namely SQ formation together with $2Fe2S^{red}$ and b_L^{ox}. Such the state seems quite advanced in the progression of EB as it must have resulted from at least two pTs and one eT (protons are already on H156 and E295 and electron is on b_L). It thus appears that transition from **R**/$\mathbf{R^Y}$ to **I2**/$\mathbf{I2^Y}$ might involve an intermediate step to be considered. Therefore, we went back to the beginning of the reaction and tested how **R** or $\mathbf{R^Y}$ responses to the initial water-mediated pT from C1-OH to E295. Surprisingly, this pT was coupled to eT from QH_2 to b_L, leading to **I1** or $\mathbf{I1^Y}$, (states containing SQH, b_L^{red} and $2Fe2S^{ox}$, Fig. 2A and Fig. S2). The emergence of b_L^{red} next to $2Fe2S^{ox}$ was unexpected result, given that E_ms of b_L and 2Fe2S , determined for proteins under equilibrium, suggests a higher electron affinity for 2Fe2S than b_L. This prompted us to scrutinize the electronic structure of **R**, which was taken as the most probable state of the Q_o-QH_2 complex ($\mathbf{R^Y}$ and following $\mathbf{I1^Y}$ were 1 and 5 kcal/mol less stable than **R** and **I1**, respectively).

<u>Asymmetry in charge and spin distribution in the initial structure</u>. In **R**, there is a shift of electron density from QH_2 toward b_L, associated with a spread of unpaired α spin density (SD) over M154 and D278 of cyt*b* toward QH_2 (Fig. 3A). At the same time, α (S_{Fe1}=5/2) and β (S_{Fe2} = -5/2) SD are present on iron ions of $2Fe2S^{ox}$ but antiferromagnetism cancels the net spin. Shifting of electron density toward b_L imposes a heterogeneous distribution of the local electric potential around the quinone ring with the more negative potential at the region of C1-OH compared to C4-OH (Fig. 3B, red arrow). At the same time, the electronic structure indicates that the highest occupied and the lowest unoccupied molecular orbital (HOMO and LUMO, respectively) are located on QH_2 and b_L, respectively (Fig. 4). The charge polarization and the location of HOMO and LUMO determines direction of eT from C1-OH to b_L accompanied with pT to carboxyl group

of E295, resulting in state **I1** (Fig. 2A and S2A). It is important to emphasize that it was not possible to obtain **I1** state when 2Fe2S is not involved (Fig. S3-S6), because in models deprived of the cluster, HOMO orbitals were no longer located on QH_2 molecule. On the other hand, for the models containing the 2Fe2S cluster but not b_L, we obtained stable state containing SQ-2Fe2S^{red} similarly to previous work[33] (see optimized geometries and HOMO, LUMO orbitals in Fig. S7). This would indicate that either electron transfer from QH_2 to 2Fe2S is exoergic, which seems incompatible with CEB, or that it is an artifact of the truncated model. If such a model was truly reproduced the first EB step, one would expect to detect an EPR signal of SQ and/or SQ–2Fe2S^{red} under equilibrium conditions in cytbc_1 mutant with b_L knocked out, which is not observed[52]. Therefore, we suggests that approaches for determining initial steps of EB using models containing only one cofactor at a time suffer from the *a priori* imposition the sequence of the reactions.

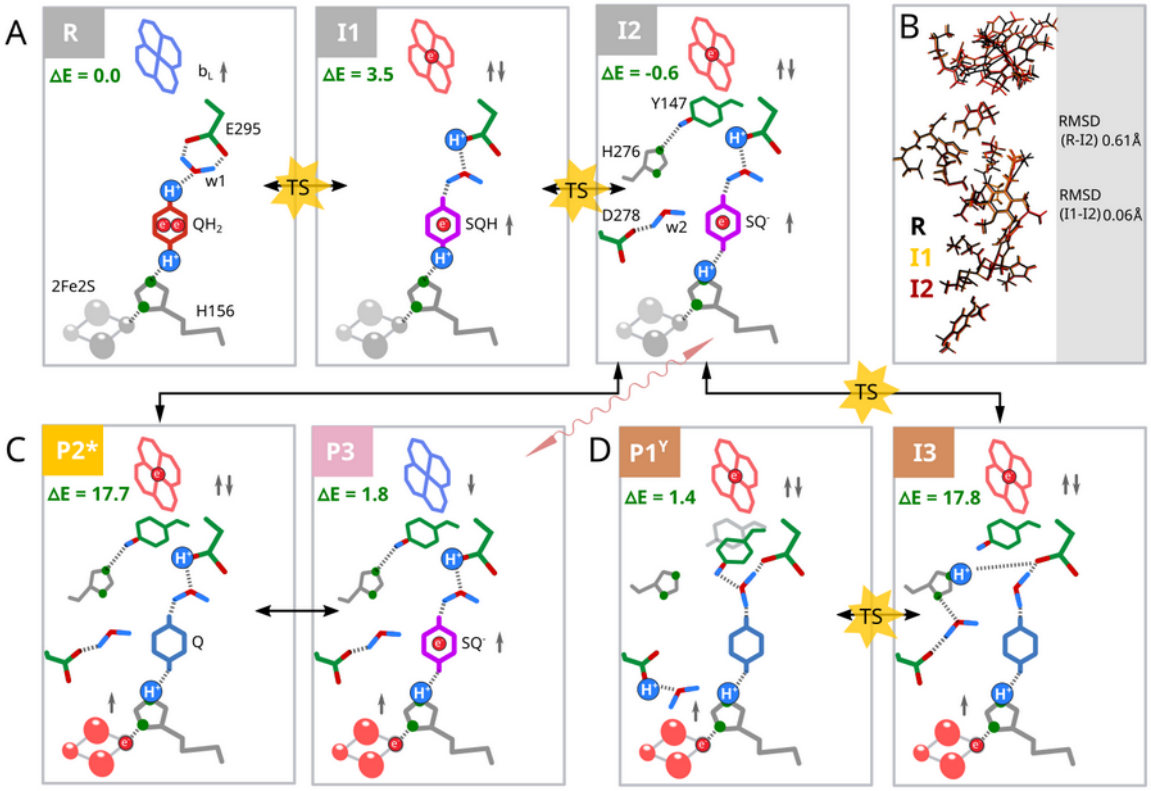

Figure 2. Primary steps of EB without involvement of eT from b_L to b_H. A) **R** denotes a starting state comprising b_L^{ox} (*blue crossed-hexagon*), QH_2 (*red hexagon*), and 2Fe2S^{ox} (*grey ovals*). The reaction progresses through transition states (TS *yellow stars* representing the energy barriers) to **I1** and **I2**, containing b_L^{red} (*red crossed-hexagon*) and SQH, or SQ^- (*magenta hexagon*), respectively. B) Superimposed geometries of **R**, **I1**, and **I2**. C) Evolution of **I2** to stable **P3** containing b_L^{ox}, SQ^-, and 2Fe2S^{red} (*red ovals*), *via* pre-TS **P2*** with b_L^{red}, Q (*blue hexagon*), and 2Fe2S^{red}. Electron tunneling directly connecting **I2** and **P3** is shown as wavy arrow. D) Evolution of **I2** to **P1^Y** containing b_L^{red}, Q, and 2Fe2S^{red} *via* high energy **I3** and two transition states. Gray arrows indicate the net spin corresponding to the redox state of the substrate and cofactors. Amino acid side chains are shown when their protonation and/or conformation state is significant. Important water molecules are labeled as "w1" and "w2" and protons derived from QH_2 in the given state are represented by blue circles.

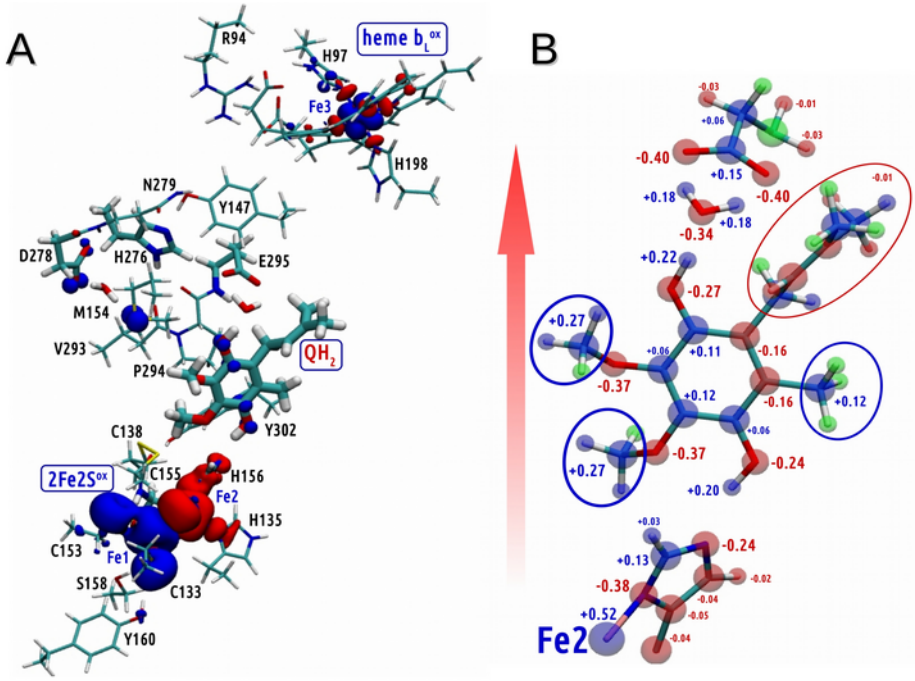

Figure 3: **Spin and charge distribution in R**. A) The distribution of α (blue) and β (red) spin density in the most stable structure containing QH_2. B) The charge distribution within the closest surrounding of the QH_2 molecule. Red arrow indicates the direction of the shift of negative charge at Q_o toward b_L.

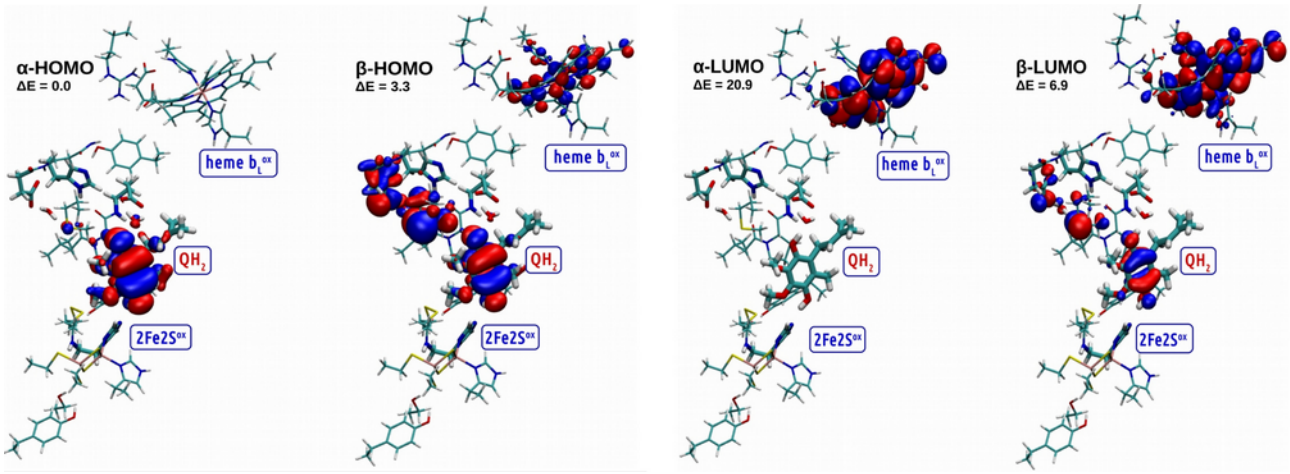

Figure 4: Location of HOMO and LUMO orbitals and their relative energy (with respect to the α-HOMO) in kcal/mol for the most stable structure containing QH_2, b_L^{ox}, $2Fe2S^{ox}$ and deprotonated H156.

Altogether, these observations indicate that reaching of **I1** requires the presence of both b_L and 2Fe2S, despite apparent lack of involvement of the latter in this process. Furthermore, 2Fe2S and its direct surrounding must be in the correct state, as the models of **R** variants with either protonated H156 and $2Fe2S^{ox}$ or deprotonated H156 without the cluster also failed to show any signs of progress to **I1** (Fig. S8).

<u>Reversible EB stages on a way toward product</u>. The state **I1** passes to **I2** by shifting H^+ originating from the C4-OH group of SQH toward H156. The RMSD parameter comparing the

positions of all atoms in **R, I1** and **I2** is about 0.06Å indicating no structural rearrangement upon **R↔I1↔I2** transitions (Fig. 2B).

The energy levels of **R**, **I1** and **I2** are relatively close to each other, which means that at room temperature (~300 K) they are expected to be similarly populated, albeit not equally, and they should transform from one to another. Thus, **R**, **I1** and **I2** are considered as degenerate, coexisting states. At this stage, the hydrogen bonds involving protonated E295 and protonated H156 stabilize **R↔I1↔I2** triad (Fig. 4A) and it is impossible to obtain low energy system containing product (Q, 2Fe2S^{red} and b_L^{red}).

We first searched for states containing stable product under conditions when electron on b_L cannot advance to b_H (like in antimycin-inhibited enzyme). One tested reaction involved elongation of the H-bond between SQ$^-$ and protonated H156. This resulted in unstable **P2*** (Fig. 2C and Fig. S9) which immediately relaxed back to **I2** or evolved to **P3**. The appearance of the **P3** state is notable because it contains b_L^{ox} together with SQ and 2Fe2S^{red}. Because both of these paramagnetic centers have parallel spins and are connected with H bond, one can expect formation of an ferromagnetically coupled SQ-2Fe2S center (discussion in SI, Fig. S10). The state **P2*** should be considered as an approximate transition state (pre-TS), with estimated a relatively high energy +18 kcal/mol, between **I2** and **P3**. We note that nearly identical geometry of nuclei in **I2** and **P3** indicates a potential contribution from electron tunneling process, which effectively decreases the barrier between these states.

The second tested reaction involved shifting the proton away from E295 to D278. This resulted in relatively stable **P1^Y** containing Q (Fig. 2D). However, as reaching of this state from **I2** is slightly endoergic and required crossing two barriers with a high energy state in between (**I3**, +18 kcal/mol, Fig S11), this process is unlikely. Consequently, when electron cannot advance from b_L to b_H, the enzyme is expected to become trapped in the states **R↔I1↔I2** and **P3** without possibility to produce a low-energy product Q.

<u>Releases from degenerate states and emergence of product.</u> In further search for exoergic processes that would push EB toward low-energy product, we estimated the net energetic cost associated with eT from b_L through b_H to Q_i (Fig. 5). We considered a state **I2'** which is a result of removal of electron from b_L in **I2**, and various states of the complementary model that mimicked the acceptance of this electron. The complementary models encompassed b_H and quinone at Q_i (details in SI and Fig. S12). The results indicate that the transition from **I2** to **I2'** would be endoergic (+67,2 kcal/mol) if the complementary model was not included. However, the average energy released per electron delivered to Q_i (-95.8 kcal/mol) lowers energy of **I2'** to -28,6 kcal/mol (Fig. 5). In this way, eT from Q_o to Q_i makes EB exoergic allowing Q_o to departure from degenerated states **R↔I1↔I2** and **P3** (the latter state is unlikely to be formed when this eT is not

blocked). The net energy released in Q_i drives the enzyme to overcome local barrier associated with pT from E295 to H276 (state **I3'**). The following pT from H276 to D278 is coupled to eT from SQ to 2Fe2S which weakens the interaction between quinone moiety and protonated H156 (the H-bond elongates from 1.5 to 2.0 Å, Fig. S13, S14). This reaction is the final step of EB leading to the low-energy state **P1'^{Y}** (-23.0 kcal/mol in respect to **R**) containing product (quinone).

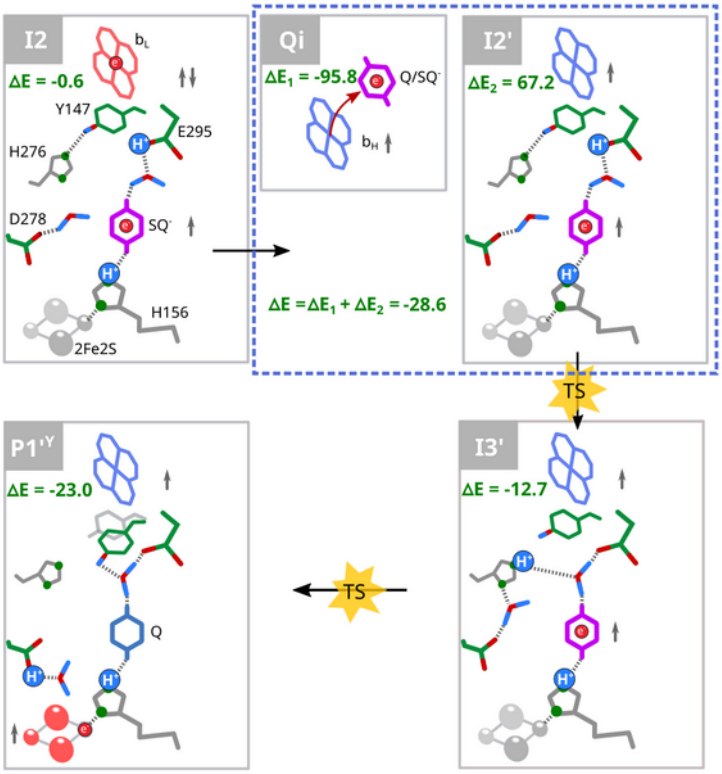

Figure 5. Completion of EB involving energy released during eT from b_H to Q_i. The eT from b_L to b_H and subsequently to Q_i provides a highly exoergic step that resolves the **R↔I1↔I2** degeneration (see Fig. 2), driving the reaction from **I2** toward **I3'**. The energy associated with this reaction was calculated using the states **Q_i** and **I2'** considered together (*blue dashed square*). **P1'^{Y}** denotes the final state of EB containing Q, 2Fe2S^{red} and protonated D278. The symbols are consistent with those used in Fig. 2. Red arrow indicates eT.

We note that while the essence in the departure from degenerated states lies in effective removal of the proton away from the quinone ring, the exact pT path is not a determinant of this process but influences its efficiency. The process might be tolerant to mutational changes and the residues that build the path may vary in different species[53–56]. We also note that, in this mechanism, completion of EB does not require the motion of the ISP away from Q_o implicated as inherent feature of catalysis. It it worth mentioning here about recent reports on structures of cytbc_1 for which ISP does not move during the catalytic cycle[57]. When the motion occurs during further steps of enzymatic catalysis that follow **P1'^{Y}**, transferring electron toward more remote cofactors (*c*-type hemes) it further lowers the energy of the system. However, as mentioned above, these steps remain beyond consideration of work.

Figure 6 summarizes the most probable enzyme states that constitute the pathway of EB-based QH_2 oxidation inferred from energetic relations between the states obtained by QM (see Fig. S15 for all the considered states). When QH_2 bound in Q_o encounters 2Fe2S^{ox} and b_L^{ox} (**R**), the negative charge from the quinol moiety initially shifts toward b_L (**I1**, **I2**). ET from the resulting SQ to 2Fe2S (**I3′**, **P1′^{Y}**) is powered by the energy released upon electron transfer from b_L to Q_i (blue line). Without this energetic input, the enzyme is trapped in states **R**, **I1**, **I2**, and **P3**, with no possibility of reaching a low-energy product state. These results highlight that productive quinol oxidation cannot be explained by a strictly sequential two-step scheme, but instead requires a cooperative route initiated at b_L.

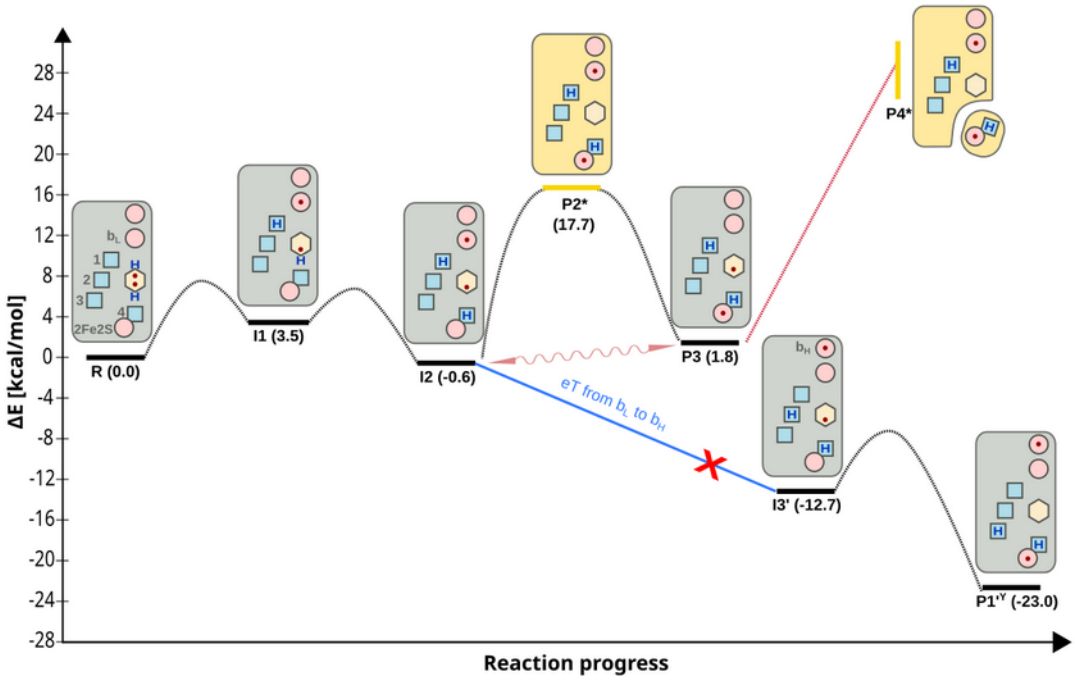

Figure 6. Key states of the EMBER model of EB. Solid black lines represent relative energy levels (numbers in parentheses) of the states on the way from the substrate (**R**) to product (**P1'^{Y}**). Yellow solid line represents energy level of pre-TS (**P2***). Red circles – electron acceptors; blue squares – proton acceptors 1, 2, 3 in cyt*b* (in *R. capsulatus* E295, H276, D278, respectively), and 4 in ISP (histidine ligand to 2Fe2S); yellow hexagon – quinone moiety; red dots and blue "H" – electrons and protons derived from QH_2; red cross - inhibition by antimycin; wavy arrow – electron tunneling; dotted lines illustrate barriers between states. Red dotted line denotes the possibility of quinone formation **P4*** from **P3** by elongation of the distance between ISP and the Qo. The energy level of **P4*** increases due to uncompensated breaking interactions, thus cannot be determined precisely (yellow vertical line).

Discussion

In this study, we performed QM calculations on multiple possible states of cytbc_1 to explore the mechanism underlying the initial stages of electron bifurcation (EB). Our motivation arose from the interpretative challenges posed by experimentally observed enzyme states, particularly under antimycin inhibition. The models explicitly included both immediate electron acceptors (2Fe2S and b_L) and proton acceptors at each reaction step. This design avoided the predefined sequence of events inherent to the CEB models, in which the reaction is partitioned into two sequential one-electron transfers: first from QH_2 to 2Fe2S, then from SQ to b_L. In contrast, our simulations reveal an alternative mechanism in which electron transfer initiates at b_L and proceeds along an energetically favorable cooperative pathway.

To distinguish this mechanism from CEB, we introduce the term EMBER (EMergent BL-first Electron Route), a conceptual model that emphasizes the spontaneous, energetically driven emergence of an alternative EB pathway not anticipated within conventional CEB assumptions. This mechanism exhibits bifurcation behavior fundamentally distinct from previously proposed models.

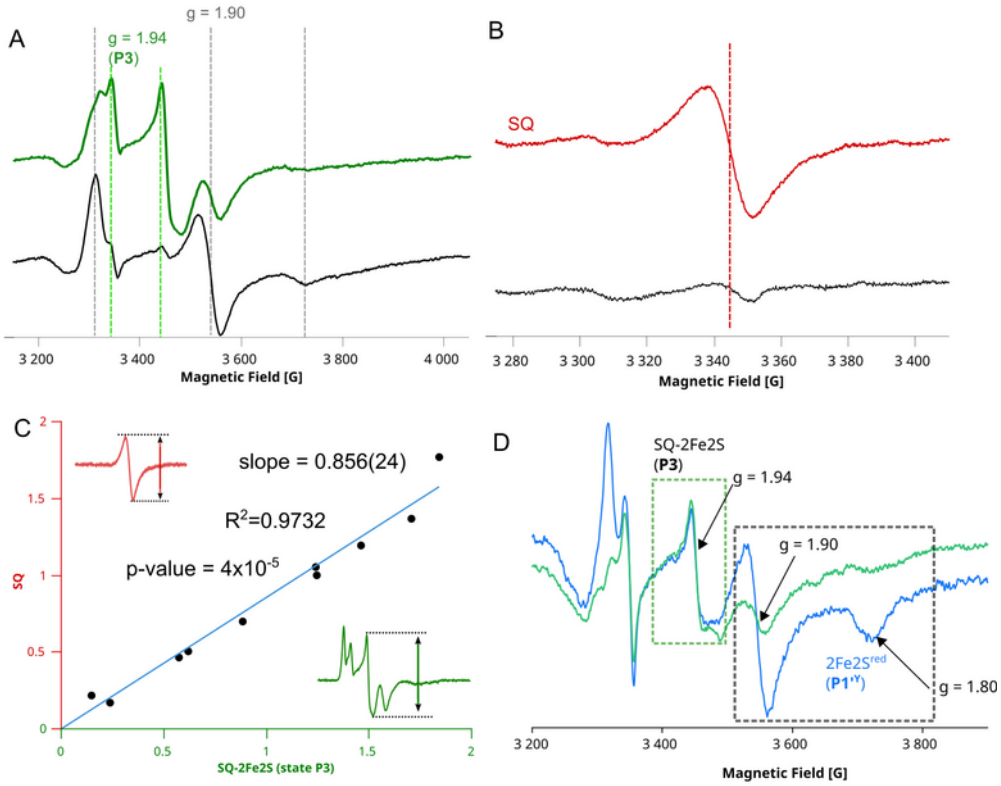

Figure 7. Experimental data obtained for antimycin-inhibited cytbc_1. (A) EPR spectra of 2Fe2S^{red} and coupled SQ–2Fe2S^{red} (**P3**) measured at 20 K for samples prepared under equilibrium (black) and non-equilibrium conditions (green; 1 s after substrate addition). Dashed vertical lines indicate the main EPR transitions of 2Fe2S^{red} (gray) and SQ–2Fe2S^{red} (green). (B) SQ radical signal measured at 200 K in the same samples as in A, under equilibrium (black) and non-equilibrium (red) conditions. (C) Correlation between the amplitudes of SQ and g = 1.94 EPR signals for samples

prepared at different time points after mixing with substrates. (D) Double-mixing EPR experiment showing spectra of enzyme pre-set to **P3**, followed by mixing with buffer (*blue*) or with an additional portion of oxidized cyt*c* (*green*). Grey and green dashed boxes highlight spectral ranges corresponding to $2Fe2S^{red}$ with bound Q and SQ–$2Fe2S^{red}$ (**P3**), respectively.

An important aspect of the EMBER mechanism is that the initial shift of negative charge toward b_L does not occur in models of **R** deprived of 2Fe2S (Fig. S3–S6). In this case, although the LUMO orbitals are still present on b_L, the HOMO orbitals do not localize on the QH_2 molecule. This fact automatically precludes the eT process in such a model. Additionally, this also eliminates the possibility of reproducing the sequence of reactions identified in our *ab initio* modeling by splitting it into two separate one-electron reactions, since in that case we would, *de facto*, be calculating an irrelevant system. Nevertheless, we checked whether the sequence of reactions predicted by CEB-based models could be reproduced by analogous splitting into two reactions. In this case, we tested the possibility of the first eT from QH_2 to $2Fe2S^{ox}$ in a model of **R** deprived of b_L. We found that SQ along with $2Fe2S^{red}$ were formed but, contrary to the assumptions of CEB, this the state has lower energy than **R**. This means that the process turned out to be exoergic, leading to the formation of stable SQ at Q_o. In contrast, the complementary reaction of the second eT from SQ to b_L (reproduced in **P3** deprived of 2Fe2S) was found to be endoergic. This introduces a high energy barrier that cannot be easily crossed. As the electron does not reach b_L, further eT toward Q_i is not possible and the system is expected to become trapped in a state with relatively stable SQ, potentially detectable under equilibrium conditions. This outcome is inconsistent with both CEB assumptions and experimental observations. Thus, splitting EB into two separate eT reactions appears to introduce artifacts, either preventing the initial reaction or producing a stable SQ. Therefore, the occurrence of EB must be viewed as an inherent emergent property of QH_2 oxidation at Q_o.

Predictions inferred from the EMBER model

Our results revealed a fundamentally new picture of the primary steps of EB catalyzed by cytbc_1, substantially different from CEB. However, it is virtually not possible to point to a single experimental observation that would directly validate this mechanism. Instead, its verification (or rejection) would require a systematic reanalysis of existing literature data, which is beyond the scope of this article. Nevertheless, we highlight several key predictions of the EMBER model along with corresponding experimental observations that, taken together, support our proposed mechanism of EB.

Prediction 1: According to the EMBER model, antimycin-inhibited cytbc_1 exposed to substrates becomes trapped in the states **R↔I1↔I2↔P3** (Fig 6). Among these states, **P3,**

containing SQ^- and $2Fe2S^{red}$ with parallel spins, appears to be the most characteristic. The structural proximity of these two centers, connected by an H bond provides a strong argument for the origin of the spin-coupled SQ-$2Fe2S^{red}$ EPR signal[18,19,58]. This signal exhibits a rhombic spectrum arising from spin-spin exchange interaction with estimated frequency ~3.6 GHz, producing the most prominent transition at g = 1.94 (Fig. 7A, green) - clearly distinguishable from the $2Fe2S^{red}$ signal at g = 1.90 (Fig. 7A, black). It can be further suggested that the amplitude of SQ-$2Fe2S^{red}$ signal should correlate with the amplitude of the SQ radical signal, posed by **I1** and/or **I2** if the system is in the stationary state. Therefore, one would expect the SQ signal to be detectable by EPR in the same samples containing SQ-$2Fe2S^{red}$. Indeed, several reports describe distinct SQ signals under non-equilibrium conditions in antimycin-inhibited cytbc_1 including ours[18–22,59,60]. In this work, we also observed SQ signal at temperatures above 150 K, together with SQ-$2Fe2S^{red}$ at 20 K (Fig. 7B). Interestingly, these two signals were found to be linearly correlated, in agreement with expectations derived form the EMBER model. While the SQ–$2Fe2S^{red}$ signal provides a specific signature of spin coupling between two defined cofactors, assigning the SQ signal itself to **I1** and/or **I2** remains inherently challenging. At this stage, we cannot rule out a possibility that the detected SQ arises from a thermally activated process related to the SQ–$2Fe2S^{red}$ state.

Prediction 2. When the system reaches equilibrium after substrate exhaustion, both the SQ and SQ–$2Fe2S^{red}$ EPR signals disappear (Fig. 5A,B; red and black, respectively). This provides clear evidence that they originate from species formed exclusively under non-equilibrium conditions and therefore represent transient intermediates trapped during the reaction. Moreover, EMBER predicts that **P3** occurs in enzyme molecules in which b_L remains oxidized. Accordingly, the signal at g = 1.94 should be accompanied by the b_L^{ox} signal, a result consistently reproduced in experiments[18,19].

Prediction 3. The transitions between **I2** and **P3** are relatively slow as they require crossing **P2***, which lies ~18 kcal/mol above both **I2** and **P3**. This barrier corresponds to the rate constant of approximately 1/s [61]. The experimentally obtained rate of growth of SQ-$2Fe2S^{red}$ signal (Fig. 8 green) is ~4.7/s, which, according to Eyring equation, corresponds to the energy barrier ~16 kcal/mol. If the observed growth rate of the SQ–$2Fe2S^{red}$ signal indeed reflects the internal barrier-crossing step rather than substrate diffusion, then the close match with the calculated values, within this assumption, supports the reliability of the energy profile in Fig. 6.

We further propose that a tunneling process (eT exchange between 2Fe2S and b_L) may contribute to the **I2** ↔ **P3** transitions, effectively lowering this barrier.

The observed decrease of SQ-2Fe2S^{red} at the rate ~0.1/s is explained by a spontaneous b_H oxidation. It reopens possibility of eT from b_L to b_H eT and progression toward the final **P1'^{Y}**. As a consequence, one may observe decrease in amplitude of 2Fe2S^{red} with Q formation at Q_o at the same rate as SQ-2Fe2S^{red} decay (Fig. 8 black). This rate is comparable to antimycin-inhibited cyt*bc*$_1$.

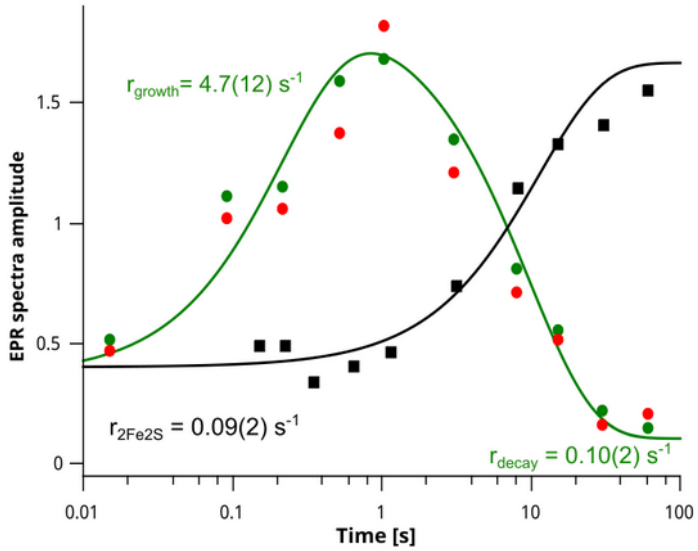

Figure 8. Time dependence of EPR signals in antimycin-inhibited cyt*bc*$_1$. Green and red circles represent the amplitudes of SQ–2Fe2S^{red} (g = 1.94) and SQ (g = 2.0), respectively. Black squares denote the amplitude of 2Fe2S^{red} with Q bound at the Qo site. The solid green line corresponds to a biexponential fit (growth and decay) of the SQ–2Fe2S^{red} signal, while the solid black line represents a single-exponential fit of the 2Fe2Sred signal.

Prediction 4. The relatively slow predicted kinetics of **P3** formation, together with the parallel spins in SQ and 2Fe2S^{red}, provide strong arguments against the possibility that SQ–2Fe2S^{red} arises as the initial step of EB resulting from electron transfer from QH_2 to 2Fe2S^{ox}. In particular, further transition of **P3** *via* the high-energy **P4*** intermediate would yield a product at Q_o and complete EB. According to CEB, such a process would entail the risk of short-circuit reactions during subsequent QH_2 oxidation to SQ, because b_L (remaining reduced from the previous cycle) could rapidly re-reduce SQ back to QH_2. To avoid such short circuits, the enzyme must minimize this pathway, for instance by making the **P3** → **P4*** transition highly unfavorable. In Fig. 7D, we show the effect of blocking 2Fe2S^{red} oxidation in **P3**. When antimycin-inhibited cyt*bc*$_1$ was mixed with a sub-stoichiometric amount of substrates, the system reached a stationary state with maximum **P3** after 1 s. At this stage, the oxidizing capacity (oxidized cyt*c*) was nearly exhausted. Under these conditions, a fraction of the enzyme contained SQ–2Fe2S^{red} (Fig. 7D, blue spectrum, g =

1.94), while another fraction contained reduced 2Fe2S^{red} with Q bound at Q_o (Fig. 7D, blue spectrum, g = 1.90). The Q molecule bound at the Q_o site is evidenced by the g = 1.80 characteristic transition[62]. Upon mixing the sample with an extra portion of cyt*c* (increasing oxidizing power), the 2Fe2S^{red} signal decreased dramatically upon oxidation (Fig. 7D, green spectrum), whereas the signal corresponding to **P3** remained unchanged. This provides strong suggestion that in the **P3** state, 2Fe2S^{red} cannot leave Q_o to generate Q, and thus the transition from **P3** to **P4*** is not possible.

Prediction 5. The existence of **P3** resembles a "dead-end" branch in the QH_2 oxidation pathway, blocking Q_o and reducing enzymatic activity from QH_2 oxidation pathway, blocks Q_o and reduces the enzymatic activity from ~400/s to approximately 4/s [63]. This blocking effect may explain why antimycin inhibits cyt*c* reduction by cytbc_1. In the absence of the inhibitor, when b_H can accept an electron from b_L, **I1** and **I2** remain transient, whereas **P3**, being kinetically isolated, does not accumulate to significant levels. Consequently, the paramagnetic signatures of **I1**, **I2**, and **P3** should remain undetectable by EPR under equilibrium conditions or in the non-inhibited enzyme. This expectation has been confirmed by previous experiments[64].

Prediction 6. Formation of **P3** requires prior eT to b_L (i.e., transition from **R** to **I1**/**I2**). Therefore, a mutation that disrupts the normal redox activity of b_L should eliminate **P3**. Indeed, the spectroscopic signature of **P3** was not detected in a mutant with impaired b_L function, caused by substitution of one of its axial histidine ligands with asparagine[52].

Prediction 7. It can be proposed that the energy released during eT from b_L to Q_i facilitates the movement of ISP, thereby enhancing the probability of rapid eT from 2Fe2S^{red} to cytc_1. Indeed, although indirect, experimental evidence supporting the existence of such a mechanism has been reported[65].

Large models *vs* transition states estimation

Several attempts have been made to calculate TSs states in modeling EB; however, these models included either the reaction of QH_2 with 2Fe2S^{ox} [34] or sequence of reactions following CEB[33]. We chose to use large models because our QM optimizations led to different electronic states when the models were artificially divided into parts considering only a single cofactor at a time, which could result in a biased energetic landscape. Such using of the large cluster models makes calculation of TSs unfeasible and unreliable. Nevertheless, given the small nuclear rearrangements observed during optimization, it is reasonable to assume that large energy barriers

for eT are unlikely. The only barrier estimated corresponded to **P2***, which likely accounts for the experimentally observed kinetic isolation of the state containing SQ–2Fe2S^{red} under conditions of blocked eT from b_L to b_H.

Equilibrium redox potentials vs dynamic changes in electron affinities of cofactors engaged in EB

According to EMBER, the catalytic reaction is initiated by eT from QH_2 to b_L. This reaction has never been considered by CEB, as in the framework of equilibrium electrochemical theory, the E_m of b_L appears too low for an effective withdrawal of electron from QH_2. Reconciliation of this apparent contradiction lies in a postulation that values of redox potentials of cofactors determined under equilibrium might not be relevant when describing individual each step of the reaction, but rather reflect the final thermodynamic relationships between the reduced and oxidized populations of all redox elements once the system has reached equilibrium and the reaction is complete. While this statement may seem controversial, it does not challenge the general validity of Marcus theory[66]. Rather, it allows us to consider that under certain transient conditions present in cytbc_1 (and possibly in other multicofactor enzymes), additional dynamic factors, such as charge separations due to eT and pT, may effectively modulate electron affinity around particular redox cofactors fixed within a protein environment of relatively low dielectric constant. This modulation may arise from dynamic changes in the protonation states of amino acid residues and in the redox states of interacting cofactors during the course of the reaction. Indeed, previous studies have shown that reduction of one heme can lower the redox potential of an adjacent heme through Coulombic interactions by tens or even hundreds of millivolts[67]. Such changes in electrostatic interactions often lead to splitting or stretching of Nernst curves (due to a lowering of the n parameter below 1) measured for cofactors spatially constrained by the protein structure[68,69]. The effect of such interactions has also been demonstrated for electron distribution in dimeric cytb_6f[70]. In the case of hemes *b* at distances similar to those in cytbc_1, shifts of up to ±100 mV should be expected[27,67]. Moreover, protonation of H156 near 2Fe2S can shift the cluster potential from approximately -120 mV to +300 mV [71]. The latter two examples have direct relevance to description of transient conditions of EB.

Considering that determined E_m for b_L corresponds to conditions where b_H is already reduced, and for 2Fe2S^{red} where protonation has already occurred, these values clearly do not reflect the state of the activated enzyme–substrate complex in which EB begins. At the onset of EB, the electron affinities of b_L and 2Fe2S may be relatively similar from the 'QH2 point of view,' because at this stage b_H is oxidized and H156 at the 2Fe2S cluster is deprotonated (protonation prevents the reaction). This effect likely elevates the electron affinity of b_L, lowering the energy levels of **I1** and **I2**. Consequently, a large potential separation between Q/SQ and SQ/QH_2 is not required at the early stages of EB. After bifurcation is completed and equilibrium is established, the system adopts

a state in which b_L and 2Fe2S exhibit potentials of approximately –120 mV and +300 mV, respectively, as determined from equilibrium redox titrations[72] .CEB, using these values to describe the initial stages would require introducing a large split in the redox potentials of the Q/SQ/QH_2 triad and, associated with this assumption, alternating sequence of uphill and downhill steps. Consequently, CEB faces a mechanistic issue of having to put additional constraints that would explain prevention of potential short circuiting of the system. EMBER, proposing a relatively flat energy profile for EB without alternating uphill/downhill steps, is devoid of this concern.

The EMBER model presented here considers the EB mechanism catalyzed by cytbc_1 at a fundamental level, providing a comprehensive explanatory framework for both current and future experiments. We believe that applying this model and moving beyond the canonical electron bifurcation concept allows several previously difficult-to-interpret observations to be clarified, and those that appeared contradictory can now be unified. As the proposed, concept of transient changes in electron affinities may apply not only to cytbc_1 but also to other multicofactor enzymes, future experiments should aim to confirm or falsify this model.

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Data availability statement

The experimental data supporting the findings of this study have been deposited in the RODBUK Cracow Open Research Data Repository under DOI: https://doi.org/10.57903/UJ/LVJICQ The data are currently under embargo and will be made publicly available upon publication of this article.

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