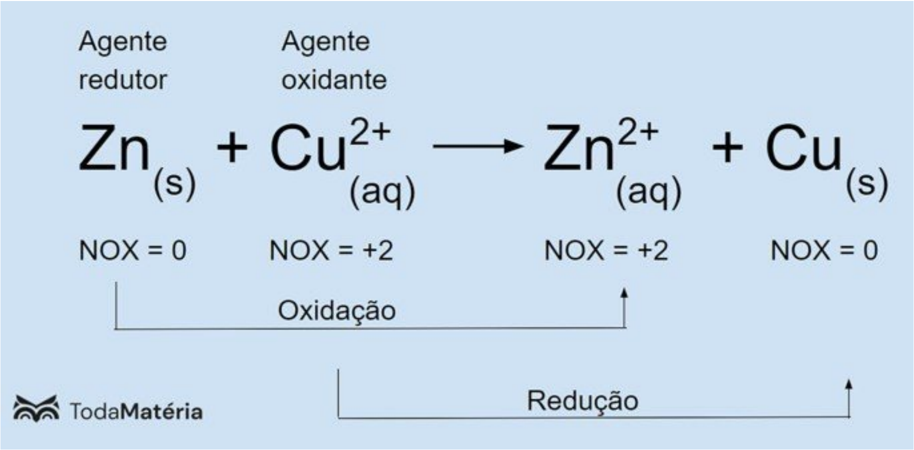
Fosforilação oxidativa

Reações de oxido-redução (ou reações redox) envolve a transferência de elétrons (geralmente em pares) de um doador para um aceptor, com a mudança do número de oxidação das espécies

Fonte: https://www.todamateria.com.br/reacoes-de-oxirreducao/



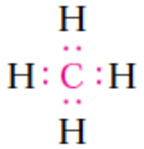
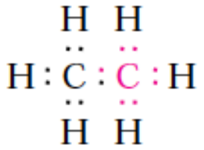
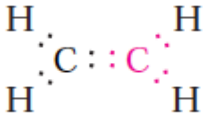
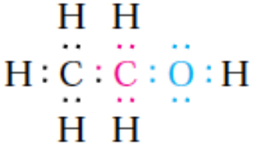
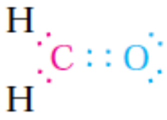
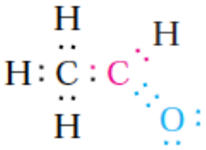
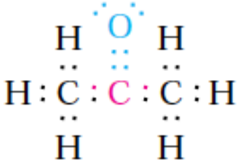
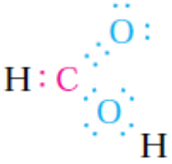
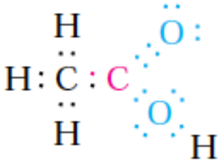
As reações redox podem ser escritas como meias reações:

$$Fe^{2+} + Cu^{2+} \rightleftharpoons Fe^{3+} + Cu^{+}$$

can be described in terms of two half-reactions:

$$(1) \quad Fe^{2+} \rightleftharpoons Fe^{3+} + e^{-}$$
$$(2) \quad Cu^{2+} + e^{-} \rightleftharpoons Cu^{+}$$

Estados de oxidação do carbono em moleçulas orgânicas pode variar de acordo com os atomos ligantes

Methane		8
Ethane (alkane)		7
Ethene (alkene)		6
Ethanol (alcohol)		5
Acetylene (alkyne)		5
Formaldehyde		4
Acetaldehyde (aldehyde)		3
Acetone (ketone)		2
Formic acid (carboxylic acid)		2
Carbon monoxide		2
Acetic acid (carboxylic acid)		1
Carbon dioxide		0

O potencial redox padrão (E^0) de uma meia reação é uma medida da tendência de uma espécie química adquirir elétrons

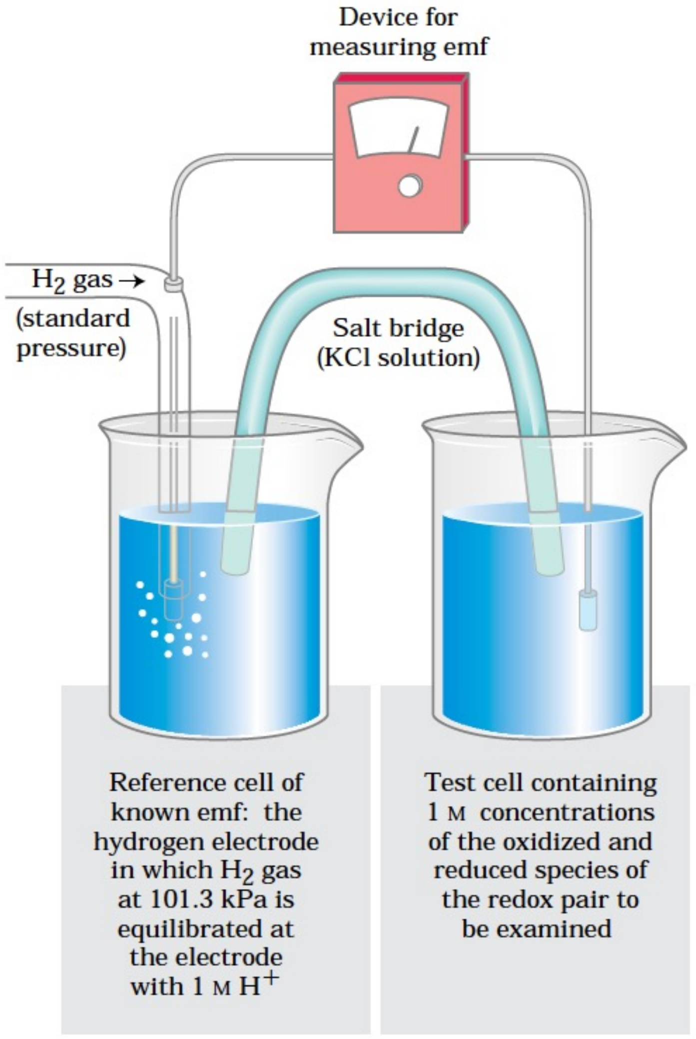


FIGURE 13–14 Measurement of the standard reduction potential (E'°) of a redox pair. Electrons flow from the test electrode to the reference electrode, or vice versa. The ultimate reference half-cell is the hydrogen electrode, as shown here, at pH 0. The electromotive force (emf) of this electrode is designated 0.00 V. At pH 7 in the test cell, E'° for the hydrogen electrode is −0.414 V. The direction of electron flow depends on the relative electron "pressure" or potential of the two cells. A salt bridge containing a saturated KCl solution provides a path for counter-ion movement between the test cell and the reference cell. From the observed emf and the known emf of the reference cell, the experimenter can find the emf of the test cell containing the redox pair. The cell that gains electrons has, by convention, the more positive reduction potential.

A transferência de elétrons entre duas moléculas será favorável se ocorrer do par redox (doador/aceptor de elétrons) mais negativo para o mais positivo (ou menos negativo)

TABLE 13–7 Standard Reduction Potentials of Some Biologically Important Half-Reactions, at pH 7.0 and 25 °C (298 K)

Half-reaction	*E′°* (V)
$\frac{1}{2}O_2 + 2H^+ + 2e^- \longrightarrow H_2O$	0.816
$Fe^{3+} + e^- \longrightarrow Fe^{2+}$	0.771
$NO_3^- + 2H^+ + 2e^- \longrightarrow NO_2^- + H_2O$	0.421
Cytochrome *f* (Fe^{3+}) + e^- ⟶ cytochrome *f* (Fe^{2+})	0.365
$Fe(CN)_6^{3-}$ (ferricyanide) + e^- ⟶ $Fe(CN)_6^{4-}$	0.36
Cytochrome a_3 (Fe^{3+}) + e^- ⟶ cytochrome a_3 (Fe^{2+})	0.35
$O_2 + 2H^+ + 2e^- \longrightarrow H_2O_2$	0.295
Cytochrome *a* (Fe^{3+}) + e^- ⟶ cytochrome *a* (Fe^{2+})	0.29
Cytochrome *c* (Fe^{3+}) + e^- ⟶ cytochrome *c* (Fe^{2+})	0.254
Cytochrome c_1 (Fe^{3+}) + e^- ⟶ cytochrome c_1 (Fe^{2+})	0.22
Cytochrome *b* (Fe^{3+}) + e^- ⟶ cytochrome *b* (Fe^{2+})	0.077
Ubiquinone + $2H^+$ + $2e^-$ ⟶ ubiquinol + H_2	0.045
$Fumarate^{2-}$ + $2H^+$ + $2e^-$ ⟶ $succinate^{2-}$	0.031
$2H^+ + 2e^- \longrightarrow H_2$ (at standard conditions, pH 0)	0.000
Crotonyl-CoA + $2H^+$ + $2e^-$ ⟶ butyryl-CoA	−0.015
$Oxaloacetate^{2-}$ + $2H^+$ + $2e^-$ ⟶ $malate^{2-}$	−0.166
$Pyruvate^-$ + $2H^+$ + $2e^-$ ⟶ $lactate^-$	−0.185
Acetaldehyde + $2H^+$ + $2e^-$ ⟶ ethanol	−0.197
FAD + $2H^+$ + $2e^-$ ⟶ $FADH_2$	−0.219*
Glutathione + $2H^+$ + $2e^-$ ⟶ 2 reduced glutathione	−0.23
$S + 2H^+ + 2e^- \longrightarrow H_2S$	−0.243
Lipoic acid + $2H^+$ + $2e^-$ ⟶ dihydrolipoic acid	−0.29
$NAD^+ + H^+ + 2e^-$ ⟶ NADH	−0.320
$NADP^+ + H^+ + 2e^-$ ⟶ NADPH	−0.324
Acetoacetate + $2H^+$ + $2e^-$ ⟶ β-hydroxybutyrate	−0.346
α-Ketoglutarate + CO_2 + $2H^+$ + $2e^-$ ⟶ isocitrate	−0.38
$2H^+ + 2e^- \longrightarrow H_2$ (at pH 7)	−0.414
Ferredoxin (Fe^{3+}) + e^- ⟶ ferredoxin (Fe^{2+})	−0.432

$$\text{Acetaldehyde} + \text{NADH} + \text{H}^+ \longrightarrow \text{ethanol} + \text{NAD}^+$$

(1) $\text{Acetaldehyde} + 2\text{H}^+ + 2e^- \longrightarrow \text{ethanol}$ $\quad E'^\circ = -0.197\ \text{V}$

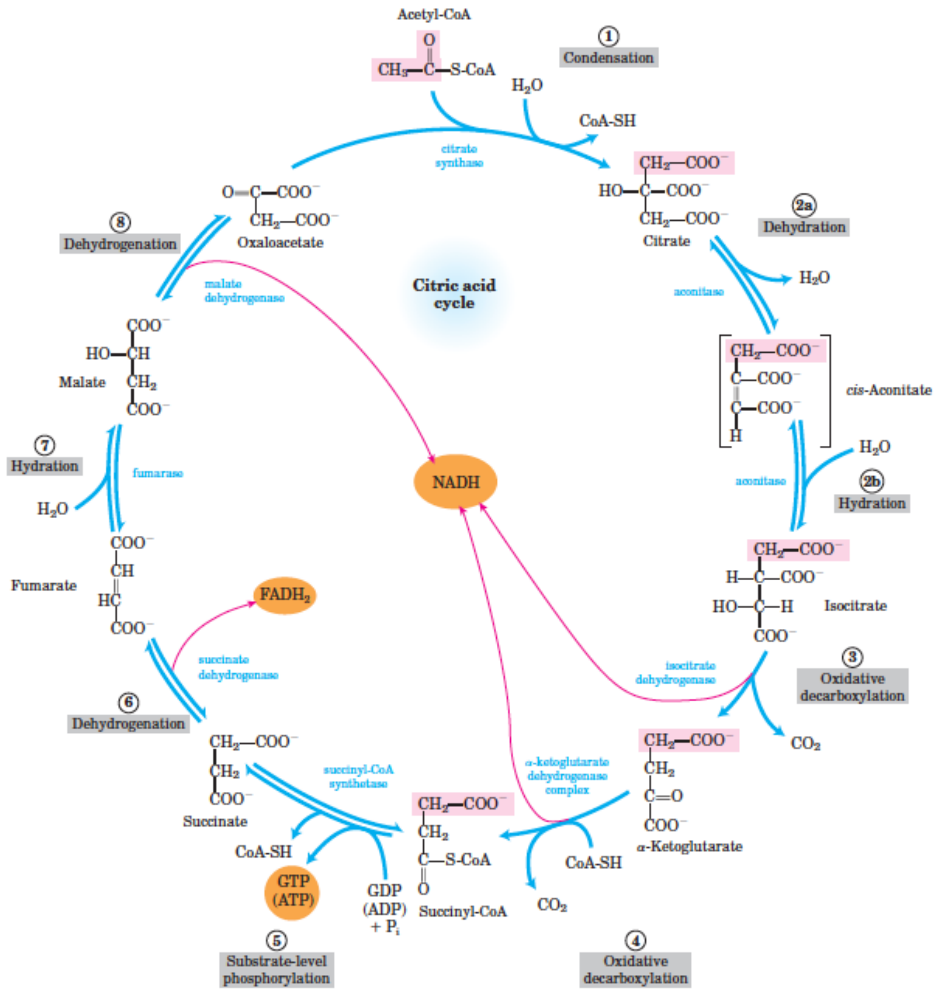
(2) $\text{NAD}^+ + 2\text{H}^+ + 2e^- \longrightarrow \text{NADH} + \text{H}^+$ $\quad E'^\circ = -0.320\ \text{V}$

$$\Delta E'^\circ = -0.197\ \text{V} - (-0.320\ \text{V}) = 0.123\ \text{V},$$

$$\Delta G = -n\mathcal{F}\,\Delta E \quad \text{or} \quad \Delta G'^\circ = -n\mathcal{F}\,\Delta E'^\circ$$

$$\Delta G'^\circ = -n\mathcal{F}\,\Delta E'^\circ = -2(96.5\ \text{kJ/V}\cdot\text{mol})(0.123\ \text{V}) = -23.7\ \text{kJ/mol}$$

Lembrem que no Ciclo de Krebs todos os carbonos provenientes da glicose foram liberados como CO2 e os elétrons transferidos para as coenzimas NAD+ e FAD, que agora estão em suas formas reduzidas, NADH e FADH2



Até aqui, o CK só produziu 1 GTP (ATP) por molécula de piruvato metabolizada

Se o rendimento da oxidação complete de glicose é entre 32-36 moles ATP/mol glicose, e lembrando que a glicolise produz apneas 2 moles ATP/mol glicose, como são formados os outros ATPs?

Qual o destino das coenzimas reduzidas produzidas no CK?

NADH e FADH2 são carreadores solúveis de elétrons em reações de oxido-redução biológicas

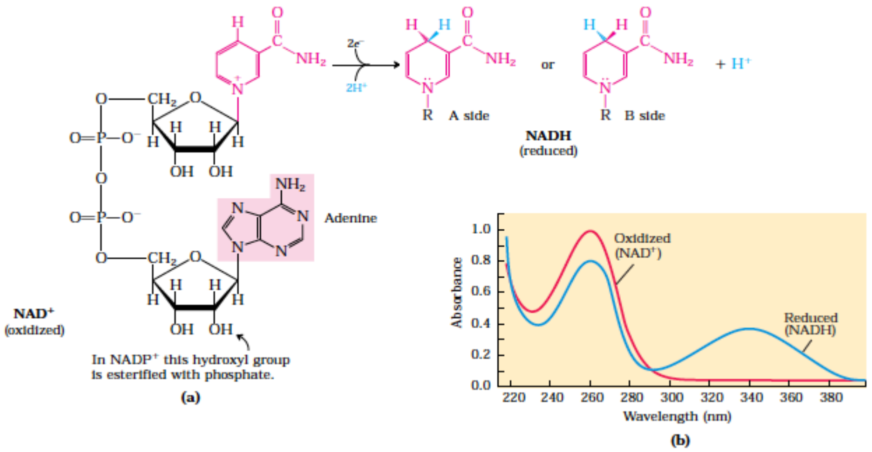


TABLE 13–8 Stereospecificity of Dehydrogenases That Employ NAD^+ or $NADP^+$ as Coenzymes

Enzyme	*Coenzyme*	*Stereochemical specificity for nicotinamide ring (A or B)*	*Text page(s)*
Isocitrate dehydrogenase	NAD^+	A	XXX–XXX
α-Ketoglutarate dehydrogenase	NAD^+	B	XXX
Glucose 6-phosphate dehydrogenase	$NADP^+$	B	XXX
Malate dehydrogenase	NAD^+	A	XXX
Glutamate dehydrogenase	NAD^+ or $NADP^+$	B	XXX
Glyceraldehyde 3-phosphate dehydrogenase	NAD^+	B	XXX
Lactate dehydrogenase	NAD^+	A	XXX
Alcohol dehydrogenase	NAD^+	A	XXX

TABLE 13–9 Some Enzymes (Flavoproteins) That Employ Flavin Nucleotide Coenzymes

Enzyme	*Flavin nucleotide*	*Text page(s)*
Acyl-CoA dehydrogenase	FAD	XXX
Dihydrolipoyl dehydrogenase	FAD	XXX
Succinate dehydrogenase	FAD	XXX
Glycerol 3-phosphate dehydrogenase	FAD	XXX
Thioredoxin reductase	FAD	XXX–XXX
NADH dehydrogenase (Complex I)	FMN	XXX
Glycolate oxidase	FMN	XXX

A ubiquinona é um carreador lipossolúvel de elétrons em reações de oxido-redução biológicas

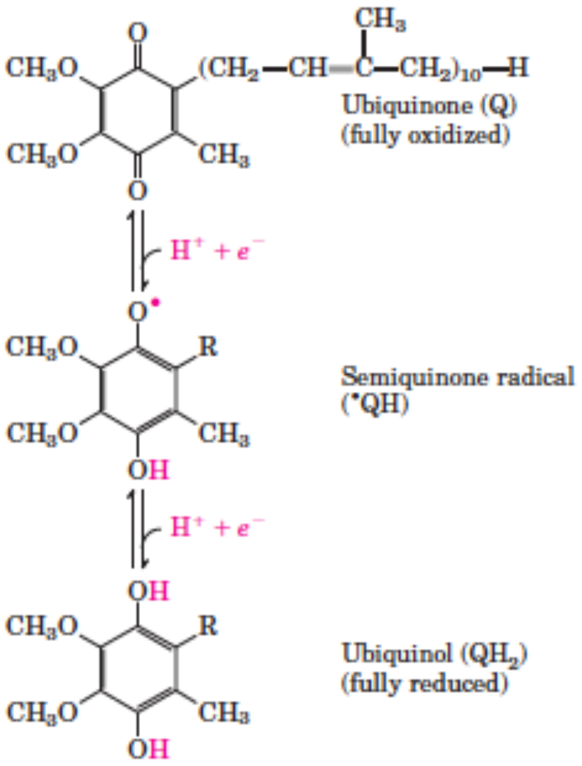


FIGURE 19–2 Ubiquinone (Q, or coenzyme Q). Complete reduction of ubiquinone requires two electrons and two protons, and occurs in two steps through the semiquinone radical intermediate.

A fosforilação oxidativa acontece na membrana mitocondrial interna

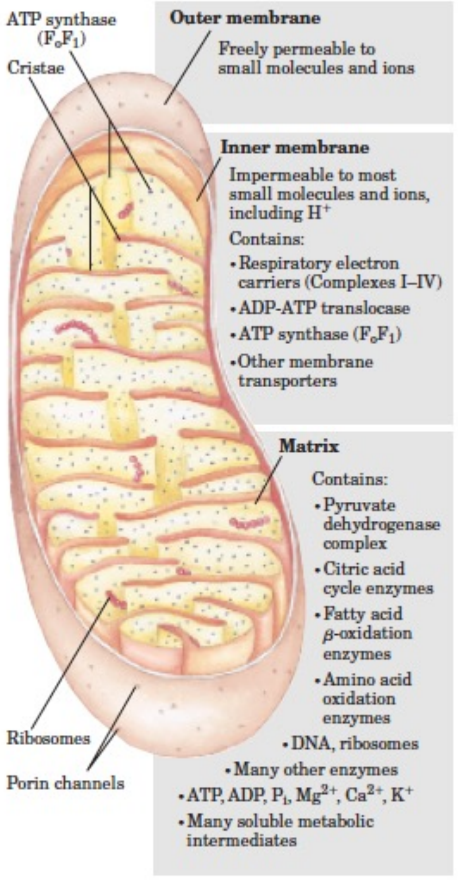
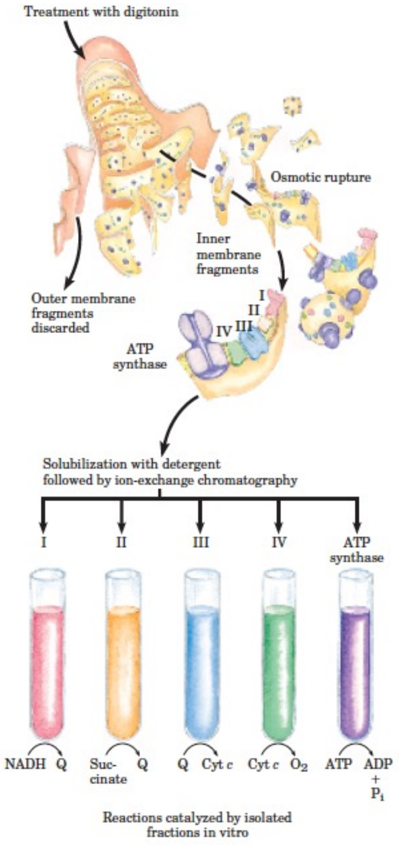


FIGURE 19–1 Biochemical anatomy of a mitochondrion. The convo-

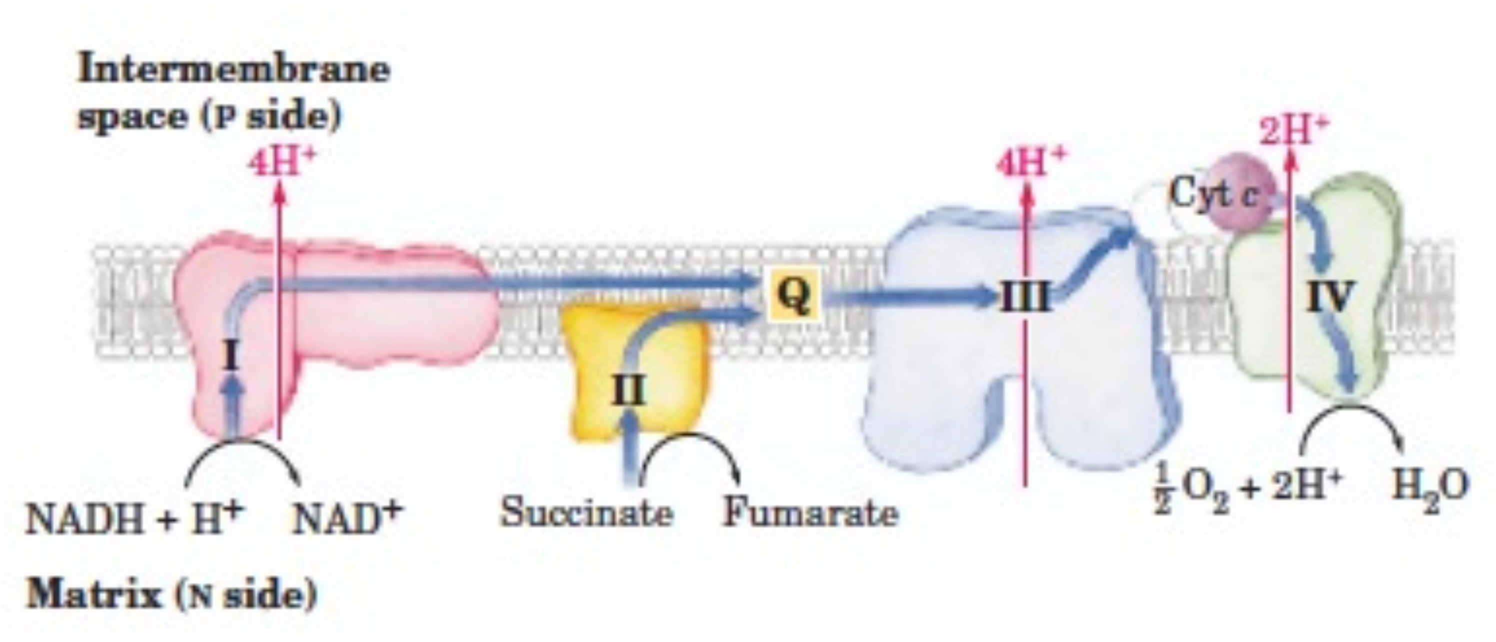
TABLE 19–3 The Protein Components of the Mitochondrial Electron-Transfer Chain

Enzyme complex/protein	*Mass (kDa)*	*Number of subunits**	*Prosthetic group(s)*
I NADH dehydrogenase	850	43 (14)	FMN, Fe-S
II Succinate dehydrogenase	140	4	FAD, Fe-S
III Ubiquinone cytochrome c oxidoreductase	250	11	Hemes, Fe-S
Cytochrome c†	13	1	Heme
IV Cytochrome oxidase	160	13 (3–4)	Hemes; Cu_A, Cu_B

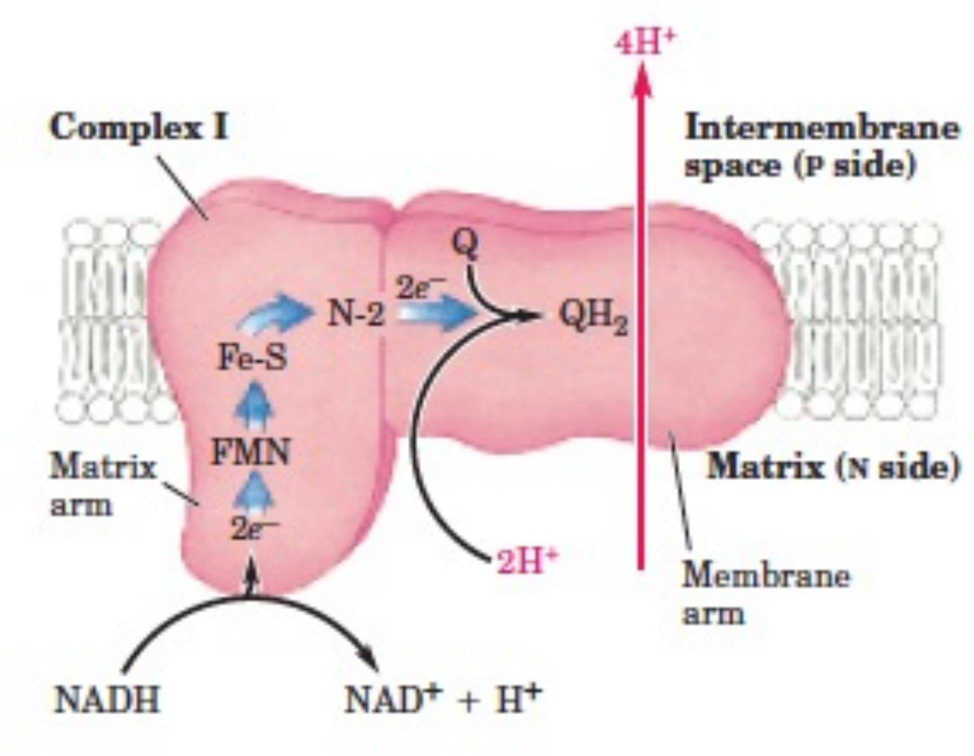
*Numbers of subunits in the bacterial equivalents in parentheses.
†Cytochrome c is not part of an enzyme complex; it moves between Complexes III and IV as a freely soluble protein.



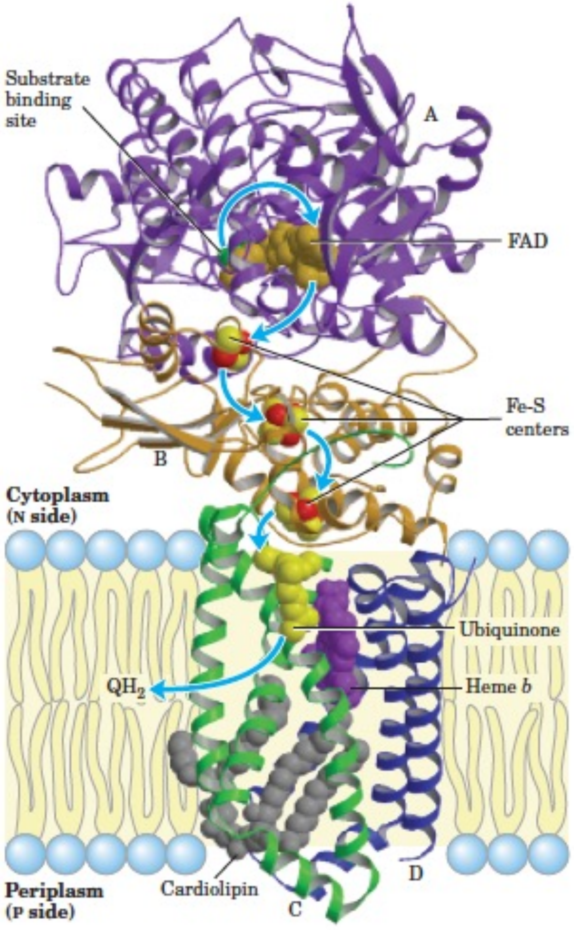
Na cadeia transportadora de elétrons, esses são transferidos das coenzimas reduzidas até O_2



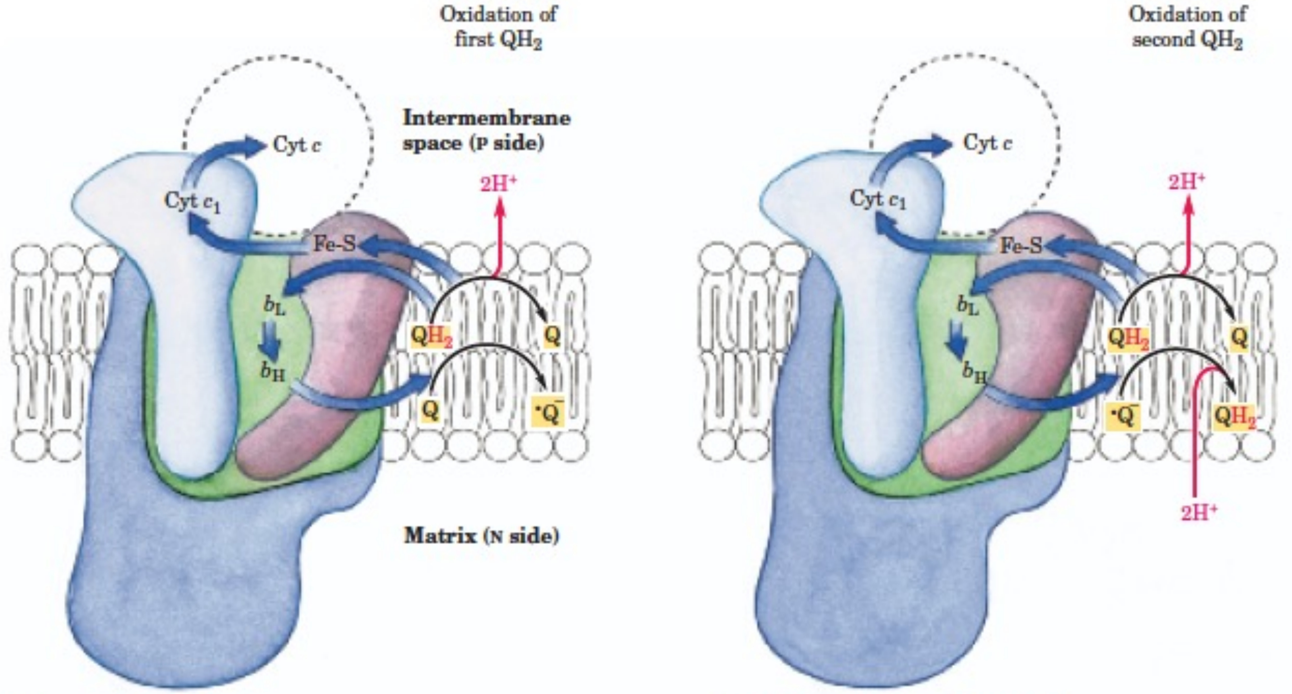
O complexo I da cadeia transportadora de elétrons



O complexo II da cadeia transportadora de elétrons



O complexo III da cadeia transportadora de elétrons



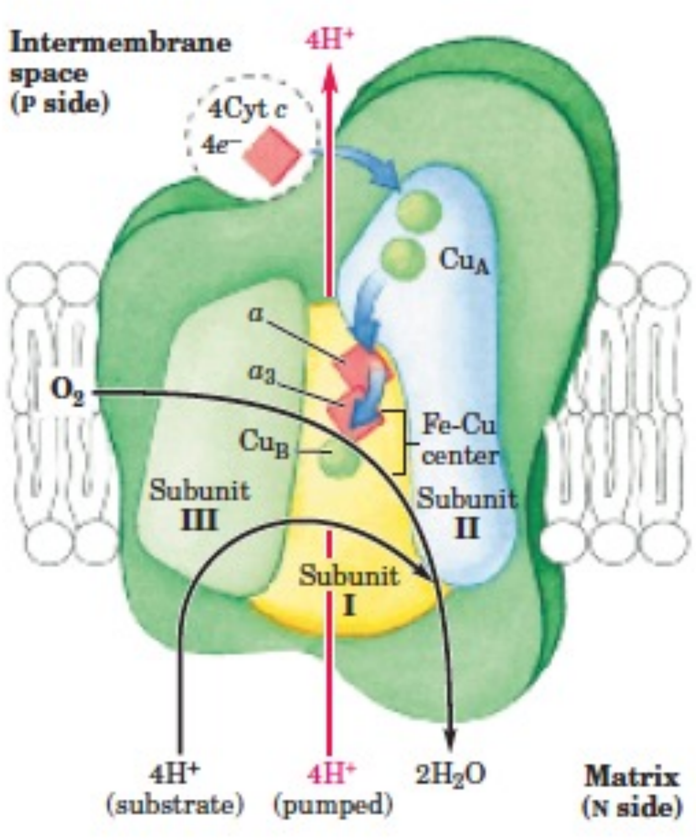
$QH_2 + \text{cyt } c_1 \text{ (oxidized)} \longrightarrow {}^{\bullet}Q^- + 2H_P^+ + \text{cyt } c_1 \text{ (reduced)}$

$QH_2 + {}^{\bullet}Q^- + 2H_N^+ + \text{cyt } c_1 \text{ (oxidized)} \longrightarrow QH_2 + 2H_P^+ + Q + \text{cyt } c_1 \text{ (reduced)}$

Net equation:

$$QH_2 + 2 \text{ cyt } c_1 \text{ (oxidized)} + 2H_N^+ \longrightarrow Q + 2 \text{ cyt } c_1 \text{ (reduced)} + 4H_P^+$$

O complexo IV da cadeia transportadora de elétrons



A energia liberada no transporte de elétrons pelos complexos da Cadeia Transportadora é armazenada na forma de gradiente de prótons

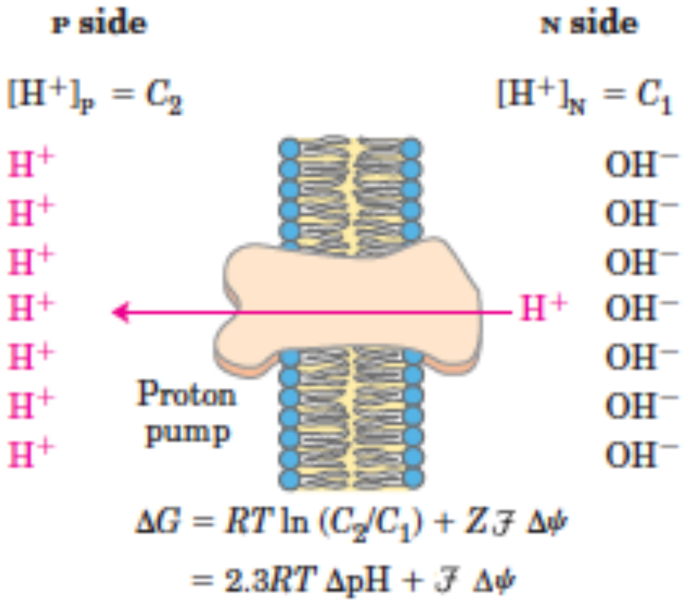


FIGURE 19–16 Proton-motive force. The inner mitochondrial membrane separates two compartments of different $[H^+]$, resulting in differences in chemical concentration (ΔpH) and charge distribution (Δψ) across the membrane. The net effect is the proton-motive force (ΔG), which can be calculated as shown here. This is explained more fully in the text.

Essa energia potencial é então utilizada para a síntese de ATP pela ATP sintase (Complexo V)

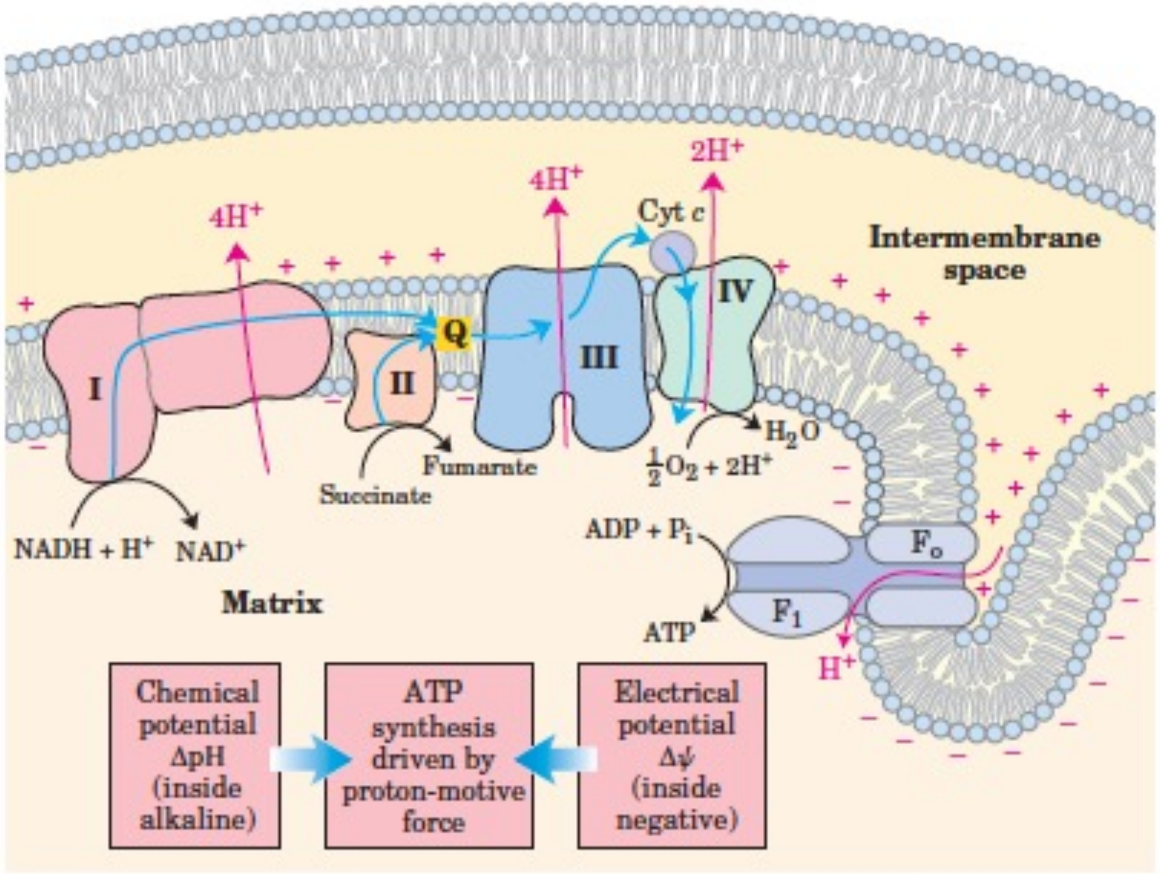


FIGURE 19–17 Chemiosmotic model. In this simple representation of the chemiosmotic theory applied to mitochondria, electrons from NADH and other oxidizable substrates pass through a chain of carriers arranged asymmetrically in the inner membrane. Electron flow is accompanied by proton transfer across the membrane, producing both a chemical gradient (ΔpH) and an electrical gradient (Δψ). The inner mitochondrial membrane is impermeable to protons; protons can reenter the matrix only through proton-specific channels (F_o). The proton-motive force that drives protons back into the matrix provides the energy for ATP synthesis, catalyzed by the F_1 complex associated with F_o.

O transporte de elétrons e a fosforilação do ADP são processos acoplados

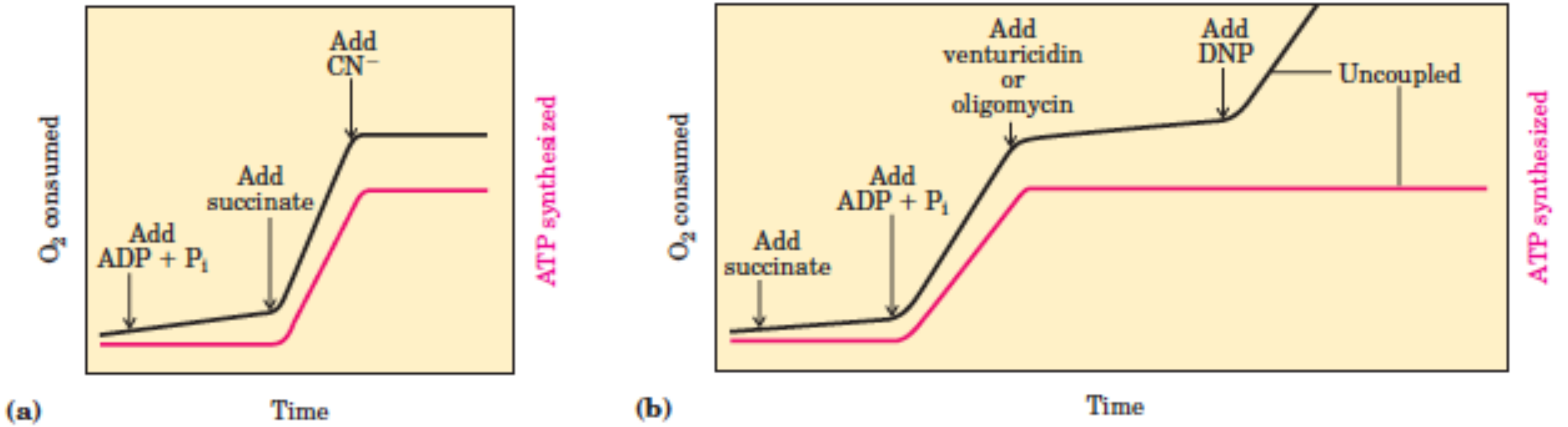


FIGURE 19–18 Coupling of electron transfer and ATP synthesis in mitochondria. In experiments to demonstrate coupling, mitochondria are suspended in a buffered medium and an O_2 electrode monitors O_2 consumption. At intervals, samples are removed and assayed for the presence of ATP. **(a)** Addition of ADP and P_i alone results in little or no increase in either respiration (O_2 consumption; black) or ATP synthesis (red). When succinate is added, respiration begins immediately and ATP is synthesized. Addition of cyanide (CN^-), which blocks electron transfer between cytochrome oxidase and O_2, inhibits both respiration and ATP synthesis. **(b)** Mitochondria provided with succinate respire and synthesize ATP only when ADP and P_i are added. Subsequent addition of venturicidin or oligomycin, inhibitors of ATP synthase, blocks both ATP synthesis and respiration. Dinitrophenol (DNP) is an uncoupler, allowing respiration to continue without ATP synthesis.

O desacoplamento desses processos libera energia na forma de calor

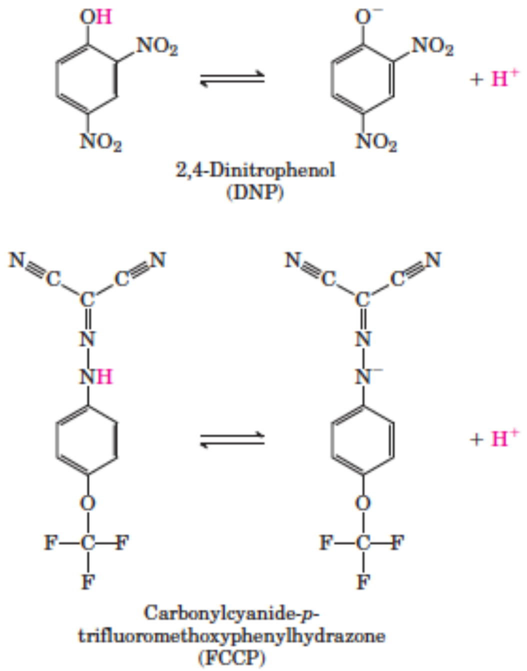
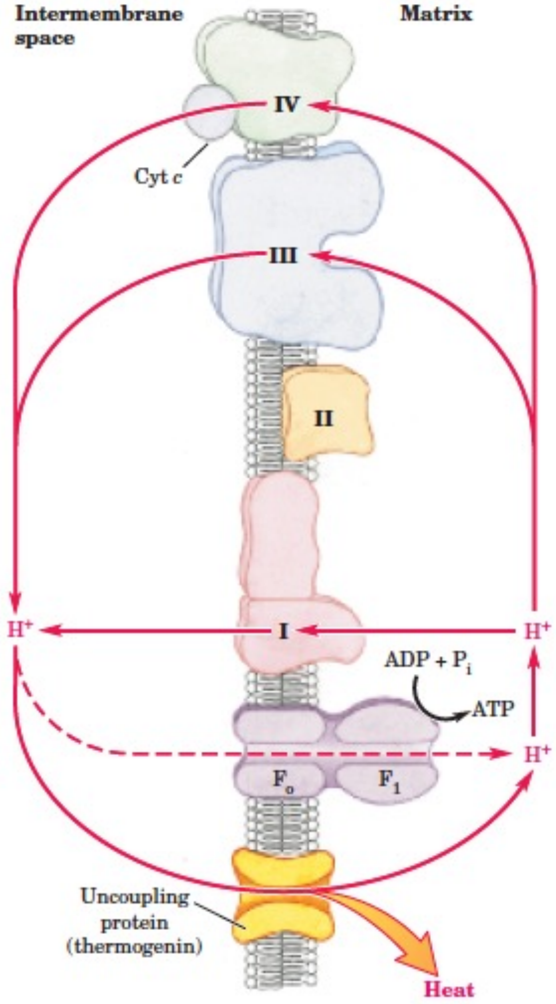
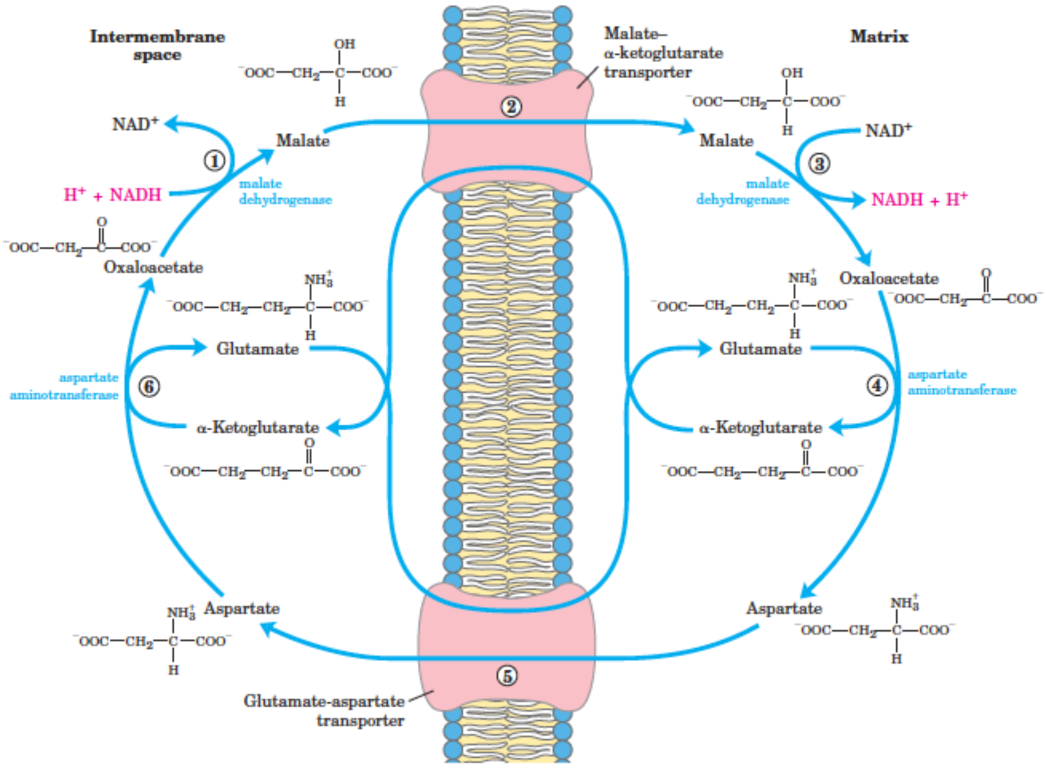
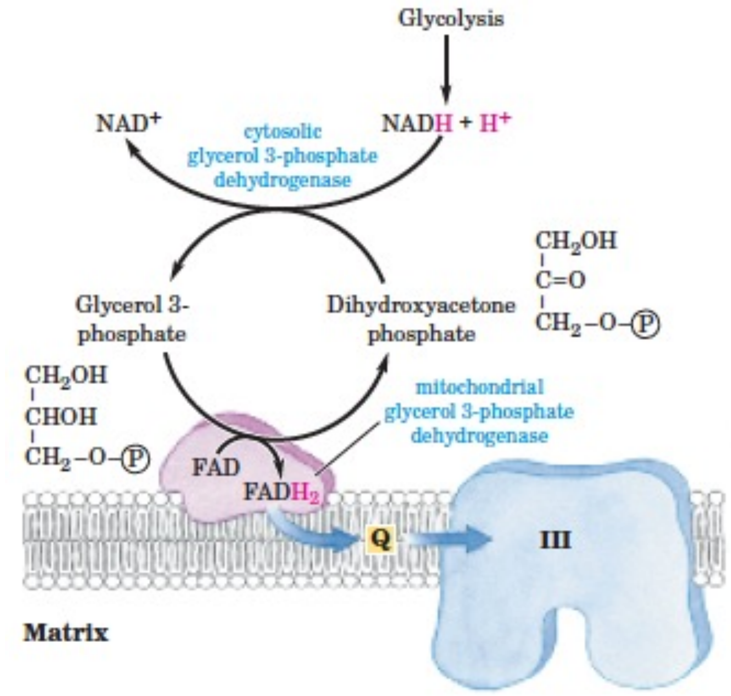


FIGURE 19–19 Two chemical uncouplers of oxidative phosphorylation. Both DNP and FCCP have a dissociable proton and are very hydrophobic. They carry protons across the inner mitochondrial membrane, dissipating the proton gradient. Both also uncouple photophosphorylation (see Fig. 19–57).



NADH citosólico é oxidado pela cadeia transportadora de elétrons indiretamente, através de lançadeiras





Assistir os seguintes vídeos:

https://www.youtube.com/watch?v=rdF3mnyS1p0

https://www.youtube.com/watch?v=kXpzp4RDGJI&t=23s