Chem 352 - Lecture 8
Carbohydrate Metabolism
Part IV: Electron Transport and ATP Synthesis

Introduction

- By combining the reactions of glycolysis with the citric acid cycle we have seen how glucose can be oxidized to CO_2 with the concomitant production of reduced nucleotides ($NADH + H^+$ and QH_2)

$$\text{Glucose} + 2\,H_2O + 10\,NAD^+ + 2\,Q + 4\,ADP + 4\,P_i \longrightarrow$$
$$6\,CO_2 + 10\,NADH + 10\,H^+ + 2\,QH_2 + 4\,ATP$$

Introduction

- The oxidation of the reduced nucleotides by oxygen and other electron receptors is tightly coupled to the the synthesis of ATP from ADP + P_i.
  - The process is called **oxidative phosphorylation.**

Introduction

des by
s
f ATP

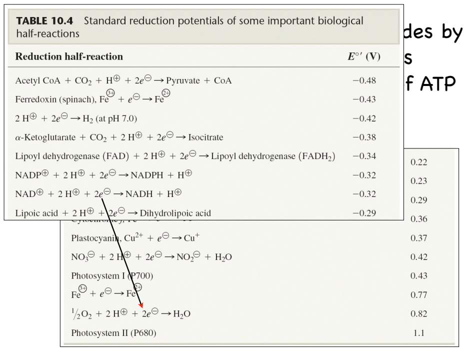
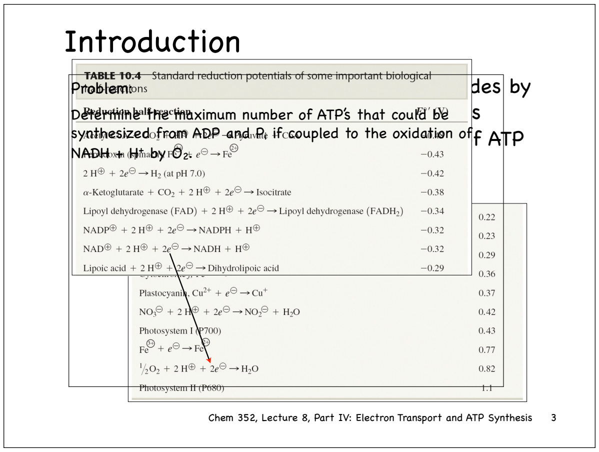


TABLE 10.4 Standard reduction potentials of some important biological half-reactions

Reduction half-reaction	$E^{\circ\prime}$ (V)
Acetyl CoA + CO_2 + $H^{\oplus}$ + $2e^{\ominus}$ → Pyruvate + CoA	−0.48
Ferredoxin (spinach), Fe^{3+} + $e^{\ominus}$ → Fe^{2+}	−0.43
$2\,H^{\oplus}$ + $2e^{\ominus}$ → H_2 (at pH 7.0)	−0.42
α-Ketoglutarate + CO_2 + $2\,H^{\oplus}$ + $2e^{\ominus}$ → Isocitrate	−0.38
Lipoyl dehydrogenase (FAD) + $2\,H^{\oplus}$ + $2e^{\ominus}$ → Lipoyl dehydrogenase ($FADH_2$)	−0.34
$NADP^{\oplus}$ + $2\,H^{\oplus}$ + $2e^{\ominus}$ → NADPH + $H^{\oplus}$	−0.32
$NAD^{\oplus}$ + $2\,H^{\oplus}$ + $2e^{\ominus}$ → NADH + $H^{\oplus}$	−0.32
Lipoic acid + $2\,H^{\oplus}$ + $2e^{\ominus}$ → Dihydrolipoic acid	−0.29

	0.22
	0.23
	0.29
	0.36
Plastocyanin, Cu^{2+} + $e^{\ominus}$ → Cu^+	0.37
$NO_3^{\ominus}$ + $2\,H^{\oplus}$ + $2e^{\ominus}$ → $NO_2^{\ominus}$ + H_2O	0.42
Photosystem I (P700)	0.43
Fe^{3+} + $e^{\ominus}$ → Fe^{2+}	0.77
$\frac{1}{2}O_2$ + $2\,H^{\oplus}$ + $2e^{\ominus}$ → H_2O	0.82
Photosystem II (P680)	1.1

3-3



Introduction

Problem:

Determine the maximum number of ATP's that could be synthesized from ADP and P_i if coupled to the oxidation of NADH + H^+ by O_2.

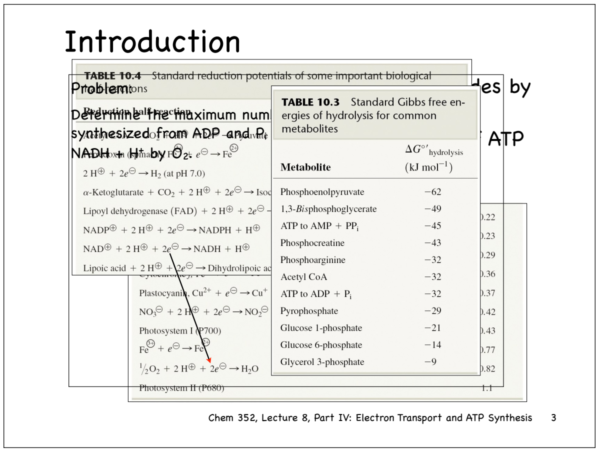
des by
s
f ATP

TABLE 10.4 Standard reduction potentials of some important biological half-reactions

Reduction half-reaction	$E^{\circ\prime}$ (V)
Acetyl CoA + CO_2 + $H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Pyruvate + CoA	−0.48
Ferredoxin (spinach), Fe^{3+} + $e^{\ominus} \rightarrow Fe^{2+}$	−0.43
$2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow H_2$ (at pH 7.0)	−0.42
α-Ketoglutarate + CO_2 + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Isocitrate	−0.38
Lipoyl dehydrogenase (FAD) + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Lipoyl dehydrogenase ($FADH_2$)	−0.34
$NADP^{\oplus}$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ NADPH + $H^{\oplus}$	−0.32
$NAD^{\oplus}$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ NADH + $H^{\oplus}$	−0.32
Lipoic acid + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Dihydrolipoic acid	−0.29

	0.22
	0.23
	0.29
	0.36
Plastocyanin, Cu^{2+} + $e^{\ominus} \rightarrow Cu^{+}$	0.37
$NO_3^{\ominus}$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow NO_2^{\ominus}$ + H_2O	0.42
Photosystem I (P700)	0.43
Fe^{3+} + $e^{\ominus} \rightarrow Fe^{2+}$	0.77
$^1/_2O_2$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow H_2O$	0.82
Photosystem II (P680)	1.1

3-4



Introduction

Problem:

Determine the maximum num
synthesized from ADP and P_i
NADH + H^+ by O_2.

des by
f ATP

TABLE 10.4 Standard reduction potentials of some important biological half-reactions

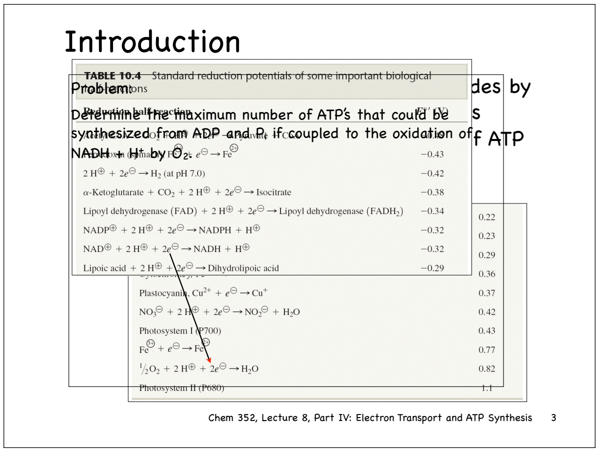
Reduction half-reaction	
$2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow H_2$ (at pH 7.0)	
α-Ketoglutarate + CO_2 + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Isoc	
Lipoyl dehydrogenase (FAD) + $2\,H^{\oplus}$ + $2e^{\ominus}$	
$NADP^{\oplus}$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ NADPH + $H^{\oplus}$	
$NAD^{\oplus}$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ NADH + $H^{\oplus}$	
Lipoic acid + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Dihydrolipoic ac	

	0.22
	0.23
	0.29
	0.36
Plastocyanin, Cu^{2+} + $e^{\ominus} \rightarrow Cu^{+}$	0.37
$NO_3^{\ominus}$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow NO_2^{\ominus}$	0.42
Photosystem I (P700)	0.43
Fe^{3+} + $e^{\ominus} \rightarrow Fe^{2+}$	0.77
$^1/_2O_2$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow H_2O$	0.82
Photosystem II (P680)	1.1

TABLE 10.3 Standard Gibbs free energies of hydrolysis for common metabolites

Metabolite	$\Delta G^{\circ\prime}_{\text{hydrolysis}}$ (kJ mol^{-1})
Phosphoenolpyruvate	−62
1,3-*Bis*phosphoglycerate	−49
ATP to AMP + PP_i	−45
Phosphocreatine	−43
Phosphoarginine	−32
Acetyl CoA	−32
ATP to ADP + P_i	−32
Pyrophosphate	−29
Glucose 1-phosphate	−21
Glucose 6-phosphate	−14
Glycerol 3-phosphate	−9

3-5



Introduction

Problem:

Determine the maximum number of ATP's that could be synthesized from ADP and P_i if coupled to the oxidation of NADH + H^+ by O_2.

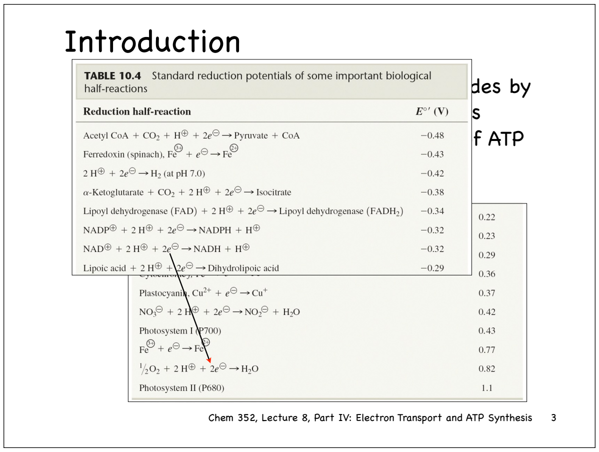
des by
s
f ATP

TABLE 10.4 Standard reduction potentials of some important biological half-reactions

Reduction half-reaction	$E^{\circ\prime}$ (V)
Acetyl CoA + CO_2 + $H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Pyruvate + CoA	−0.48
Ferredoxin (spinach), Fe^{3+} + $e^{\ominus} \rightarrow Fe^{2+}$	−0.43
$2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow H_2$ (at pH 7.0)	−0.42
α-Ketoglutarate + CO_2 + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Isocitrate	−0.38
Lipoyl dehydrogenase (FAD) + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Lipoyl dehydrogenase ($FADH_2$)	−0.34
$NADP^{\oplus}$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ NADPH + $H^{\oplus}$	−0.32
$NAD^{\oplus}$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ NADH + $H^{\oplus}$	−0.32
Lipoic acid + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Dihydrolipoic acid	−0.29

	0.22
	0.23
	0.29
	0.36
Plastocyanin, Cu^{2+} + $e^{\ominus} \rightarrow Cu^{+}$	0.37
$NO_3^{\ominus}$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow NO_2^{\ominus}$ + H_2O	0.42
Photosystem I (P700)	0.43
Fe^{3+} + $e^{\ominus} \rightarrow Fe^{2+}$	0.77
$^1/_2O_2$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow H_2O$	0.82
Photosystem II (P680)	1.1

3-6



Introduction

des by
s
f ATP

TABLE 10.4 Standard reduction potentials of some important biological half-reactions

Reduction half-reaction	$E^{\circ\prime}$ (V)
Acetyl CoA + CO_2 + $H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Pyruvate + CoA	−0.48
Ferredoxin (spinach), Fe^{3+} + $e^{\ominus} \rightarrow Fe^{2+}$	−0.43
$2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow H_2$ (at pH 7.0)	−0.42
α-Ketoglutarate + CO_2 + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Isocitrate	−0.38
Lipoyl dehydrogenase (FAD) + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Lipoyl dehydrogenase ($FADH_2$)	−0.34
$NADP^{\oplus}$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ NADPH + $H^{\oplus}$	−0.32
$NAD^{\oplus}$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ NADH + $H^{\oplus}$	−0.32
Lipoic acid + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Dihydrolipoic acid	−0.29

	0.22
	0.23
	0.29
	0.36
Plastocyanin, Cu^{2+} + $e^{\ominus} \rightarrow Cu^{+}$	0.37
$NO_3^{\ominus}$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow NO_2^{\ominus}$ + H_2O	0.42
Photosystem I (P700)	0.43
Fe^{3+} + $e^{\ominus} \rightarrow Fe^{2+}$	0.77
$^1/_2O_2$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow H_2O$	0.82
Photosystem II (P680)	1.1

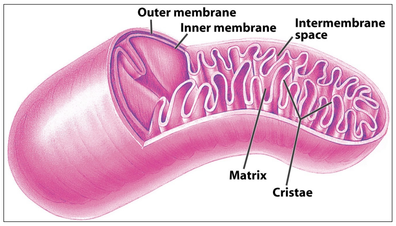
Introduction

- The oxidation of the reduced nucleotides by oxygen and other electron receptors is tightly coupled to the the synthesis of ATP from ADP + P_i.
  - The process is called **oxidative phosphorylation.**

3-7

The Mitochondria

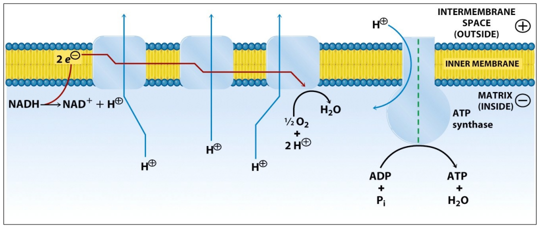
- For eukaryotes, the coupling of the reoxidation of the reduced nucleotides to the synthesis of ATP from ADP + P_i occurs in the mitochondria.



4-1

The Mitochondria

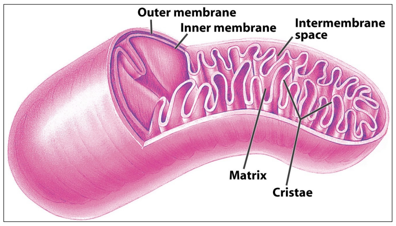
- For eukaryotes, the coupling of the reoxidation of the reduced nucleotides to the synthesis of ATP from ADP + P_i occurs in the mitochondria.



4-2

The Mitochondria

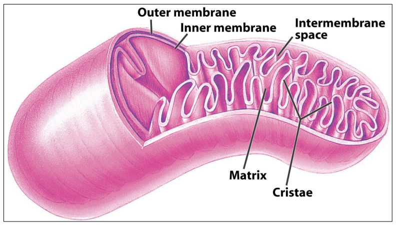
- For eukaryotes, the coupling of the reoxidation of the reduced nucleotides to the synthesis of ATP from ADP + P_i occurs in the mitochondria.



4-3

Introduction

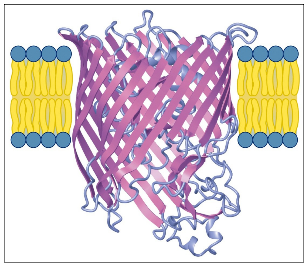
- The mitochondria are believed to have evolved from free living bacteria.



5

Introduction

- The outer membrane is quite porous to small molecules (<10,000 Da).



6

The Chemiosmotic Theory

•The chemiosmotic theory was first proposed by Peter Mitchell in the early 1960's.

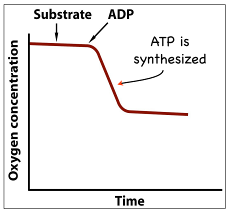
- The theory explained how the two process are linked

Peter Mitchell
(1920 – 1992)
Nobel Prize in Chemistry, 1978

7

The Chemiosmotic Theory

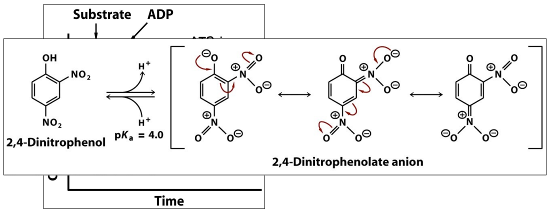
•Demonstration that the proton flow across membranes is linked to ATP synthesis.



8-1

The Chemiosmotic Theory

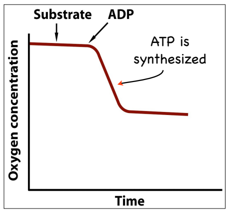
- Demonstration that the proton flow across membranes is linked to ATP synthesis.



8-2

The Chemiosmotic Theory

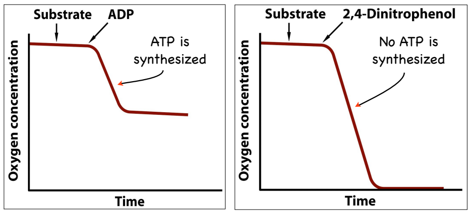
- Demonstration that the proton flow across membranes is linked to ATP synthesis.



8-3

The Chemiosmotic Theory

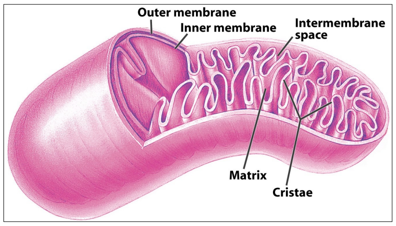
- Demonstration that the proton flow across membranes is linked to ATP synthesis.



8-4

The Mitochondria

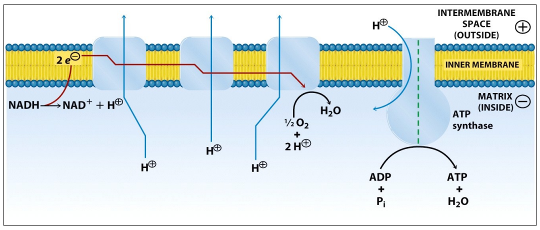
- For eukaryotes, the coupling of the reoxidation of the reduced nucleotides to the synthesis of ATP from ADP + P$_i$ occurs in the mitochondria.



9-1

The Mitochondria

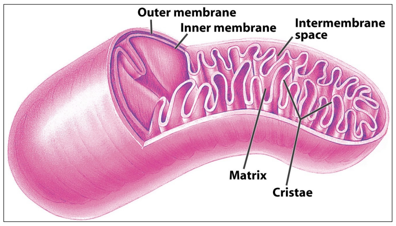
- For eukaryotes, the coupling of the reoxidation of the reduced nucleotides to the synthesis of ATP from ADP + P_i occurs in the mitochondria.



9-2

The Mitochondria

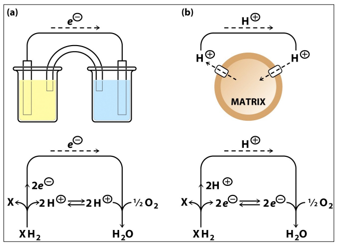
- For eukaryotes, the coupling of the reoxidation of the reduced nucleotides to the synthesis of ATP from ADP + P_i occurs in the mitochondria.



9-3

The Chemiosmotic Theory

- The **protonmotive force** is analogous to the electronmotive force (emf).



10-1

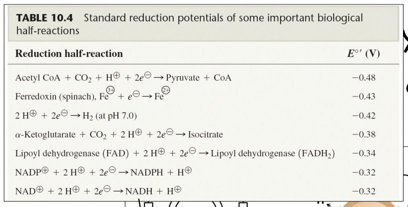
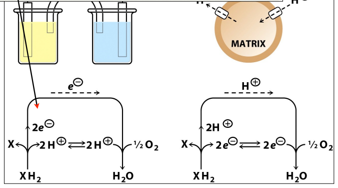


TABLE 10.4 Standard reduction potentials of some important biological half-reactions

Reduction half-reaction	$E^{\circ\prime}$ (V)
Acetyl CoA + CO_2 + $H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Pyruvate + CoA	−0.48
Ferredoxin (spinach), $Fe^{\textcircled{3+}}$ + $e^{\ominus} \rightarrow Fe^{\textcircled{2+}}$	−0.43
$2\,H^{\oplus} + 2e^{\ominus} \rightarrow H_2$ (at pH 7.0)	−0.42
α-Ketoglutarate + CO_2 + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Isocitrate	−0.38
Lipoyl dehydrogenase (FAD) + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Lipoyl dehydrogenase ($FADH_2$)	−0.34
$NADP^{\oplus}$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ NADPH + $H^{\oplus}$	−0.32
$NAD^{\oplus}$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ NADH + $H^{\oplus}$	−0.32

y

analogous (emf).



10-2

10-3

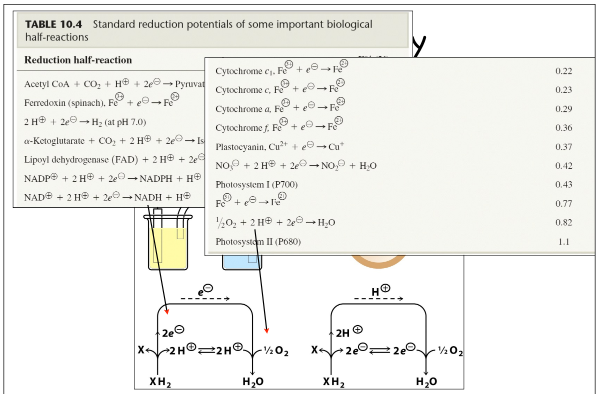


TABLE 10.4 Standard reduction potentials of some important biological half-reactions

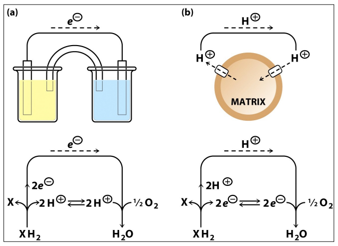
Reduction half-reaction
Acetyl CoA + CO_2 + $H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Pyruvat
Ferredoxin (spinach), Fe^{3+} + $e^{\ominus} \rightarrow Fe^{2+}$
$2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow H_2$ (at pH 7.0)
α-Ketoglutarate + CO_2 + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ Is
Lipoyl dehydrogenase (FAD) + $2\,H^{\oplus}$ + $2e^{\ominus}$
$NADP^{\oplus}$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ NADPH + $H^{\oplus}$
$NAD^{\oplus}$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow$ NADH + $H^{\oplus}$

Cytochrome c_1, Fe^{3+} + $e^{\ominus} \rightarrow Fe^{2+}$	0.22
Cytochrome c, Fe^{3+} + $e^{\ominus} \rightarrow Fe^{2+}$	0.23
Cytochrome a, Fe^{3+} + $e^{\ominus} \rightarrow Fe^{2+}$	0.29
Cytochrome f, Fe^{3+} + $e^{\ominus} \rightarrow Fe^{2+}$	0.36
Plastocyanin, Cu^{2+} + $e^{\ominus} \rightarrow Cu^{+}$	0.37
$NO_3^{\ominus}$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow NO_2^{\ominus}$ + H_2O	0.42
Photosystem I (P700)	0.43
Fe^{3+} + $e^{\ominus} \rightarrow Fe^{2+}$	0.77
$^1/_2O_2$ + $2\,H^{\oplus}$ + $2e^{\ominus} \rightarrow H_2O$	0.82
Photosystem II (P680)	1.1

10-4

The Chemiosmotic Theory

- The **protonmotive force** is analogous to the electronmotive force (emf).



11

The Chemiosmotic Theory

- The free energy for proton movement across a membrane

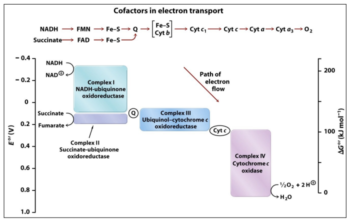
$$\Delta G_{transport} = RT\ln\left(\frac{[H^+_{in}]}{[H^+_{out}]}\right) + \mathscr{F}\Delta\Psi$$

$$\Delta G_{transport} = \mathscr{F}\Delta\Psi - 2.303\ RT\Delta pH$$

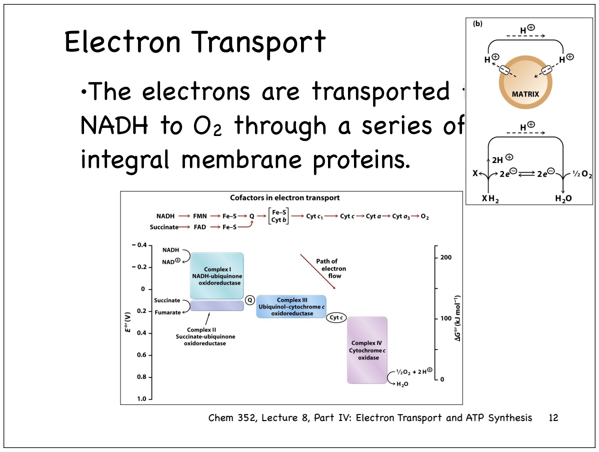
12-1

Electron Transport

- The electrons are transported from NADH to O_2 through a series of integral membrane proteins.



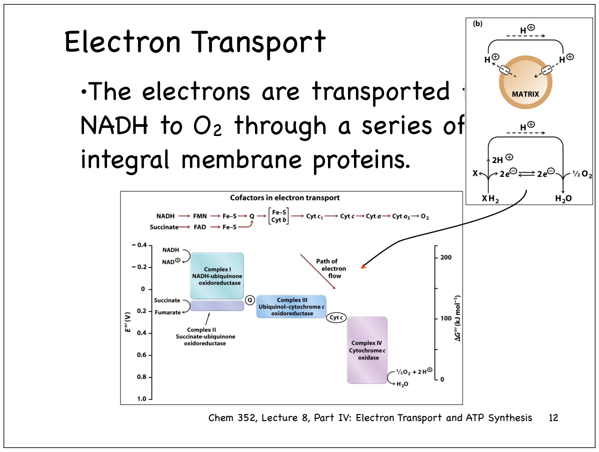
12-2



Electron Transport

- The electrons are transported NADH to O_2 through a series of integral membrane proteins.

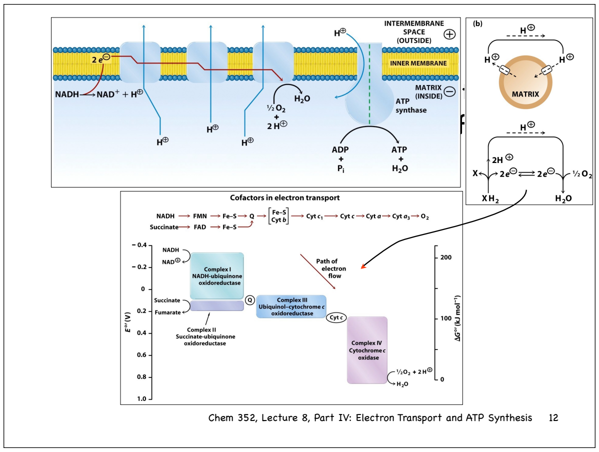
12-3



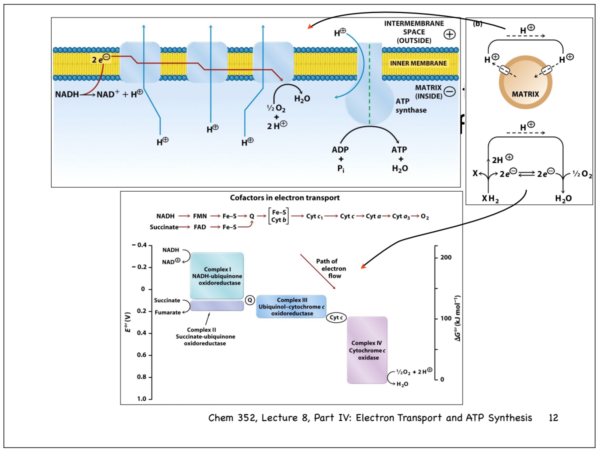
Electron Transport

- The electrons are transported NADH to O_2 through a series of integral membrane proteins.

12-4



12-5



Electron Transport Chain

The electron transport chain comprises a series of electron carriers.

- These are located in the inner mitochondrial membrane
- They are arrange in the order of increasing reduction potential (increasing affinity for electrons).

13

Electron Transport Chain

The electron transport chain comprises a series of electron carriers.

- These are located in the inner mitochondrial membrane
- They are arrange in the order of increasing reduction potential (increasing affinity for electrons).

14-1

Electron Transport Chain

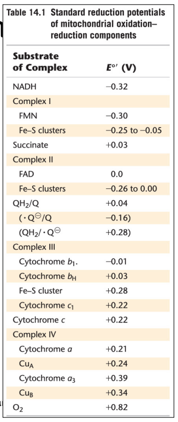
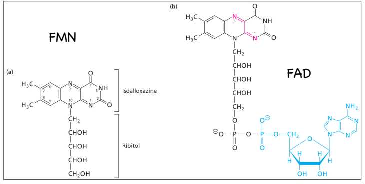


Table 14.1 Standard reduction potentials of mitochondrial oxidation–reduction components

Substrate of Complex	$E^{\circ\prime}$ (V)
NADH	−0.32
Complex I	
FMN	−0.30
Fe–S clusters	−0.25 to −0.05
Succinate	+0.03
Complex II	
FAD	0.0
Fe–S clusters	−0.26 to 0.00
QH_2/Q	+0.04
$(\cdot Q^{\ominus}/Q$	−0.16)
$(QH_2/\cdot Q^{\ominus}$	+0.28)
Complex III	
Cytochrome b_1.	−0.01
Cytochrome b_H	+0.03
Fe–S cluster	+0.28
Cytochrome c_1	+0.22
Cytochrome c	+0.22
Complex IV	
Cytochrome a	+0.21
Cu_A	+0.24
Cytochrome a_3	+0.39
Cu_B	+0.34
O_2	+0.82

14-2

Electron Transport Chain



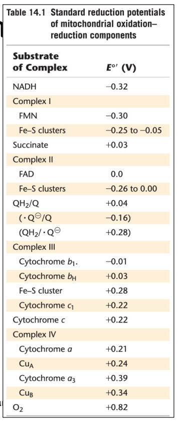


Table 14.1 Standard reduction potentials of mitochondrial oxidation–reduction components

Substrate of Complex	$E^{\circ\prime}$ (V)
NADH	−0.32
Complex I	
FMN	−0.30
Fe–S clusters	−0.25 to −0.05
Succinate	+0.03
Complex II	
FAD	0.0
Fe–S clusters	−0.26 to 0.00
QH_2/Q	+0.04
$(\cdot Q^{\ominus}/Q$	−0.16)
$(QH_2/\cdot Q^{\ominus}$	+0.28)
Complex III	
Cytochrome b_1.	−0.01
Cytochrome b_H	+0.03
Fe–S cluster	+0.28
Cytochrome c_1	+0.22
Cytochrome c	+0.22
Complex IV	
Cytochrome a	+0.21
Cu_A	+0.24
Cytochrome a_3	+0.39
Cu_B	+0.34
O_2	+0.82

14-3

Electron Transport Chain

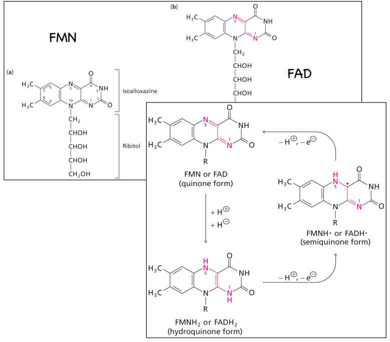


Table 14.1 Standard reduction potentials of mitochondrial oxidation–reduction components

Substrate of Complex	***E*°′ (V)**
NADH	−0.32
Complex I	
FMN	−0.30
Fe–S clusters	−0.25 to −0.05
Succinate	+0.03
Complex II	
FAD	0.0
Fe–S clusters	−0.26 to 0.00
QH_2/Q	+0.04
$(\cdot Q^{\ominus}/Q$	−0.16)
$(QH_2/\cdot Q^{\ominus}$	+0.28)
Complex III	
Cytochrome b_1.	−0.01
Cytochrome b_H	+0.03
Fe–S cluster	+0.28
Cytochrome c_1	+0.22
Cytochrome *c*	+0.22
Complex IV	
Cytochrome *a*	+0.21
Cu_A	+0.24
Cytochrome a_3	+0.39
Cu_B	+0.34
O_2	+0.82

14-4

Electron Transport Chain

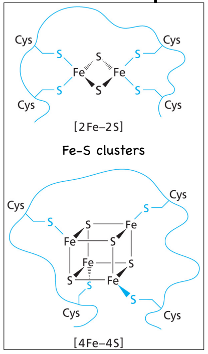


Table 14.1 Standard reduction potentials of mitochondrial oxidation–reduction components

Substrate of Complex	***E*°′ (V)**
NADH	−0.32
Complex I	
FMN	−0.30
Fe–S clusters	−0.25 to −0.05
Succinate	+0.03
Complex II	
FAD	0.0
Fe–S clusters	−0.26 to 0.00
QH_2/Q	+0.04
$(\cdot Q^{\ominus}/Q$	−0.16)
$(QH_2/\cdot Q^{\ominus}$	+0.28)
Complex III	
Cytochrome b_1.	−0.01
Cytochrome b_H	+0.03
Fe–S cluster	+0.28
Cytochrome c_1	+0.22
Cytochrome *c*	+0.22
Complex IV	
Cytochrome *a*	+0.21
Cu_A	+0.24
Cytochrome a_3	+0.39
Cu_B	+0.34
O_2	+0.82

14-5

Electron Transport Chain

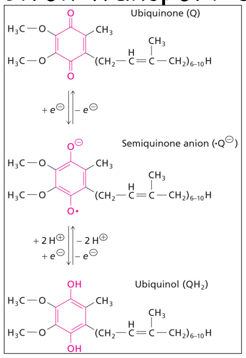


Table 14.1 Standard reduction potentials of mitochondrial oxidation–reduction components

Substrate of Complex	***E*°′ (V)**
NADH	−0.32
Complex I	
FMN	−0.30
Fe–S clusters	−0.25 to −0.05
Succinate	+0.03
Complex II	
FAD	0.0
Fe–S clusters	−0.26 to 0.00
QH_2/Q	+0.04
$(\cdot Q^{\ominus}/Q$	−0.16)
$(QH_2/\cdot Q^{\ominus}$	+0.28)
Complex III	
Cytochrome b_1.	−0.01
Cytochrome b_H	+0.03
Fe–S cluster	+0.28
Cytochrome c_1	+0.22
Cytochrome *c*	+0.22
Complex IV	
Cytochrome *a*	+0.21
Cu_A	+0.24
Cytochrome a_3	+0.39
Cu_B	+0.34
O_2	+0.82

14-6

Electron Transport Chain

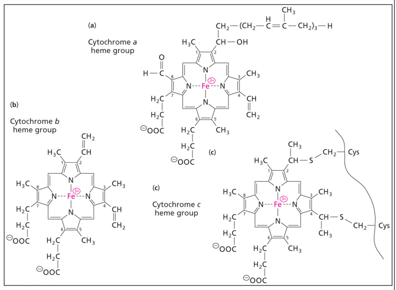


Table 14.1 Standard reduction potentials of mitochondrial oxidation–reduction components

Substrate of Complex	***E*°′ (V)**
NADH	−0.32
Complex I	
FMN	−0.30
Fe–S clusters	−0.25 to −0.05
Succinate	+0.03
Complex II	
FAD	0.0
Fe–S clusters	−0.26 to 0.00
QH_2/Q	+0.04
$(\cdot Q^{\ominus}/Q$	−0.16)
$(QH_2/\cdot Q^{\ominus}$	+0.28)
Complex III	
Cytochrome b_1.	−0.01
Cytochrome b_H	+0.03
Fe–S cluster	+0.28
Cytochrome c_1	+0.22
Cytochrome *c*	+0.22
Complex IV	
Cytochrome *a*	+0.21
Cu_A	+0.24
Cytochrome a_3	+0.39
Cu_B	+0.34
O_2	+0.82

14-7

15-1

Electron Transport Chain

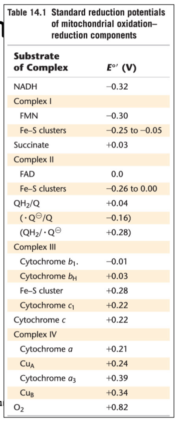
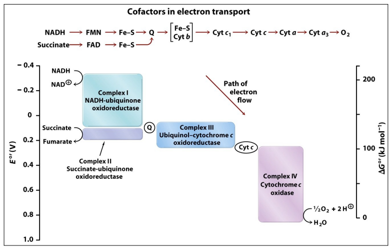


Table 14.1 Standard reduction potentials of mitochondrial oxidation–reduction components

Substrate of Complex	$E^{\circ\prime}$ (V)
NADH	−0.32
Complex I	
FMN	−0.30
Fe–S clusters	−0.25 to −0.05
Succinate	+0.03
Complex II	
FAD	0.0
Fe–S clusters	−0.26 to 0.00
QH_2/Q	+0.04
($\cdot Q^{\ominus}$/Q	−0.16)
(QH_2/$\cdot Q^{\ominus}$	+0.28)
Complex III	
Cytochrome b_1.	−0.01
Cytochrome b_H	+0.03
Fe–S cluster	+0.28
Cytochrome c_1	+0.22
Cytochrome *c*	+0.22
Complex IV	
Cytochrome *a*	+0.21
Cu_A	+0.24
Cytochrome a_3	+0.39
Cu_B	+0.34
O_2	+0.82

15-2

Electron Transport Chain



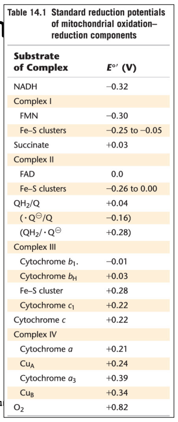
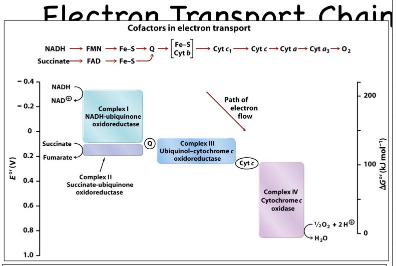


Table 14.1 Standard reduction potentials of mitochondrial oxidation–reduction components

Substrate of Complex	$E^{\circ\prime}$ (V)
NADH	−0.32
Complex I	
FMN	−0.30
Fe–S clusters	−0.25 to −0.05
Succinate	+0.03
Complex II	
FAD	0.0
Fe–S clusters	−0.26 to 0.00
QH_2/Q	+0.04
($\cdot Q^{\ominus}$/Q	−0.16)
(QH_2/$\cdot Q^{\ominus}$	+0.28)
Complex III	
Cytochrome b_1.	−0.01
Cytochrome b_H	+0.03
Fe–S cluster	+0.28
Cytochrome c_1	+0.22
Cytochrome *c*	+0.22
Complex IV	
Cytochrome *a*	+0.21
Cu_A	+0.24
Cytochrome a_3	+0.39
Cu_B	+0.34
O_2	+0.82

15-3

Electron Transport Chain



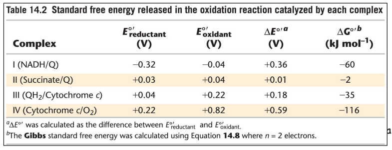


Table 14.2 Standard free energy released in the oxidation reaction catalyzed by each complex

Complex	$E^{\circ\prime}_{\text{reductant}}$ (V)	$E^{\circ\prime}_{\text{oxidant}}$ (V)	$\Delta E^{\circ\prime a}$ (V)	$\Delta G^{\circ\prime b}$ (kJ mol^{-1})
I (NADH/Q)	−0.32	−0.04	+0.36	−60
II (Succinate/Q)	+0.03	+0.04	+0.01	−2
III (QH_2/Cytochrome *c*)	+0.04	+0.22	+0.18	−35
IV (Cytochrome *c*/O_2)	+0.22	+0.82	+0.59	−116

[a] $\Delta E^{\circ\prime}$ was calculated as the difference between $E^{\circ\prime}_{\text{reductant}}$ and $E^{\circ\prime}_{\text{oxidant}}$.

[b] The **Gibbs** standard free energy was calculated using Equation **14.8** where $n = 2$ electrons.

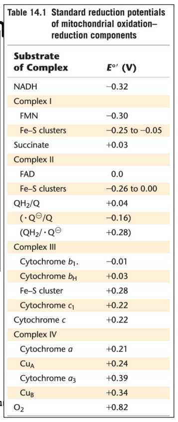
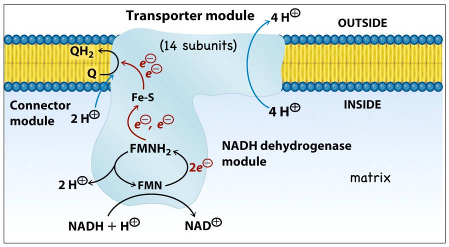


Table 14.1 Standard reduction potentials of mitochondrial oxidation–reduction components

Substrate of Complex	$E^{\circ\prime}$ (V)
NADH	−0.32
Complex I	
FMN	−0.30
Fe–S clusters	−0.25 to −0.05
Succinate	+0.03
Complex II	
FAD	0.0
Fe–S clusters	−0.26 to 0.00
QH_2/Q	+0.04
($\cdot Q^{\ominus}$/Q	−0.16)
(QH_2/$\cdot Q^{\ominus}$	+0.28)
Complex III	
Cytochrome b_1.	−0.01
Cytochrome b_H	+0.03
Fe–S cluster	+0.28
Cytochrome c_1	+0.22
Cytochrome *c*	+0.22
Complex IV	
Cytochrome *a*	+0.21
Cu_A	+0.24
Cytochrome a_3	+0.39
Cu_B	+0.34
O_2	+0.82

16-1

Complex I (NADH-Q Oxidoreductase)



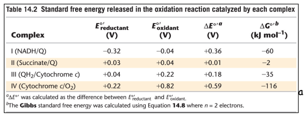


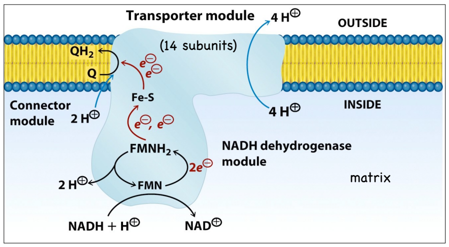
Table 14.2 Standard free energy released in the oxidation reaction catalyzed by each complex

Complex	$E^{\circ\prime}_{\text{reductant}}$ (V)	$E^{\circ\prime}_{\text{oxidant}}$ (V)	$\Delta E^{\circ\prime a}$ (V)	$\Delta G^{\circ\prime b}$ (kJ mol^{-1})
I (NADH/Q)	−0.32	−0.04	+0.36	−60
II (Succinate/Q)	+0.03	+0.04	+0.01	−2
III (QH_2/Cytochrome c)	+0.04	+0.22	+0.18	−35
IV (Cytochrome c/O_2)	+0.22	+0.82	+0.59	−116

[a] $\Delta E^{\circ\prime}$ was calculated as the difference between $E^{\circ\prime}_{\text{reductant}}$ and $E^{\circ\prime}_{\text{oxidant}}$.

[b] The **Gibbs** standard free energy was calculated using Equation **14.8** where $n = 2$ electrons.

Complex I (NADH-Q Oxidoreductase)



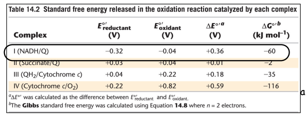


Table 14.2 Standard free energy released in the oxidation reaction catalyzed by each complex

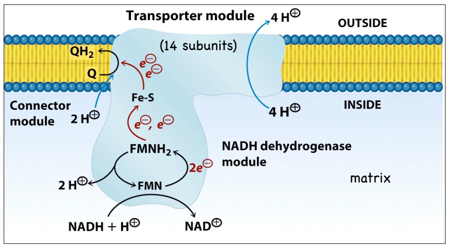
Complex	$E^{\circ\prime}_{reductant}$ (V)	$E^{\circ\prime}_{oxidant}$ (V)	$\Delta E^{\circ\prime a}$ (V)	$\Delta G^{\circ\prime b}$ (kJ mol^{-1})
I (NADH/Q)	−0.32	−0.04	+0.36	−60
II (Succinate/Q)	+0.03	+0.04	+0.01	−2
III (QH_2/Cytochrome *c*)	+0.04	+0.22	+0.18	−35
IV (Cytochrome *c*/O_2)	+0.22	+0.82	+0.59	−116

[a] $\Delta E^{\circ\prime}$ was calculated as the difference between $E^{\circ\prime}_{reductant}$ and $E^{\circ\prime}_{oxidant}$.

[b] The **Gibbs** standard free energy was calculated using Equation **14.8** where $n = 2$ electrons.

16-2

Complex I (NADH-Q Oxidoreductase)



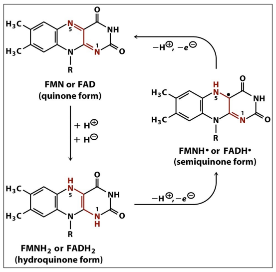
View Model

16-3

Complex I (NADH-Q Oxidoreductase)

FMN

- FMN is a 1-or 2-electron carrier (Chapter 7.5)



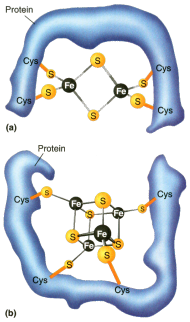
17

Complex I (NADH-Q Oxidoreductase)

Iron-Sulfur Centers

- Some of the complexes contain iron-sulfur centers
- Iron-sulfur centers are 1-electron carriers.

$$Fe^{3+} + 1e^- \Leftrightarrow Fe^{2+}$$

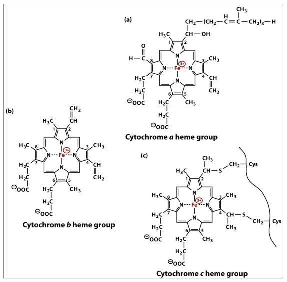


18

Complex III (Q-Cyt *c* oxidoreductase)

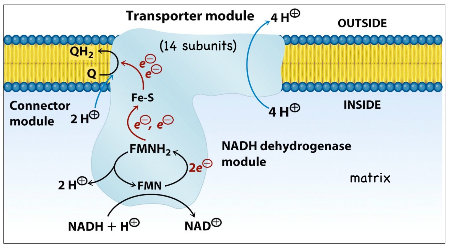
- Cytochromes are proteins that contain heme groups; they are 1-electron carriers. (Chapter 7.17)

$Fe^{3+} + 1e^{-} \Leftrightarrow Fe^{2+}$



19

Complex I (NADH-Q Oxidoreductase)

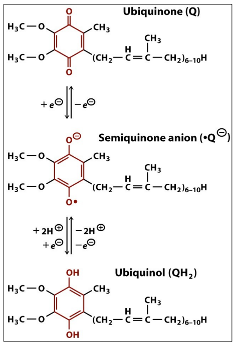


View Model

20

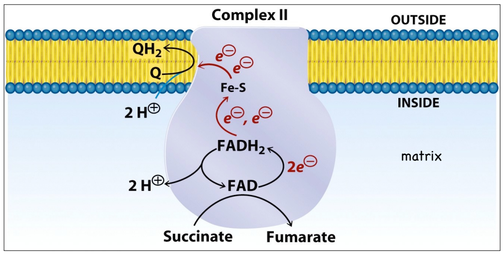
Carriers Between Complexes

- Coenzyme Q (Ubiquinone) carries the electrons from Complexes I & II to Complex III (Chapter 7.14)
  - Like FMN, ubiquinone is either a 1- or 2-electron carrier.



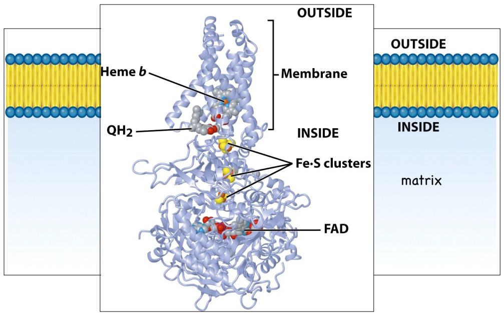
21

Complex II (Succinate Dehydrogenase)



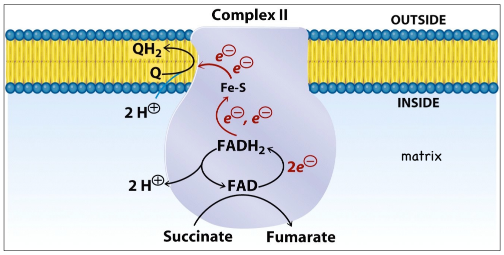
22-1

Complex II (Succinate Dehydrogenase)



22-2

Complex II (Succinate Dehydrogenase)

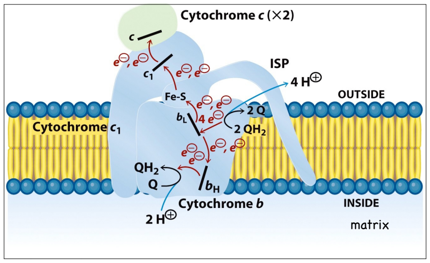


22-3

Complex III (Q-Cyt c oxidoreductase)

- Also called cytochrome bc
- Location of the "Q"-cycle

View Structure

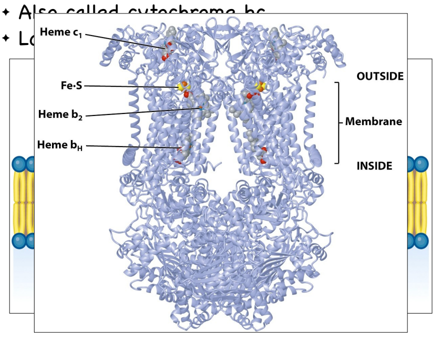


23-1

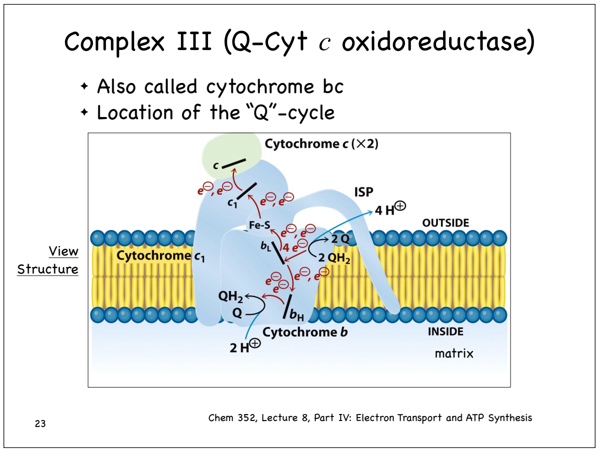
Complex III (Q-Cyt c oxidoreductase)

- Also called cytochrome bc
- Lo

View Structure



23-2

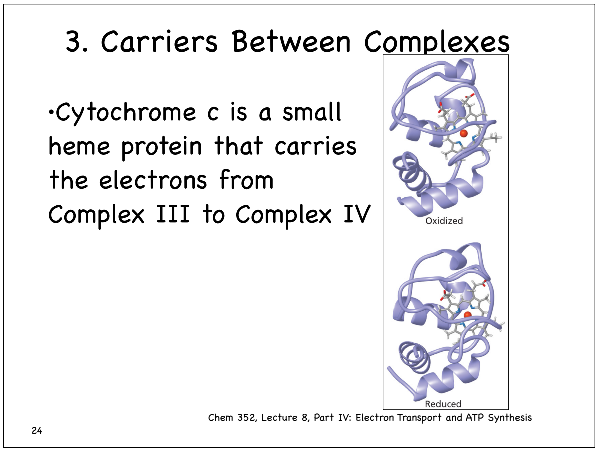


Complex III (Q-Cyt *c* oxidoreductase)

- Also called cytochrome bc
- Location of the "Q"-cycle

View Structure

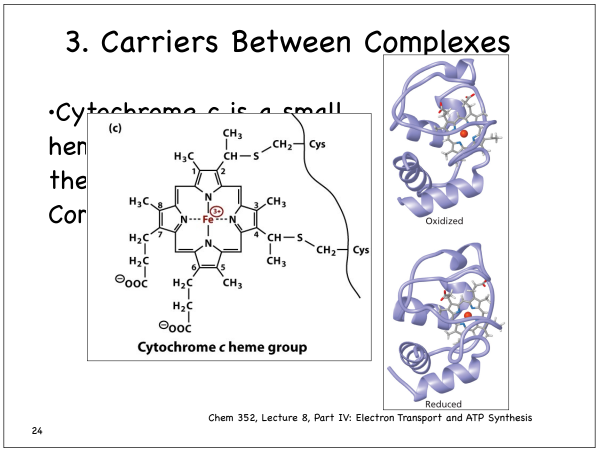
23-3



3. Carriers Between Complexes

•Cytochrome c is a small heme protein that carries the electrons from Complex III to Complex IV

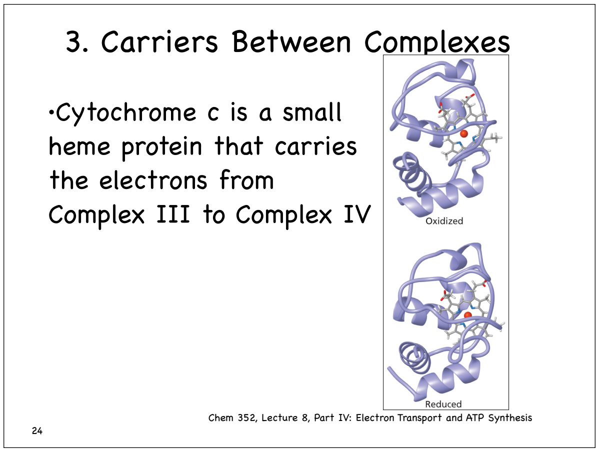
24-1



3. Carriers Between Complexes

•Cy
hen
the
Cor

24-2



3. Carriers Between Complexes

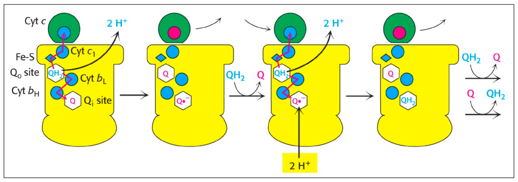
•Cytochrome c is a small heme protein that carries the electrons from Complex III to Complex IV

24-3

Complex III (Q-Cyt *c* oxidoreductase)

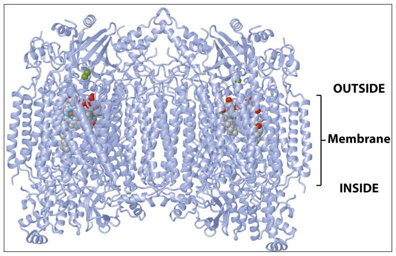
The "Q-cycle"

- Converting from a 2 electron carrier (QH_2) to a 1 electron carrier (Cyt c)



25

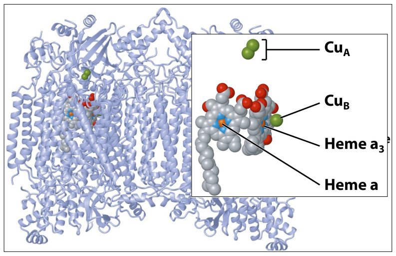
Complex IV (Cyt *c* oxidase)



View Structure

26-1

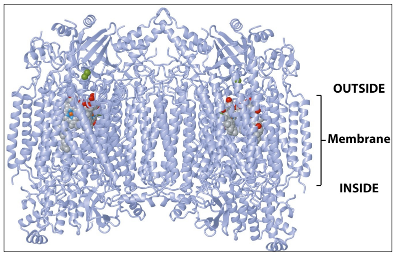
Complex IV (Cyt *c* oxidase)



View Structure

26-2

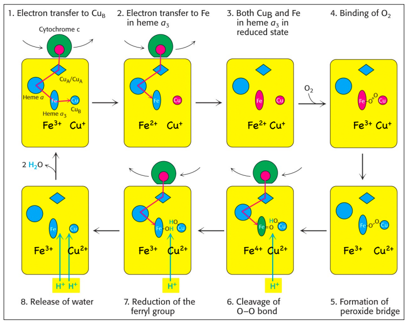
Complex IV (Cyt *c* oxidase)



View Structure

26-3

Complex IV (Cyt *c* oxidase)



27

Electron Transport

- At this point, glucose has been completely oxidized to CO_2 and H_2O

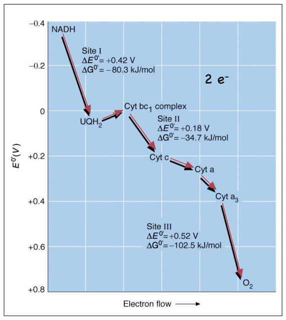
glucose ($C_6H_{12}O_6$) + $6O_2$ → $6CO_2$ + $6H_2O$

28

Electron Transport

Energy change

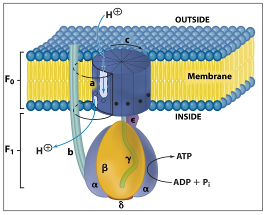
- $\Delta G^{\circ\prime}$ = -220 *kJ/mol* = -45.7 *kcal/mol*
- This is more than enough energy to make 2.5 ATP's (3 x 32 kJ/mol = 96 kJ/mol)



29

ATP Synthesis

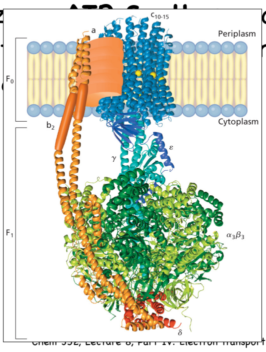
- The enzyme **ATP Synthase** couples ATP synthesis to the movement of protons across the membrane



30-1

ATP Synthesis

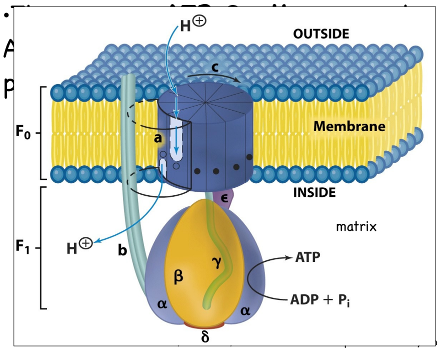
•The enz ouples
ATP syn nt of
protons



30-2

ATP Synthesis

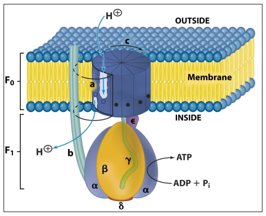
•
A
p



30-3

ATP Synthesis

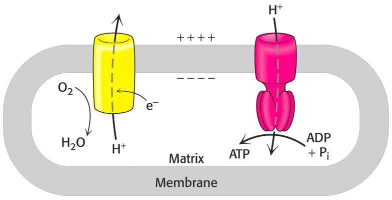
•The enzyme **ATP Synthase** couples ATP synthesis to the movement of protons across the membrane



30-4

ATP Synthesis

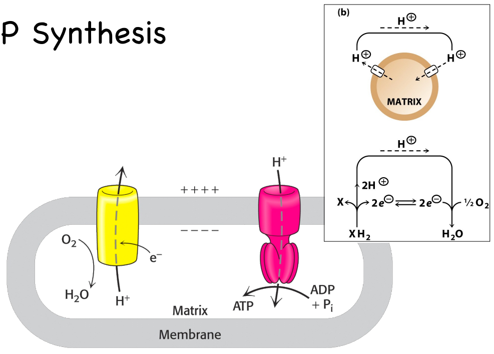
•The enzyme ATP Synthase couples ATP synthesis to the movement of protons across the membrane



A proton gradient powers the synthesis of ATP

31-1

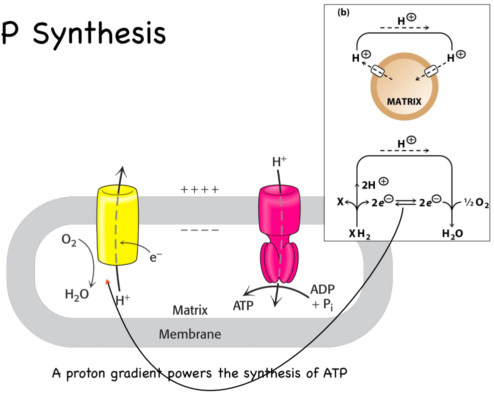
ATP Synthesis



A proton gradient powers the synthesis of ATP

31-2

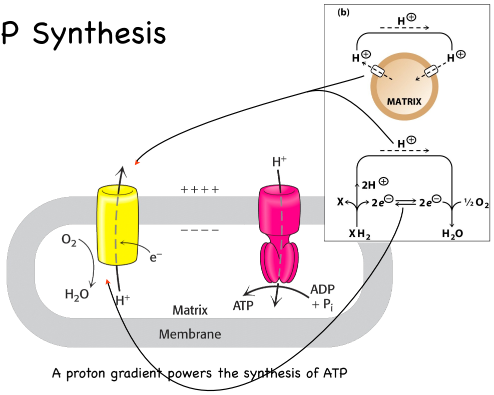
ATP Synthesis



A proton gradient powers the synthesis of ATP

31-3

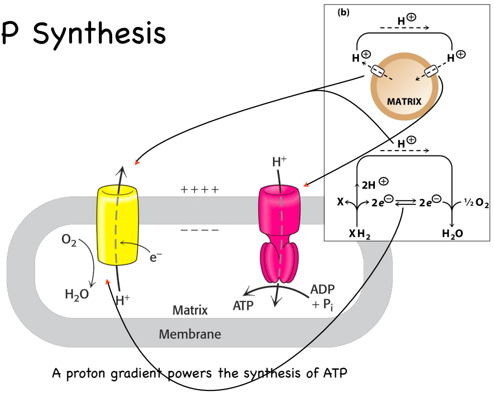
ATP Synthesis



A proton gradient powers the synthesis of ATP

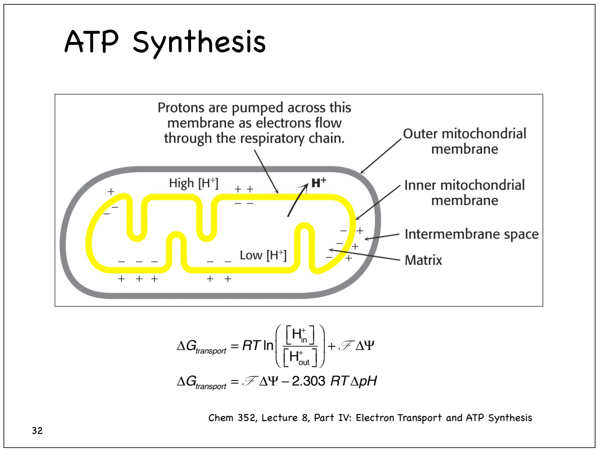
31-4

ATP Synthesis



A proton gradient powers the synthesis of ATP

31-5

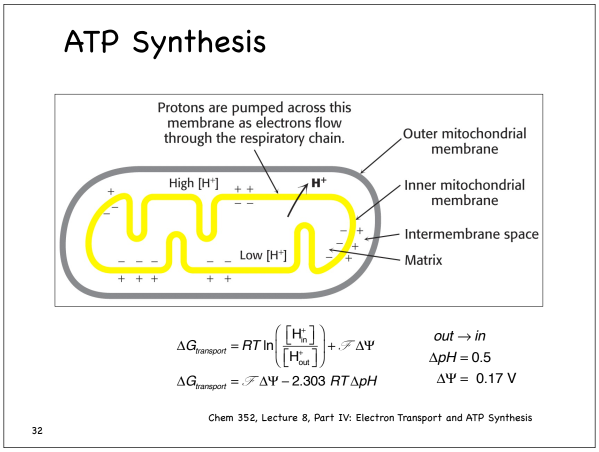


ATP Synthesis

$$\Delta G_{transport} = RT\ln\left(\frac{[H^+_{in}]}{[H^+_{out}]}\right) + \mathscr{F}\Delta\Psi$$

$$\Delta G_{transport} = \mathscr{F}\Delta\Psi - 2.303\ RT\Delta pH$$

32-1



ATP Synthesis

$$\Delta G_{transport} = RT\ln\left(\frac{[H^+_{in}]}{[H^+_{out}]}\right) + \mathscr{F}\Delta\Psi$$

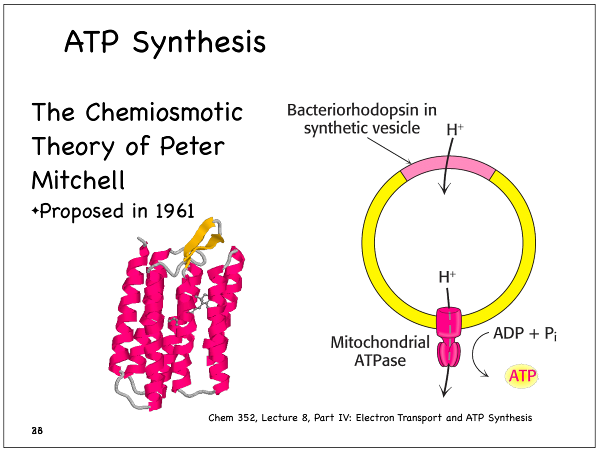
$$\Delta G_{transport} = \mathscr{F}\Delta\Psi - 2.303\ RT\Delta pH$$

$out \rightarrow in$

$\Delta pH = 0.5$

$\Delta\Psi = 0.17$ V

32-2

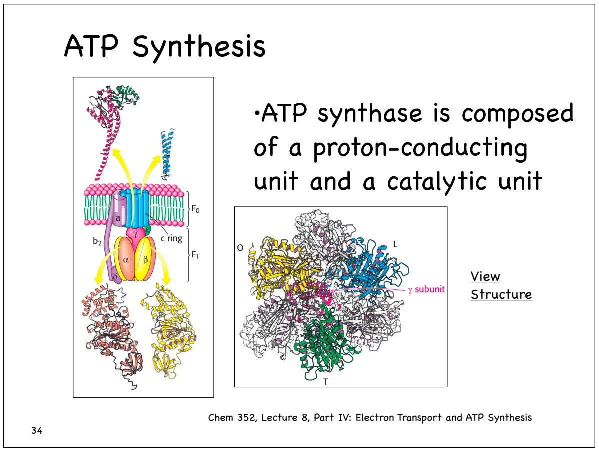


ATP Synthesis

The Chemiosmotic Theory of Peter Mitchell

- Proposed in 1961

33



ATP Synthesis

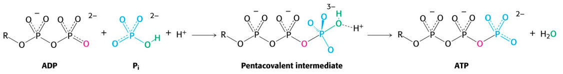
- ATP synthase is composed of a proton-conducting unit and a catalytic unit

View Structure

34

ATP Synthesis

- ATP is synthesized on β subunit

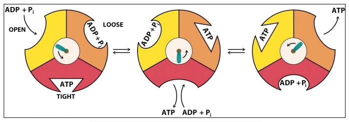


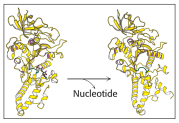
S_N2 reaction

35

ATP Synthesis

- The turning of the γ-subunit leads to the synthesis and release of ATP





36

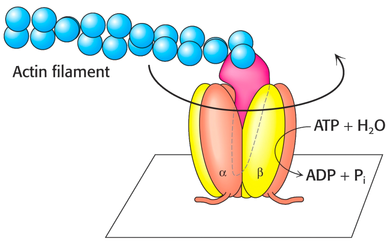
ATP Synthesis

- The turning of the γ-subunit leads to the synthesis and release of ATP
  - Rotation of the γ-subunit is coupled to proton movement down the proton gradient

37

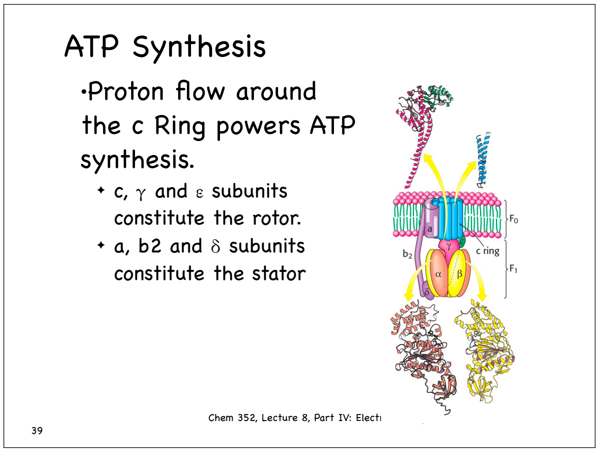
ATP Synthesis

- The world's smallest molecular motor
  - Rotational catalysis



38

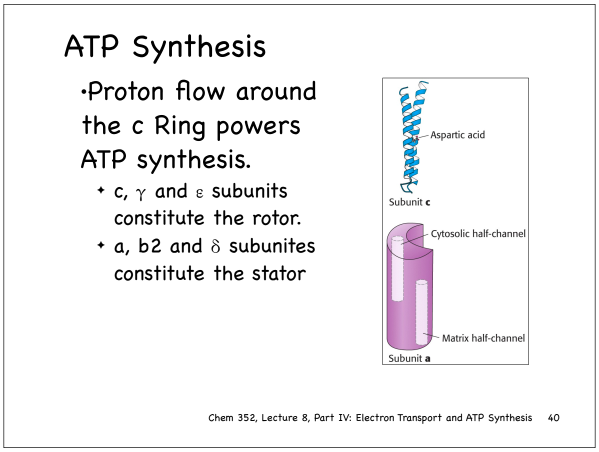
39



ATP Synthesis

- Proton flow around the c Ring powers ATP synthesis.
  - c, γ and ε subunits constitute the rotor.
  - a, b2 and δ subunits constitute the stator

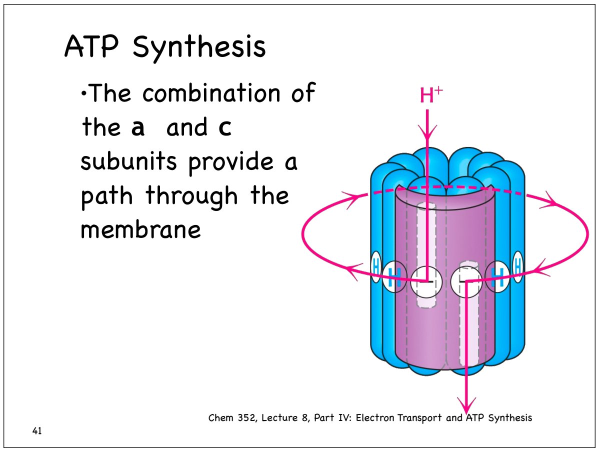
40



ATP Synthesis

- Proton flow around the c Ring powers ATP synthesis.
  - c, γ and ε subunits constitute the rotor.
  - a, b2 and δ subunites constitute the stator

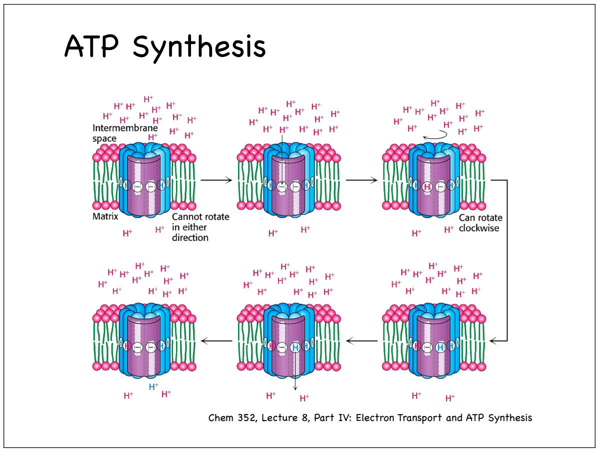
41



ATP Synthesis

- The combination of the **a** and **c** subunits provide a path through the membrane

42

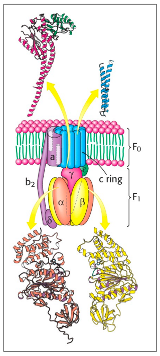


ATP Synthesis

43

ATP Synthesis

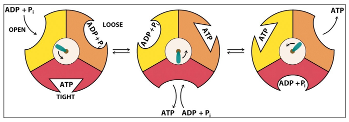
- Proton flow around the c Ring powers ATP synthesis.
  - c, γ and ε subunits constitute the rotor.
  - a, b2 and δ subunits constitute the stator

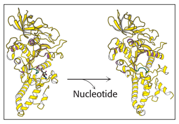


44

ATP Synthesis

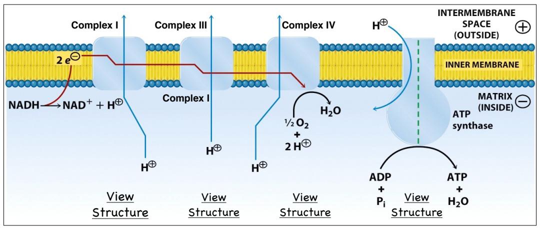
- Proton flow through ATP synthase leads to the release of tightly bound ATP





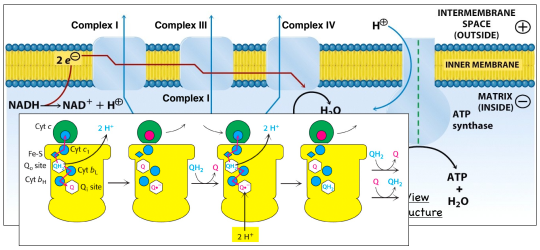
45-1

Electron Transport/ATP Synthase Structures



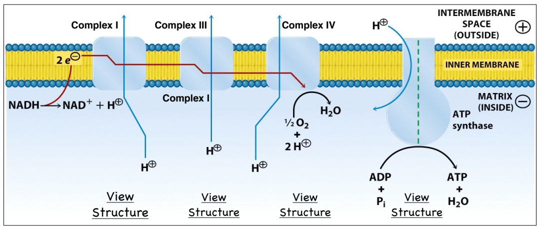
45-2

Electron Transport/ATP Synthase Structures



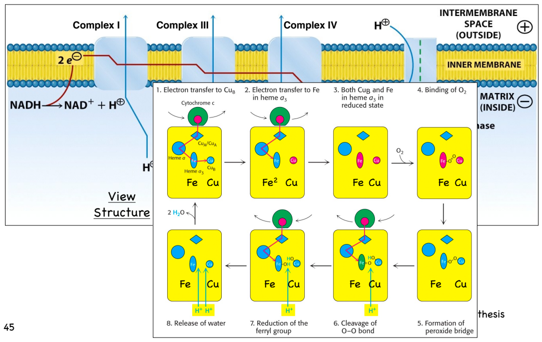
45-3

Electron Transport/ATP Synthase Structures



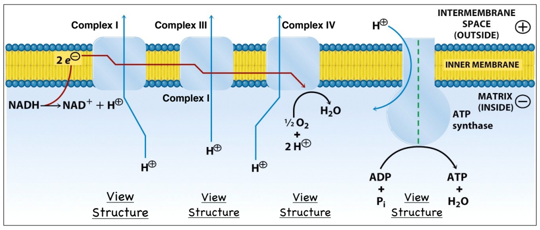
45-4

Electron Transport/ATP Synthase Structures



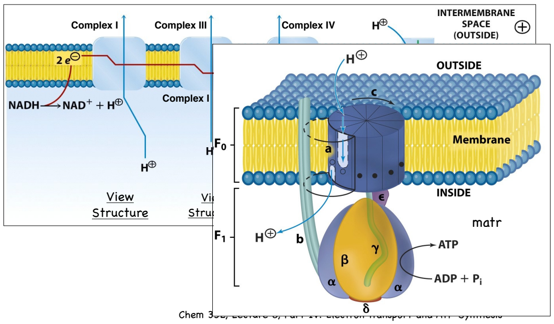
45-5

Electron Transport/ATP Synthase Structures

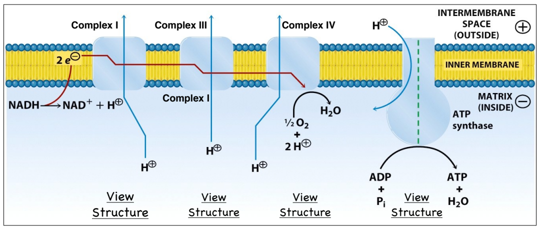


45-6

Electron Transport/ATP Synthase Structures



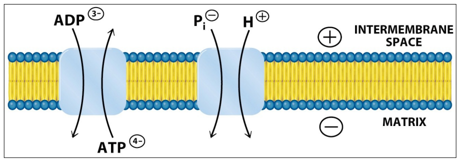
Electron Transport/ATP Synthase Structures



45-7

ATP Transport In/Out of Mitochondria

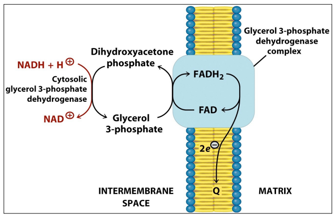
- Transport of ATP, ADP and P_i across the inner membrane is driven by both the proton and electropotential gradient.



46

Shuttles

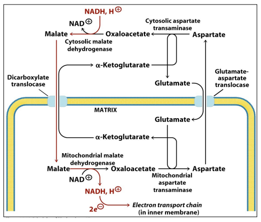
- The NADH + H^+ that is produced in glycolysis is on the cytosolic side of the mitochondrial inner membrane.



47

Shuttles

- The NADH + H^+ that is produced in glycolysis is on the cytosolic side of the mitochondrial inner membrane.



48

Next Up

- Lecture 9 - Photosynthesis
  Chapter 15 in Moran et al.