9。均相催化

Homogeneous catalysis

- ♣ Acid and base catalysis
- ♣ The mechanisms of some catalysed reactions
- ♣ Catalysis by non-covalent binding

（5 学时）

The rates of many organic reactions are enhanced by the presence of catalysis, species which do not themselves appear in the products but which in various way assist the progress of the reaction.

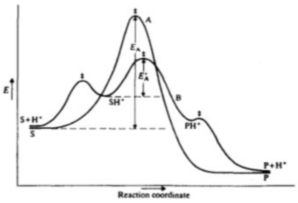
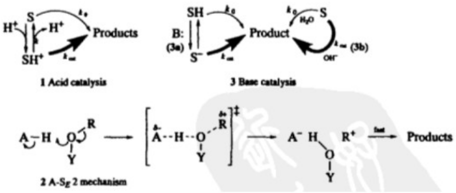


Fig. 9.1 Schematic energy profile for uncatalysed (A) and acid-catalysed (B) reactions in which a substrate, S, is converted to a product, P: S, substrate; P, product; E_A, principal energy barrier for an uncatalysed reaction; E'_A, principal energy barrier for a catalysed reaction.

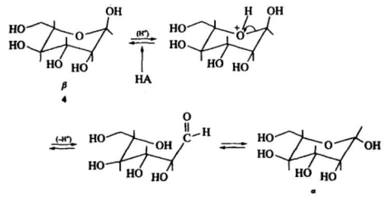
Homogeneous catalysis *(i·e· those that act in solution rather than, say, at solid surfaces) clearly must participate in the chemistry of the reaction and be regenerated at the formation of the product·*

9.1 Acid and base catalysis



9.1.1 Specific and general catalysis

The kinetics of an acid- or base-catalysis reaction are frequently complex, the empirical rate equation containing several terms.



$$\boxed{\text{Rate} = [\text{G}](k_{\text{H}_2\text{O}} + k_{\text{H}_3\text{O}^+}[\text{H}_3\text{O}^+] + k_{\text{AcOH}}[\text{AcOH}]). \qquad [9.1]}$$

This is termed *general acid catalysis* and can be inferred from a plot of rate constant against buffer concentration; as the latter changes, constancy of the hydronium ion concentration is ensured but [AcOH] varies.

$$\text{Rate} = \sum^{\text{acids}} k_{\text{HA}}[\text{S}][\text{HA}],$$

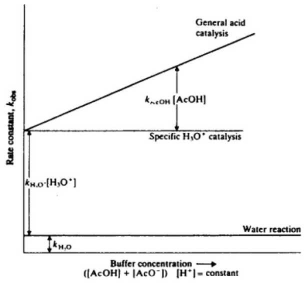
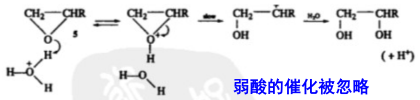


Fig. 9.2
Effect of buffer concentration of rates of specific H_3O^+-catalysed and general acid-catalysed reactions.

Similarly, a reaction may be catalysed by all bases present (e.g. H_2O, OH^-, A^-): *general base catalysis,* and it is also possible to have a reaction which is catalysed by both acids and bases.

$$\text{Rate} = \sum^{\text{acids}} k_{\text{HA}}[\text{S}][\text{HA}] + \sum^{\text{bases}} k_{\text{B}}[\text{S}][\text{B}]. \qquad [9.2]$$

On the other hand, some reactions respond to catalysis only by hydronium or hydroxide ions (in general, lyonium and lyate ions) and are then deemed to show *specific acid or base catalysis*.



弱酸的催化被忽略

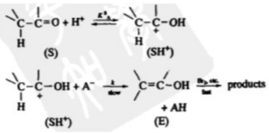
$$\text{S} + \text{H}^+ \rightleftarrows \text{SH}^+;$$

$$\text{SH}^+ \ (+\ \text{solvent}) \xrightarrow[\text{slow}]{k} \text{products},$$

$$\text{Rate} = k[\text{SH}^+]$$

or, since the acidity of the substrate, $K^{\text{S}}_{\text{A}} = [\text{SH}^+]/[\text{S}][\text{H}^+]$,

$$\text{Rate} = kK^{\text{S}}_{\text{A}}[\text{S}][\text{H}^+],$$



特殊酸催化k_{H2O}/k_{D2O} ~1/6
普遍酸催化决速步是质子转移， k_{H2O}/k_{D2O} ~ 1/6*7

$$\text{Rate} = k[\mathrm{SH^+}][\mathrm{A^-}],$$

but $K_A^S = [\mathrm{SH^+}]/[\mathrm{S}][\mathrm{H^+}]$ and $[\mathrm{A^-}] = K_A^C[\mathrm{HA}]/[\mathrm{H^+}]$. Hence

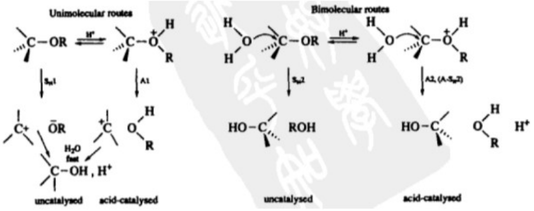
$$\text{Rate} = kK_A^S K_A^C[\mathrm{S}][\mathrm{HA}].$$

Table 9.1
Examples of acid- and base-catalysed reactions.

Reaction	Type*
Esterification and hydrolysis of carboxylic and phosphoric esters and amides	A, B
Hydrolysis of acetals, ketals and orthoesters	(sp) A
Hydrolysis and alcoholysis of anhydrides	A
Carbonyl condensation reactions with $X{-}NH_2$	A, B
Enolization and electrophilic substitution *α- to a carbonyl group*	A, B
Hydration of alkenes and dehydration of alcohols	A
Additions of CN^-, HSO_3^-, H_2O, etc., to $>C{=}O$	A, B
Cleavage of C–Hg, C–Sn bonds	A
Decomposition of NH_2NO_2 to N_2O and H_2O	B
Aldol and Michael reactions	B
Aromatic electrophilic proton exchange	A
Beckmann rearrangement	A
Hydrolysis of epoxides	(sp) A, B

* A, acid-catalysed; B, base-catalysed; sp, specific.

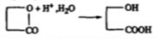
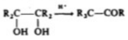
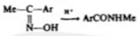
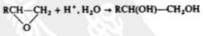
9.1.2 Mechanism of acid catalysis



单分子酸催化A1

双分子酸催化A2

Table 9.2
Examples of acid-catalysed reactions.

Reaction	Reference
A1 mechanism	
1 Esterification $ROH + R'COOH \xrightarrow{H_2SO_4} R'COOR$	12
2 Hydrolyses of tertiary alkyl esters ($A_{Al}1$) $RCOO\textit{t}\text{-}Bu + H^+, H_2O \rightarrow RCOOH + \textit{t}\text{-}BuOH$	13, 14
3 Hydrolyses of *β*-lactones 	15
4 Hydrolyses of anhydrides $RCOOCOR + H_2O, H^+ \rightarrow 2RCOOH$	16
5 Cleavage of tertiary ethers $R_3C{-}OR' \xrightarrow{H^+} R_3C{-}OH + R'OH$	17
6 Hydrolyses of acetals and ketals $R_2C(OR')_2 \xrightarrow{H^+} R_2C{=}O + 2R'OH$	18
7 Pinacol rearrangement  $R_2C(OH){-}C(OH)R_2 \xrightarrow{H^+} R_3C{-}COR$	19
8 Beckmann rearrangement  $Me{-}C({=}N{-}OH){-}Ar \xrightarrow{H^+} ArCONHMe$	20
9 Epoxide ring-opening  $RCH(O)CH_2 + H^+, H_2O \rightarrow RCH(OH){-}CH_2OH$	21
A2 Mechanism	
10 Cleavage of primary ethers $Et{-}O{-}Et + H^+, H_2O \rightarrow 2EtOH$	22
11 Ester hydrolysis ($A_{Ac}2$)	23

9.1.3 Method of distinguishing between A1 and A2 reactions

The Hammett-Zucker postulate

For A1 reactions, catalytic rates should follow H_0 rather than $[H_3O^+]$ and a plot of k against H_0 should have unit slope. On the other hand, for A2 process,

$$\text{Rate} \approx k_2[\mathrm{SH^+}][\mathrm{H_2O}] = k_2\,K[\mathrm{S}][\mathrm{H_3O^+}] \qquad [9.3]$$

Bunnett's w-values

Plot of ($\ln k$ - H_0) against the activity of water, a_{H2O}, to give a slope, w, varying over the range -8 to +7, is measure of this deviation, which has mechanistic significance.

w	Function of water in rate-determining step
−2·5 to 0	Not involved; A1 mechanism,
+1·2 to +3·3	Acts as nucleophile; A–S_N2 reaction.
> +3·3	Proton transfer agent; A2 reaction.

The Bunnett and Olsen parameter, ϕ

$$\log I + H_0 = \phi(H_0 + \log[\mathrm{H^+}]) + \mathrm{p}K_A. \qquad [9.5]$$

$$\log k + H_0 = \phi(H_0 + \log[\mathrm{H^+}]) + \text{constant}. \qquad [9.6]$$

Table 9.4
Examples of Bunnett's *w*- and *ϕ*-parameters.[2,8,28]

ϕ	Function of water in rate-determining step
<0	Not involved
+0·22 to +0·56	Acts as nucleophile
> +0·58	Acts as proton-transfer agent

Reaction	*w*	*ϕ*
A1 reactions: $w < 0$, $\phi < 0$		
Hydrolysis of $MeCH(OEt)_2$, HCl, 0 °C	−7·86	−1·02
Paraldehyde → MeCHO, 25 °C	−4·32	−0·58
Hydrolysis of $MeCOOCH_2OEt$, 25 °C	−3·57	−0·44
Inversion of sucrose (→ glucose + fructose)	−0·43	−0·04
H–D exchange in anisole, *para*-position, H_2SO_4		−0·24
A—S_N2 reactions: $w = 1{\cdot}2$–$3{\cdot}3$		
$\textit{t}\text{-}Bu^{18}OH \xrightarrow{H_2S^{16}O_4} \textit{t}\text{-}Bu^{16}OH$	+0·82	−0·29
Racemization *of* (+)-MeCHOHEt, $HClO_4$, 100 °C	+1·28	+0·17
Hydrolysis of $MeCONH_2$, HCl, 50 °C	+2·65	
Hydrolysis of $MeCONHNH_2$, 60 °C		+1·07
Hydrolysis of $(MeO)_2S{=}O$, $HClO_4$, 0 °C	+2·36	
Proton transfer, $w > 3{\cdot}3$		
Hydrolysis of HCOOMe, HCl, 25 °C	+4·21	+0·74
Hydrolysis of MeCOOEt, H_2SO_4, 25 °C	+4·5	+0·84
Hydrolysis of *γ*-butyrolacetone, $HClO_4$	+8·5	+1·04
Pinacol rearrangement	+4·99	
Enolization (iodination) of acetone		+0·83
Carbon-centred reactions		
$C_6D_6 \xrightarrow{H_2SO_4} C_6H_6$	−0·58	
$PhC^{18}OOH \xrightarrow{H_2S^{16}O_4} PhC^{16}OOH$		+0·94
Cis-trans isomerization of PhCOCH=CHPh		+0·44

9.1.4 Linear free-energy relationships: the Bronsted Catalysis Law

Catalytic rate constants can be expected to increase with increasing strength of acid or bases, and a very good linear relationship between k_{cat} and K_A is known as the **Bronsted Catalysis Law**.

$$k_A = G_A K_A^{\alpha} \quad \text{or} \quad \log k_A = \alpha \mathrm{p}K_A + \text{constant}; \qquad [9.7]$$

$$k_B = G_B K_A^{-\beta} \quad \text{or} \quad \log k_B = -\beta \mathrm{p}K_A + \text{constant}; \qquad [9.8]$$

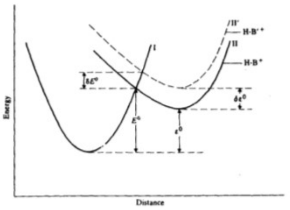


Fig. 9.4 Potential curves (energy versus distance) for the systems A–H---B (curve I) and A⁻ ··· H–B⁺ (curve II). BH⁺ is a weaker acid than AH by an amount proportional to ε^0. The proton transfer proceeds by stretching of the A–H bond until the energy is such that the two curves intersect. Continuation of the motion results in product formation with an energy barrier E^0. B'H⁺ is a still weaker acid and the additional activation energy required for proton transfer from HA is δE^0, proportional to its difference in $\mathrm{p}K_A$, $\delta\varepsilon$. The Brønsted relationship shows linearity as long as curves II, II' are parallel.

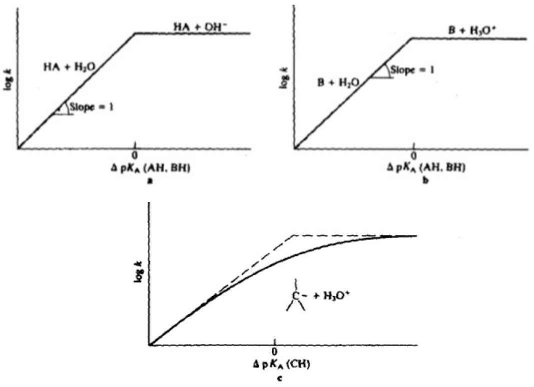


Fig. 9.5 Schematic relationships between rates of proton transfer between two bases, and their difference in pK_A.[16] As long as pK_A of the proton acceptor is greater than that of the donor, the reaction is diffusion-controlled and the rate is large and constant, independent of the donor strength. At ΔpK ~ 0 there is a change in slope giving a normal Brønsted plot, α, β ~ 1, as the reverse reaction becomes diffusion-controlled. Carbon acids, c, tend to transfer protons at less than diffusion-controlled rates and may give curved Brønsted plots.

9.1.5 Interprelation of the Bronsted coefficients

The coefficients α and β have the significance of LFER susceptibility parameters and are a measure of the sensitivity of the catalysed reaction to the strength in water of its catalysis as acids and as base respectively.

Assuming the thermodynamic properties of the transition state for a proton transfer to be intermediate between those of reagents and products, a structural change will affect the free energy of the transition state by the amount δG‡ such that

$$\delta G^{\ddagger} = \alpha\delta G_p + (1-\alpha)\delta G_r, \qquad [9.9]$$

where G_p, G_r are free energies of products and regents. Therefore, α is a parameter measuring the position of the transition state on the reaction coordinate.

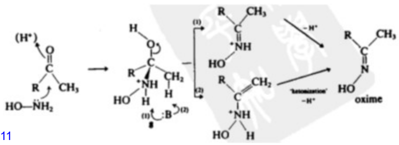


Table 9.6
Examples of Brønsted coefficients for some acid- and base-catalysed reactions.

Reaction	α*	β	Reference
$MeCH(OH)_2 \xrightarrow{H^+} MeCHO + H_2O$	0·54		38
α-D-glucose mutarotation $\xrightarrow{H^+}$ / $\xrightarrow{B}$ (α ⇄ β)-D-glucose	0·30		39
		0·40	
$CH_2(OH)_2 \xrightarrow{H^+}$ / $\xrightarrow{B}$ $HCHO + H_2O$	0·10		40
		0·40	
$(EtO)_4C \xrightarrow{H^+} 4EtOH + CO_2$	0·69		18, 41
$(EtO)_3CH \xrightarrow[aq.]{H^+}$ $3EtOH + HCOOH$	0·77		
$(EtO)_3CH \xrightarrow[dioxane]{aq.}$ $3EtOH + HCOOH$	1·00		
$(EtO)_2CPh_2 \xrightarrow{H^+} 2EtOH + Ph_2CO$	0·78		

* α ~ 1 indicates specific H_3O^+ catalysis with pre-equilibrium protonation of the substrate; α < 1 indicates general acid-catalysis and is a measure of the extent of protonation in the transition state.

Table 9.7
Percentage of product formed by acidic species present in 0·1 M acetate buffer as a function of Brønsted α.

α	H_3O^+	AcOH	H_2O
1	99·8	0·2	5×10^{-12}
0·5	3·6	96·4	0·01
0·1	0·002	2	98

9.1.6 Nucleophilic catalysis

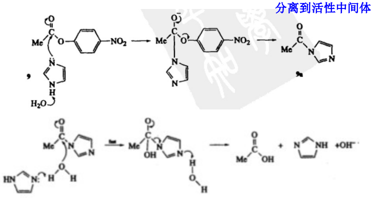
The following characteristics enable general base and nucleophilic catalysis to be distinguished.

(a) Catalysis by the leaving group: a general base action; negative catalysis: nucleophilic catalysis 被离去基团催化：普遍碱催化；负催化：亲核催化

(b) Reaction with respect to the catalyst in a second order kinetics: a general base action, 6 涉及催化剂的反应呈二级动力学：普遍碱催化

(c) non-parallel for base strength and nucleophilic activity at carbon: nucleophilic catalysis 碱强度与在碳上亲核活性的非同向关系：亲核催化

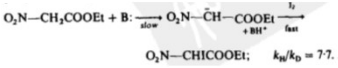
(d) isolated reactive intermediate: nucleophilic catalysis, 9a 分离到活性中间体：亲核催化



9.1.7 Solvent isotope effects

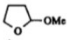
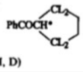
Acid-catalysed reactions are faster in D$_2$O, and values of k_{H2O}/k_{D2O} =0.3~0.43 for pre-equilibrium protonation; 0.45~1 for concerted reactions.

When proton transfer becomes RDS, a full PKIE



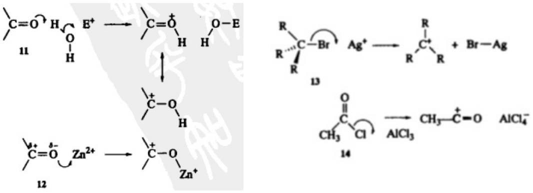
$$O_2N\text{—}CH_2COOEt + B{:} \xrightarrow[slow]{} O_2N\text{—}\bar{C}H\text{—}COOEt \underset{+BH^+}{} \xrightarrow[fast]{I_2} O_2N\text{—}CHICOOEt; \quad k_H/k_D = 7{\cdot}7.$$

Table 9.8
Some solvent isotope effects in acid-catalysed hydrolyses.

Substrate	k_{H_2O}/k_{D_2O}
Ethyl orthocarbonate, $(EtO)_4C$	0·714
Ethyl orthoacetate, $MeC(OEt)_3$	0·534
Ethyl orthoformate, $HC(OEt)_3$	0·335
Acetaldehyde diethylacetal, $MeCH(OEt)_2$	0·379
1,3-Dioxane,	0·36
2-Methoxytetrahydrofuran, 	0·34
Sucrose (→ glucose + fructose)	0·568
Ionization of  at H* (L = H, D)	(SKIE)1.24

9.1.8 Electrophilic catalysis

The elecrophilic catalyst may release a proton from water (11); it may coordinate with an elecrophilic reagent and increase its electrophilicity (12) or to a nuleophilic leaving group and increase its nucleofugacity (13, 14).



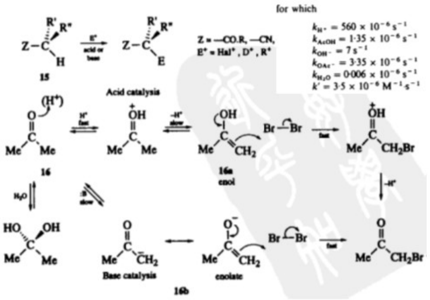
9.2 The mechanisms of some catalysed reactions

9.2.1 Substitution α to a carbonyl group

$$\text{rate} = k_{H^+}[H^+] + k_{AcOH}[AcOH] + k_{OH^-}[OH^-] + k_{OAc^-}[AcO^-] + k_{H_2O} + k'[AcOH][Ac\bar{O}]$$

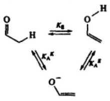
for which

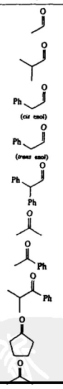
$k_{H^+} = 560 \times 10^{-6}\ s^{-1}$
$k_{AcOH} = 1{\cdot}35 \times 10^{-6}\ s^{-1}$
$k_{OH^-} = 7\ s^{-1}$
$k_{OAc^-} = 3{\cdot}35 \times 10^{-6}\ s^{-1}$
$k_{H_2O} = 0{\cdot}006 \times 10^{-6}\ s^{-1}$
$k' = 3{\cdot}5 \times 10^{-6}\ M^{-1}s^{-1}$


Z = —CO.R, —CN,
E⁺ = Hal⁺, D⁺, R⁺
E⁺
acid or base
15
Acid catalysis
16
16a
enol
fast
slow
Base catalysis
16b
enolate

9.2.2 Keto-enol equilibra

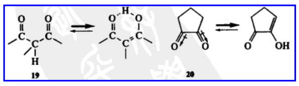
Table 9.10
Acid–base properties of carbonyl compounds.

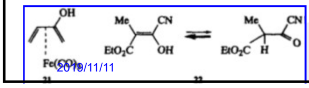




Carbonyl compound	pK_E	pK_A^E	pK_A^K	$10^5\,k$ (enolization)/s^{-1}
	6·23	10·50	16·73	1·6
	3·86	11·63	15·49	
(cis enol)	3·35	9·76	13·11	
(trans enol)	3·07	9·46	12·53	
	0·98	9·40	10·42	
	8·33	10·94	19·27	2·76
	7·96	10·34	18·31	1·26
	6·48	11·78	18·26	
	7·94			4·4

Compd.	*keto:enol*
acetone	1:4×10^{-9}
acetaldehyde	1:5.9×10^{-7}


19
20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9.2.3 Hydrolyses of acetals, ketals, orthosters and related compounds

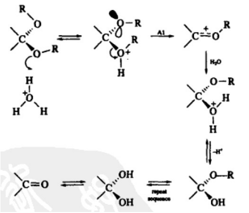
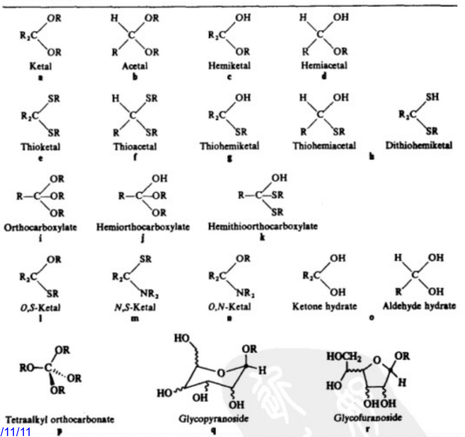

A1
H₂O
-H⁺
repeat sequence

Table 9.11
LFER constants for acetal and ketal hydrolysis.

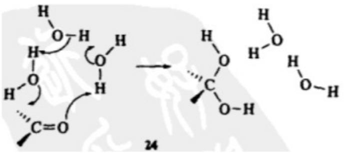
Compound hydrolysed	ρ^*	w	ϕ	k_{D_2O}/k_{H_2O}
$ArCH(OEt)_2$	−3·35 to −4·1		−1·02	
$RR'C(OR'')_2$	−3·9	0·6		2·6
$CH_2(OR)_2$	−4·3			
$ArC(OMe)_3$	−2·0	0·7		2·2
(Glucose)—OAr (acid-catalysed)	−0·06			
(base-catalysed)	+2·48			

Table 9.9 The ketal family.

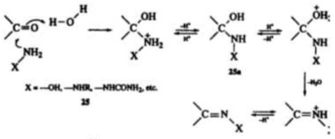

Ketal
a
Acetal
b
Hemiketal
c
Hemiacetal
d
Thioketal
e
Thioacetal
f
Thiohemiketal
g
Thiohemiacetal
h
Dithiohemiketal
Orthocarboxylate
i
Hemiorthocarboxylate
j
Hemithioorthocarboxylate
k
O,S-Ketal
l
N,S-Ketal
m
O,N-Ketal
n
Ketone hydrate
o
Aldehyde hydrate
Tetraalkyl orthocarbonate
p
Glycopyranoside
q
Glycofuranoside
r

9.2.4 Dehydration of aldehyde hydrates and related compounds

The structural unit >C(OH)$_2$ is found in the hydrates of aldehydes and ketones, and in hemiorthoesters, which are intermediates in hydrolyses of carboxylic esters and which rapidly revert to the carbonyl form. Aliphatic aldehydes are largely hydrated in aqueous solution (HCHO ~99.95%).

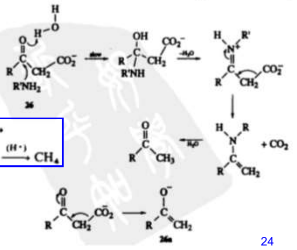

24

9.2.5 The formation of oximes(肟), semicarbazones(缩氨基脲) and hydrazones(腙)

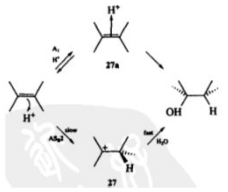

X = —OH, —NHR, —NHCONH₂, etc.
25
25a
-H⁺
H⁺
-H₂O

9.2.6 Decarboxylation

$$Na^+OH^- + CH_3COO^- \rightarrow [Na^+CH_2^-COO^-] \rightarrow [Na^+CH_3^{2-}] + CO_2 \xrightarrow{(H^+)} CH_4$$


26
26a
slow
-H₂O
+ CO₂

9.2.7 Acid-catalysed alkene-alcohol interchange


H⁺
27a
A₁
H⁺
H⁺
OH
H
ASE2
slow
fast
H₂O
H
27

9.2.8 Some acid-catalysed rearrangements

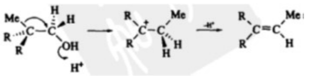

Me
R
R
H
H
OH
H⁺
R
R
Me
H
H
-H⁺
R
R
Me
H

Table 9.12 Some catalysed rearrangements.

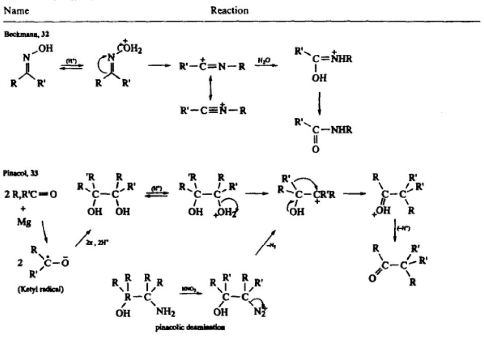
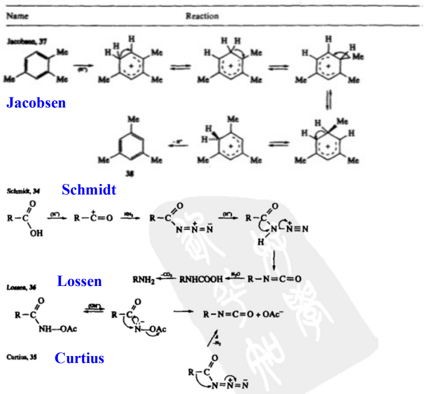

Name
Reaction
Beckmann, 32
Pinacol, 33
2 R,R'C=O
Mg
(Ketyl radical)
pinacolic deamination
HNO₂

Table 9.12 (cont.)

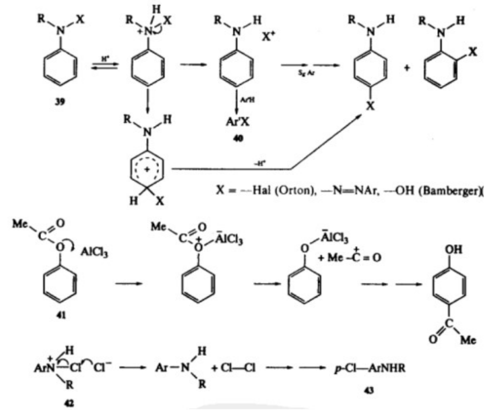

Name
Reaction
Jacobsen, 37
38
Schmidt, 34
Lossen, 36
Curtius, 35

Jacobsen

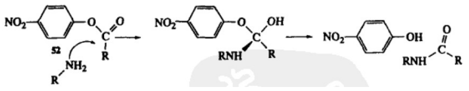
Schmidt

Lossen

Curtius

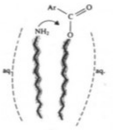

39
40
41
42
43
ArH
Ar'X
SE Ar
-H⁺
X = —Hal (Orton), —N=NAr, —OH (Bamberger)
AlCl₃
p-Cl—ArNHR

9.3 Catalysis by non-covalent binding



$R{-}OSO_2O^- + H_2O^+ \rightarrow ROH + H_2SO_4;$

R	k_{rel}
C_1–C_5	1
C_{10}	8
C_{14}	56
C_{18}	100


53

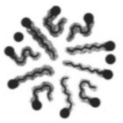
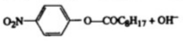
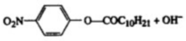
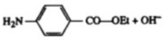
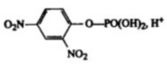
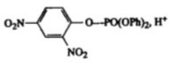
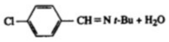
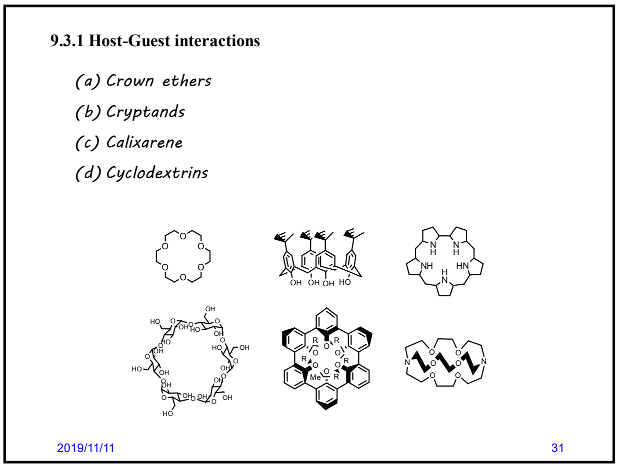

54

Table 9.14
Some reactions catalysed by micelles.

Reaction	Ionic type of surfactant	k_{cat}/k_0
 $O_2N{-}C_6H_4{-}O{-}COC_8H_{17} + OH^-$	–	30
 $O_2N{-}C_6H_4{-}O{-}COC_{10}H_{21} + OH^-$	–	21
 $H_2N{-}C_6H_4{-}CO{-}OEt + OH^-$	+ –	1 18
$Na^+\bar{O}SO_2O{-}C_{10}H_{21} + H_3O^+$	–	36
 $O_2N{-}C_6H_3(NO_2){-}O{-}PO(OH)_2, H^+$	+	22, 50
 $O_2N{-}C_6H_3(NO_2){-}O{-}PO(OPh)_2, H^+$	+ –	50 70
 $Cl{-}C_6H_4{-}CH{=}N\ t\text{-}Bu + H_2O$	+ –	1 290



9.3.1 Host-Guest interactions

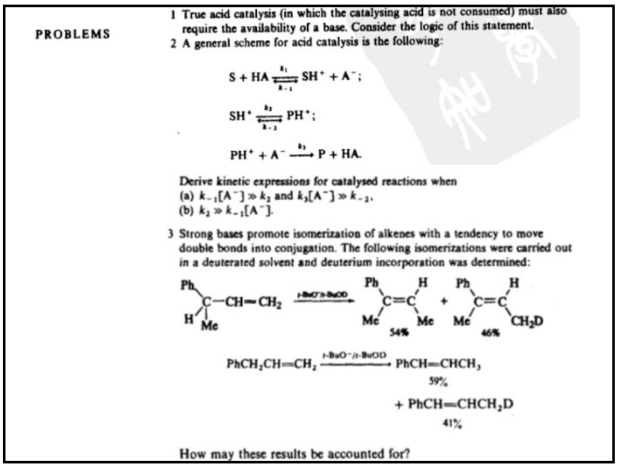
(a) Crown ethers

(b) Cryptands

(c) Calixarene

(d) Cyclodextrins

NH
HN
OH OH OH HO
HO
OH
R
Me
O
N



PROBLEMS

1 True acid catalysis (in which the catalysing acid is not consumed) must also require the availability of a base. Consider the logic of this statement.

2 A general scheme for acid catalysis is the following:

$$S + HA \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} SH^+ + A^-;$$

$$SH^+ \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} PH^+;$$

$$PH^+ + A^- \xrightarrow{k_3} P + HA.$$

Derive kinetic expressions for catalysed reactions when

(a) $k_{-1}[A^-] \gg k_2$ and $k_3[A^-] \gg k_{-2}$,

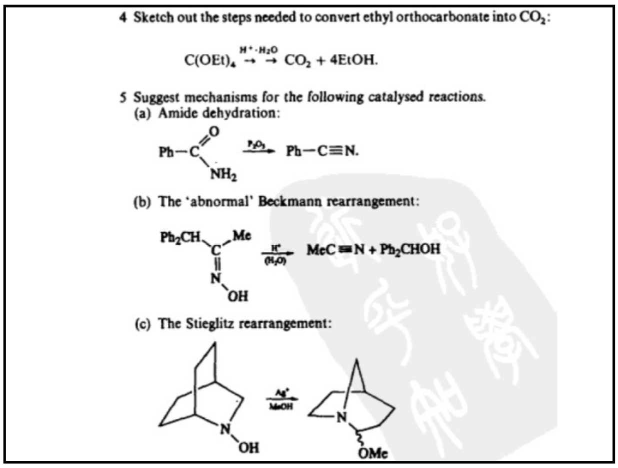
(b) $k_2 \gg k_{-1}[A^-]$.

3 Strong bases promote isomerization of alkenes with a tendency to move double bonds into conjugation. The following isomerizations were carried out in a deuterated solvent and deuterium incorporation was determined:

Ph
C—CH=CH₂
H
Me
t-BuO⁻/t-BuOD
Ph
H
C=C
Me
Me
54%
Ph
H
C=C
Me
CH₂D
46%

$$PhCH_2CH{=}CH_2 \xrightarrow{t\text{-BuO}^-/t\text{-BuOD}} \underset{59\%}{PhCH{=}CHCH_3} + \underset{41\%}{PhCH{=}CHCH_2D}$$

How may these results be accounted for?



4 Sketch out the steps needed to convert ethyl orthocarbonate into CO_2:

$$C(OEt)_4 \overset{H^+\cdot H_2O}{\rightarrow\rightarrow} CO_2 + 4EtOH.$$

5 Suggest mechanisms for the following catalysed reactions.

(a) Amide dehydration:

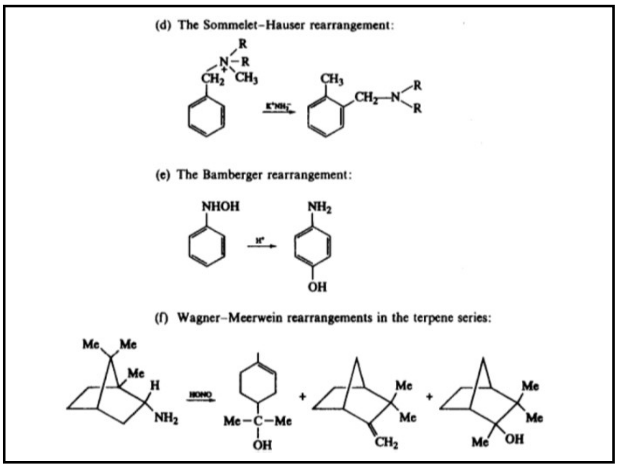
Ph—C
O
NH₂
P₂O₅
Ph—C≡N.

(b) The 'abnormal' Beckmann rearrangement:

Ph₂CH
Me
C
N
OH
H⁺
(H₂O)
MeC≡N + Ph₂CHOH

(c) The Stieglitz rearrangement:

N
OH
Ag⁺
MeOH
N
OMe



(d) The Sommelet–Hauser rearrangement:

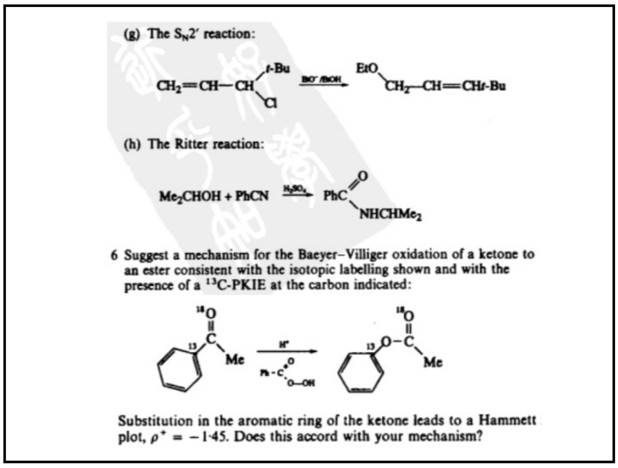
R
N
R
CH₂
CH₃
K⁺NH₂⁻
CH₃
CH₂—N
R
R

(e) The Bamberger rearrangement:

NHOH
H⁺
NH₂
OH

(f) Wagner–Meerwein rearrangements in the terpene series:

Me
Me
Me
H
NH₂
HONO
Me—C—Me
OH
+
Me
Me
CH₂
+
Me
Me
Me
OH



(g) The S_N2' reaction:

t-Bu
CH₂=CH—CH
Cl
EtO⁻/EtOH
EtO
CH₂—CH=CHt-Bu

(h) The Ritter reaction:

Me₂CHOH + PhCN
H₂SO₄
PhC
O
NHCHMe₂

6 Suggest a mechanism for the Baeyer–Villiger oxidation of a ketone to an ester consistent with the isotopic labelling shown and with the presence of a ^{13}C-PKIE at the carbon indicated:

¹⁸O
13
C
Me
H⁺
Ph-C
O
O—OH
¹⁸O
13
O—C
Me

Substitution in the aromatic ring of the ketone leads to a Hammett plot, $\rho^+ = -1{\cdot}45$. Does this accord with your mechanism?

@阅读：

书1：第9章; 书2：第9章

@课后练习：

书1: Page 412-415，1-6