

7. 同位素效应

Kinetic Isotope effects



(4 学时)

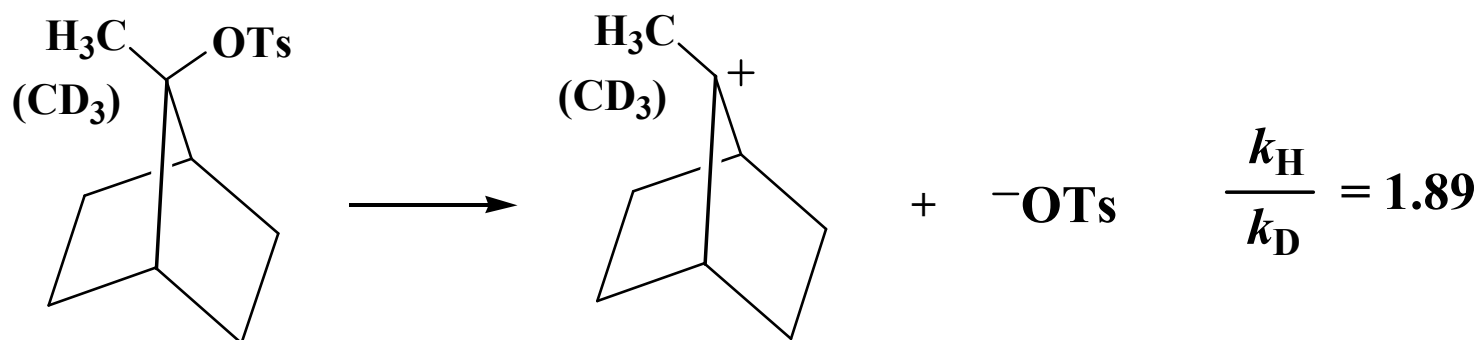
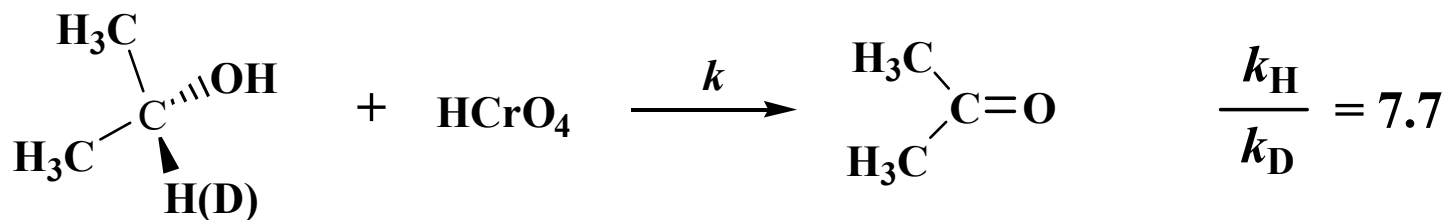
7.1 Introduction

若反应物中原子被其同位素取代，将表现出不同的化学
反应性，称为同位素效应，表现在两个方面：

1. 平衡同位素效应



2. 动力学同位素效应(Kinetic isotope effects, KIE)



如果 $k_{\text{H}} \neq k_{\text{D}}$ 表示存在KIE, 用 $k_{\text{H}}/k_{\text{D}}$ 表示:

$k_{\text{H}}/k_{\text{D}} > 1$ (normal); $k_{\text{H}}/k_{\text{D}} < 1$ (inverse)

Types of KIE:

a. 一级动力学同位素效应 (*primary*, PKIE)

连接同位素原子的键在决速步中断裂

b. 二级动力学同位素效应 (*secondary*, SKIE)

连接同位素原子的键在决速步中不断裂

c. 溶剂同位素效应(*solvent isotope effects*)

由反应介质中的不同的同位素引起 速率变化

7.2 Theory of isotope effects: the primary effect

同位素取代不影响分子的势能面，也不影响电子态的能级。它仅影响那些与原子质量有关的量，如：振转动频率。那么，同位素异构分子在性质上的差别必然是由于势能面上振动和转动能级的差异引起。

1. 同位素的改变引起振动能的改变

C-H(D)伸缩振动能可由双原子谐振子的Schrödinger方程得到：

$$E_v = hc\tilde{\nu} = \left(v + \frac{1}{2}\right)h\nu \quad v = 0, 1, 2, \dots$$

v – 振动量子数

ν – 从一级振动能级另一能级跃迁的频率

$\tilde{\nu}$ – 波数 ($1/\lambda$) cm^{-1}

零点能

$$E_v = \frac{1}{2}h\nu \quad v = 0$$

由Hooke定律可知，化学键的伸缩振动频率与原子质量有关：

$$\nu = \frac{1}{2\pi} \left(\frac{f_{\text{H}}}{\mu_{\text{H}}} \right)^{1/2}$$

C-H与C-D的相对伸缩振动频率：

$$\frac{\nu_{\text{H}}}{\nu_{\text{D}}} = \left(\frac{f_{\text{H}} / \mu_{\text{H}}}{f_{\text{D}} / \mu_{\text{D}}} \right)^{1/2}$$

折合质量， $\mu = \frac{m_1 m_2}{m_1 + m_2}$ 力常数， $f_{\text{H}} \approx f_{\text{D}}$

$$\nu_{\text{H}} / \nu_{\text{D}} \approx (m_{\text{D}} / m_{\text{H}})^{1/2} = 2^{1/2} = 1.41$$

$$\nu_{\text{H}} / \nu_{\text{T}} \approx 3^{1/2} = 1.73$$

从IR得到的值， $\nu_{\text{H}} / \nu_{\text{D}} = 1.34$ ， $\nu_{\text{H}} / \nu_{\text{T}} = 1.59$

同位素的改变引起反应速率变化

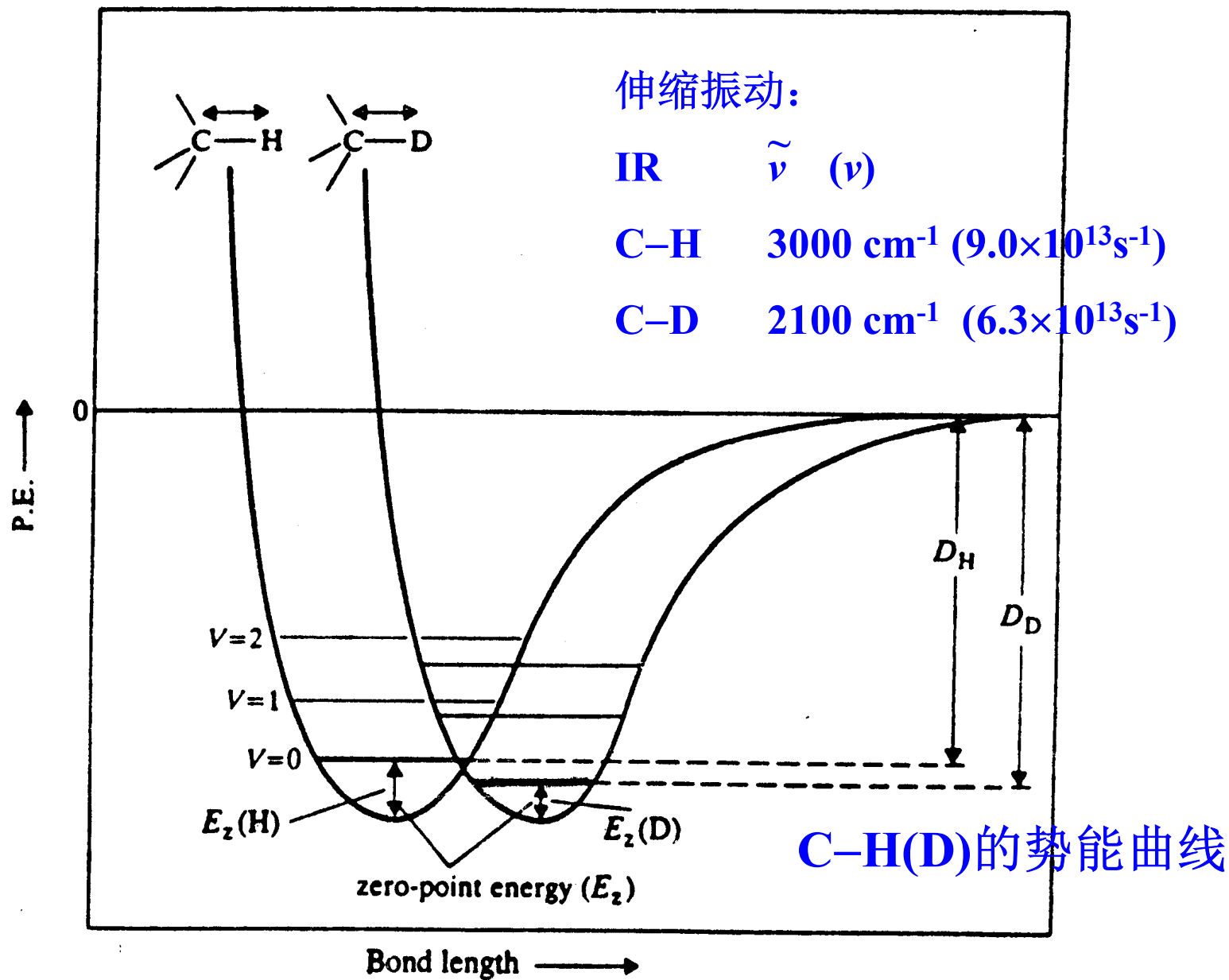


Fig. 7.1 Potential energy curves for C-H and C-D bonds showing the different dispositions of vibrational levels and the origins of their different bond dissociation energies. $E_z = E_v$ at $V = 0 =$ zero point energy.

- a. 振动能级的每一跃迁比室温下的热能 (k_T) 要大得多，因此，几乎所有的分子25°C时都分布在基态的振动能级上 ($v=0$) ；
- b. C-D比C-H基态振动能级低；
- c. 随 v 增大，上述差别减小，直至与电离限一致；
- d. $D_D > D_H$, C-D断裂比C-H需要的能量多

因此， k_D 具有比 k_H 低的速率，这就是通常的PKIE, 用 k_H/k_D 表示。一般地，一个连接重同位素的键的裂解能比轻同位素（同一元素）的大，相应的速率低。

Table 7.2
Maximum normal values of
PKIEs.

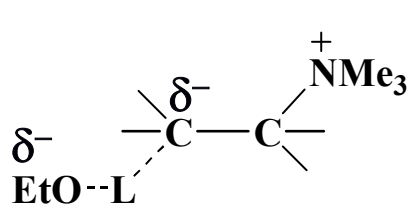
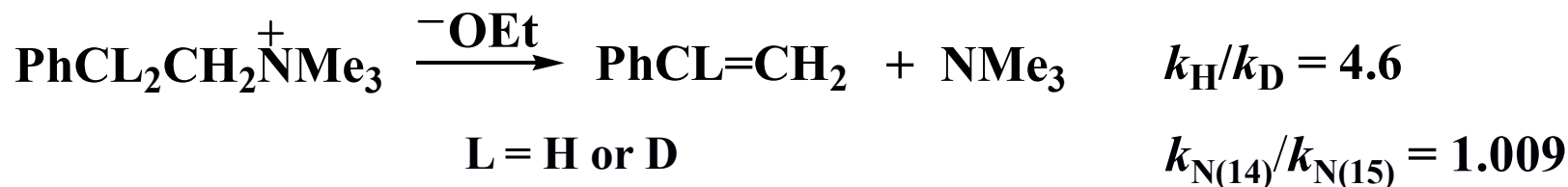
Element	Isotope		$T/^\circ\text{C}$	k_A/k_B
	A	B		
H	1	2(D)	0	8.3
H	1	2(D)	25	6.4
H	1	2(D)	100	4.7
H	1	2(D)	200	3.4
H	1	2(D)	500	2.1
H	1	3(T)	25	13
C	12	13	25	1.04
C	12	14	25	1.07
N	14	15	25	1.03
O	16	18	25	1.02
S	32	34	25	1.01
Cl	35	37	25	1.01

Some typical kinetic isotope effects

	Reaction	k_H/k_D
Primary	$\text{Me}_2\text{C}-\text{OH} + \text{CrO}_3 \rightarrow \text{Me}_2\text{C}=\text{O}$	7.0
	$\text{Me}_2\text{C}-\text{OH} + \text{Br}_2 \rightarrow \text{Me}_2\text{C}=\text{O}$	3
	$\text{RCOCL}_2\text{R}' + \text{SeO}_2 \rightarrow \text{RCOCOR}'$	7
	$\text{RCOCL}_3 + \text{Br}_2 \rightarrow \text{RCOCL}_2\text{Br} + \text{LBr}$	7
	$\text{CL}_3\text{NO}_2 + \text{Br}_2 \rightarrow \text{BrCL}_2\text{NO}_2 + \text{LBr}$	4.5-6.5
	$\text{PhCLCH}_2\text{Br} + \text{EtO}^- \rightarrow \text{PhC}=\text{CH}_2 + \text{EtOL} + \text{Br}^-$	7.51
	$\begin{array}{c} \text{Me} \qquad \qquad \qquad \text{Me} \\ \qquad \qquad \qquad \\ \text{---} \qquad \qquad \qquad \text{---} \end{array}$	
Secondary	$\text{R}-\text{OTos} + \text{AcOH} \rightarrow \text{R}-\text{OAc} + \text{HOTos}$	
k_H/k_D :	1.15 1.16 1.22 2.06	

用同位素效应研究反应机理的例子：

a. Elimination mechanisms



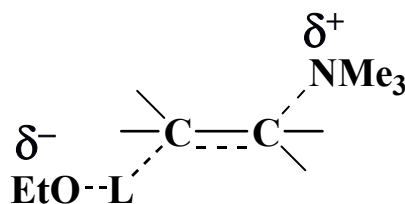
E1cb

$k_{\text{H}}/k_{\text{D}}$

✓

$k_{\text{N}(14)}/k_{\text{N}(15)}$

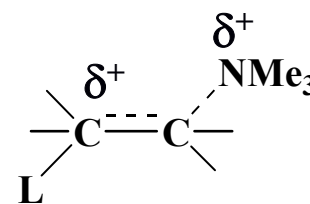
✗



E2

✓

✓



E1

✗

✓

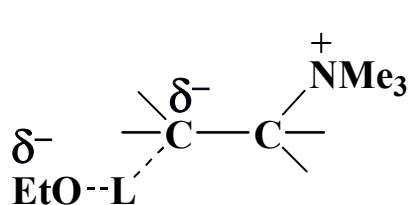
$k_{\text{H}}/k_{\text{D}} = 4.6, k_{\text{N}(14)}/k_{\text{N}(15)} = 1.009$ 是协同反应过程(E2)的有力证据。



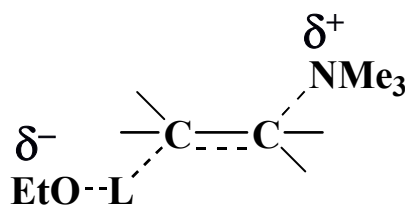
L = H or D

$$k_{\text{H}}/k_{\text{D}} = 1.1$$

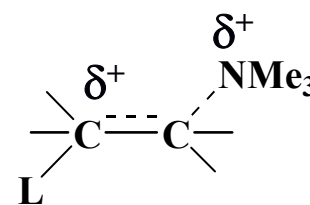
$$k_{\text{N}(14)}/k_{\text{N}(15)} = 1.009$$



E1cb



E2



E1

$$k_{\text{H}}/k_{\text{D}}$$

×

×

✓

$$k_{\text{N}(14)}/k_{\text{N}(15)}$$

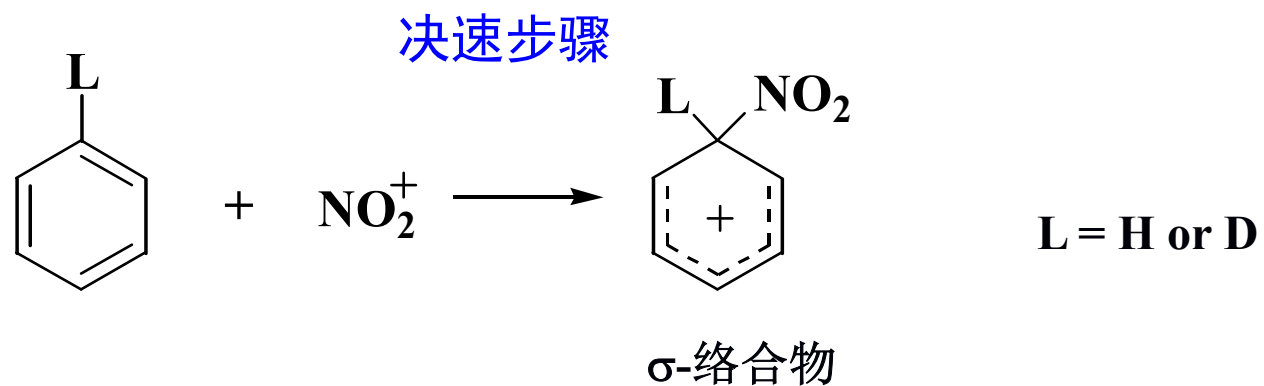
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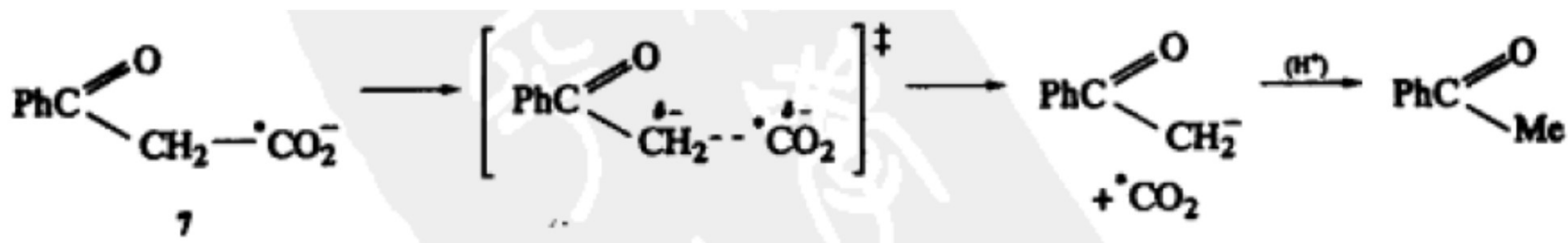
$k_{\text{H}}/k_{\text{D}} = 1.1, k_{\text{N}(14)}/k_{\text{N}(15)} = 1.009$ 是E1机理的有力证据。

b. Aromatic nitration



$k_{\text{H}}/k_{\text{D}} = 1.0$ 没有PKIE, 说明C-H在慢过程中不断裂。

c. Decarboxylation

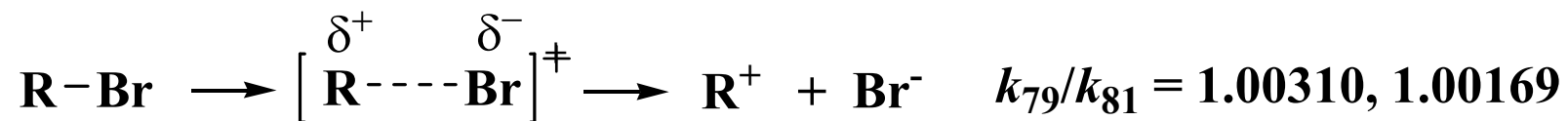


$$k_{12}/k_{13} = 1.04$$

d. Heavy atom isotope effects



$k_{\text{S}32}/k_{\text{S}34} = 1.072$ 说明C-S在慢过程中断裂PKIE



R = *t*-Bu, 1-Pr

7.3 Transition-state geometry

The position of the transition state along the reaction coordinate:

maximum

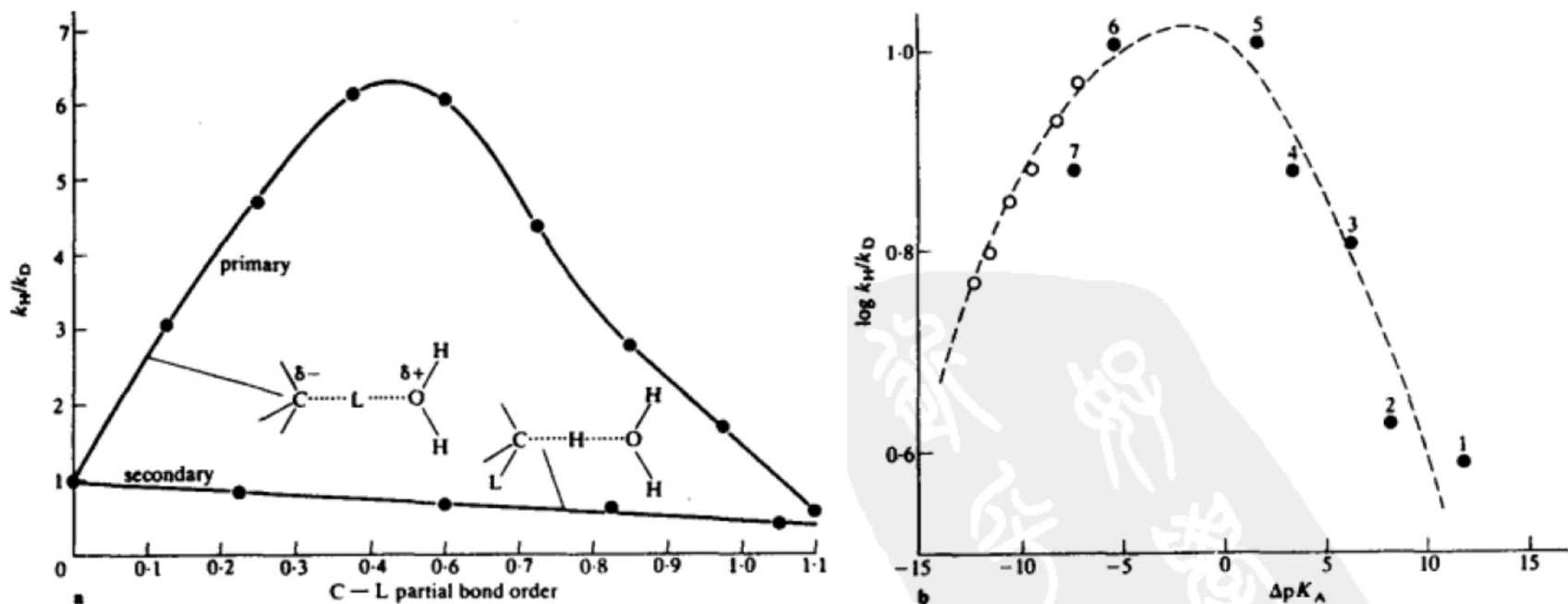
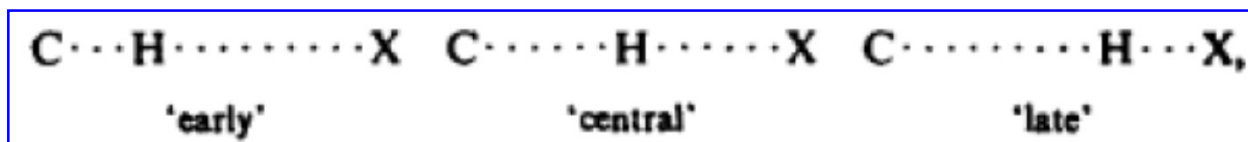
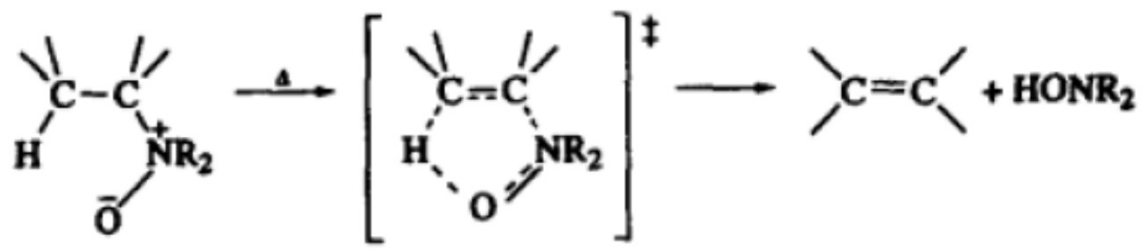


Fig. 7.2 a, Calculated curve showing the variation of isotope effect (primary and secondary) for proton transfer from a carbon acid as a function of the degree of bond-breaking. b, Experimental curve of the observed isotope effect versus difference in $\text{p}K_A$ between acid (MeNO_2 (I) or Me_2CHNO_2 (II)) and base for the reaction $\text{CHNO}_2 + \text{B} \rightarrow \text{C}^-\text{NO}_2 + \text{BH}^+$. The acid-base pairs are: 1, I + H_2O ; 2, I + $\text{CH}_2\text{ClCOO}^-$; 3, I + OAc^- ; 4, II + OAc^- ; 5, II + pyridine; 6, I + OH^- ; 7, II + OH^- .

质子转移：直线、中心过渡态，给出最大的 k_H/k_D



非直线，反常的小 $k_H/k_D \sim 3$

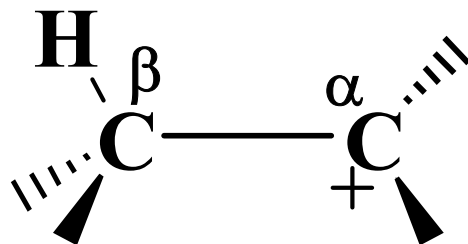
7.4 Secondary kinetic isotope effects

SKIE连接同位素原子的键反应期间不断裂，而引起的速率改变。 k_H/k_D 值较小，通常只能测得氢的SKIE。

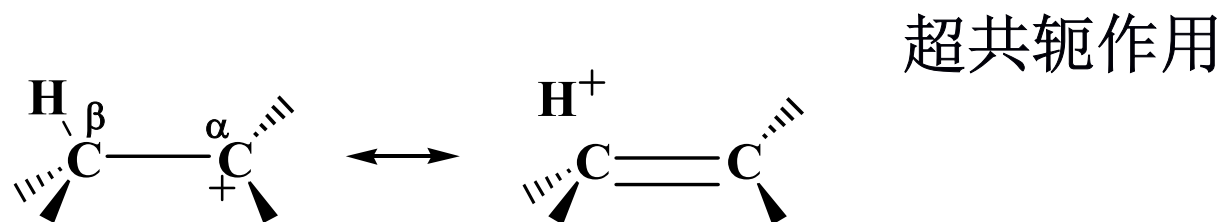
1. 二级动力学同位素效应的来源：超共轭作用



通常 $\alpha\text{-SKIE} < \beta\text{-SKIE}$ 。

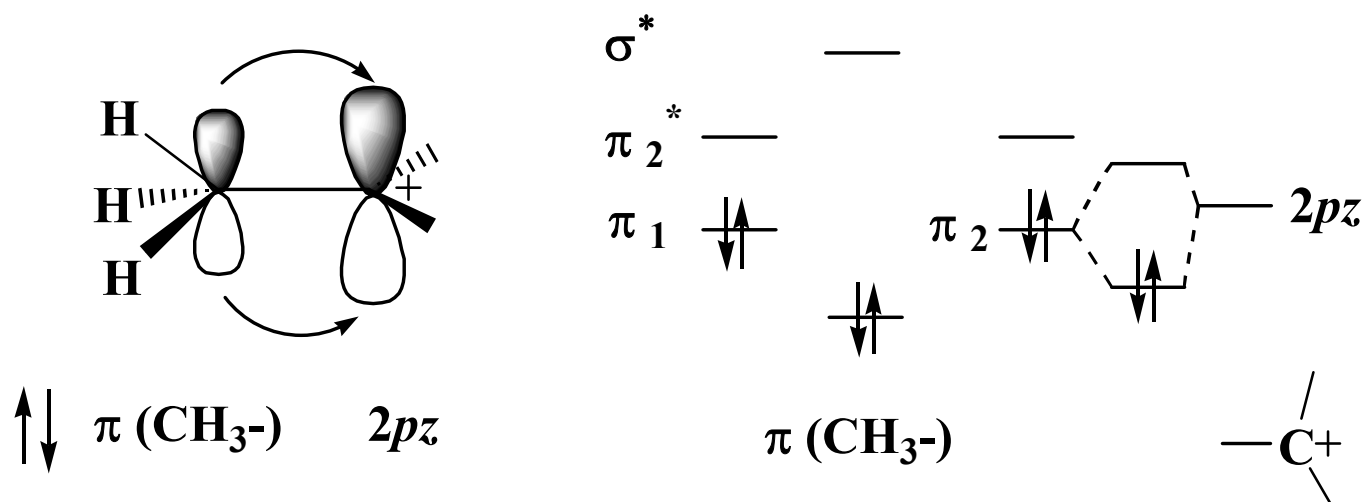


VB解释: β -C-H与空轨道的相互作用



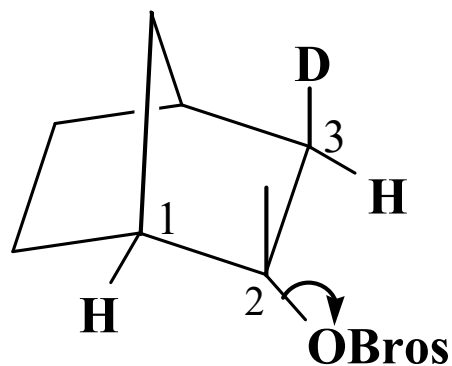
共振结构中包括一种“无键”结构

MO解释: p -空轨道与连接甲基的 π -重叠

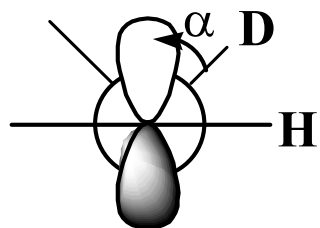


2. 构象关系

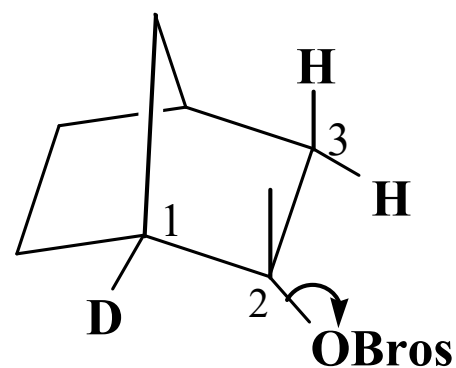
与超共轭来源一致，对于相互作用轨道，有效的超共轭要求两轨道最大重叠



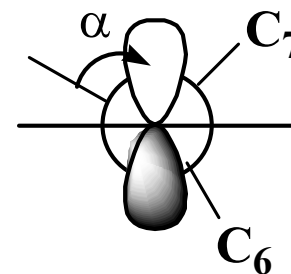
$$k_{\text{H}}/k_{\text{D}} = 1.19$$



$$\alpha \sim 30^\circ$$



$$k_{\text{H}}/k_{\text{D}} = 1.00$$

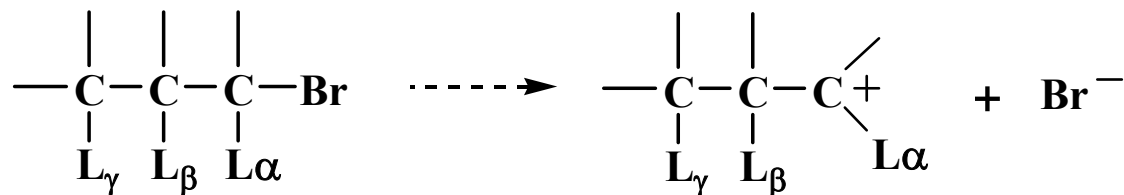


$$\alpha \sim 80^\circ$$

π -重叠程度依赖于二面角：

β -C-H键平行于2p轨道时，SKIE最大（最大重叠，有最大共轭作用）

β -C-H键垂直于2p轨道时，SKIE最小（最小重叠，有最小共轭作用）



Isotope position	$k_{\text{H}}/k_{\text{D}}$	Percentage effect per D
α	1.1–1.2	10–20
β	1.15–1.25	15–25
γ	0.92–1.02	–8 to +2

SKIE适合研究溶剂解反应和周环反应

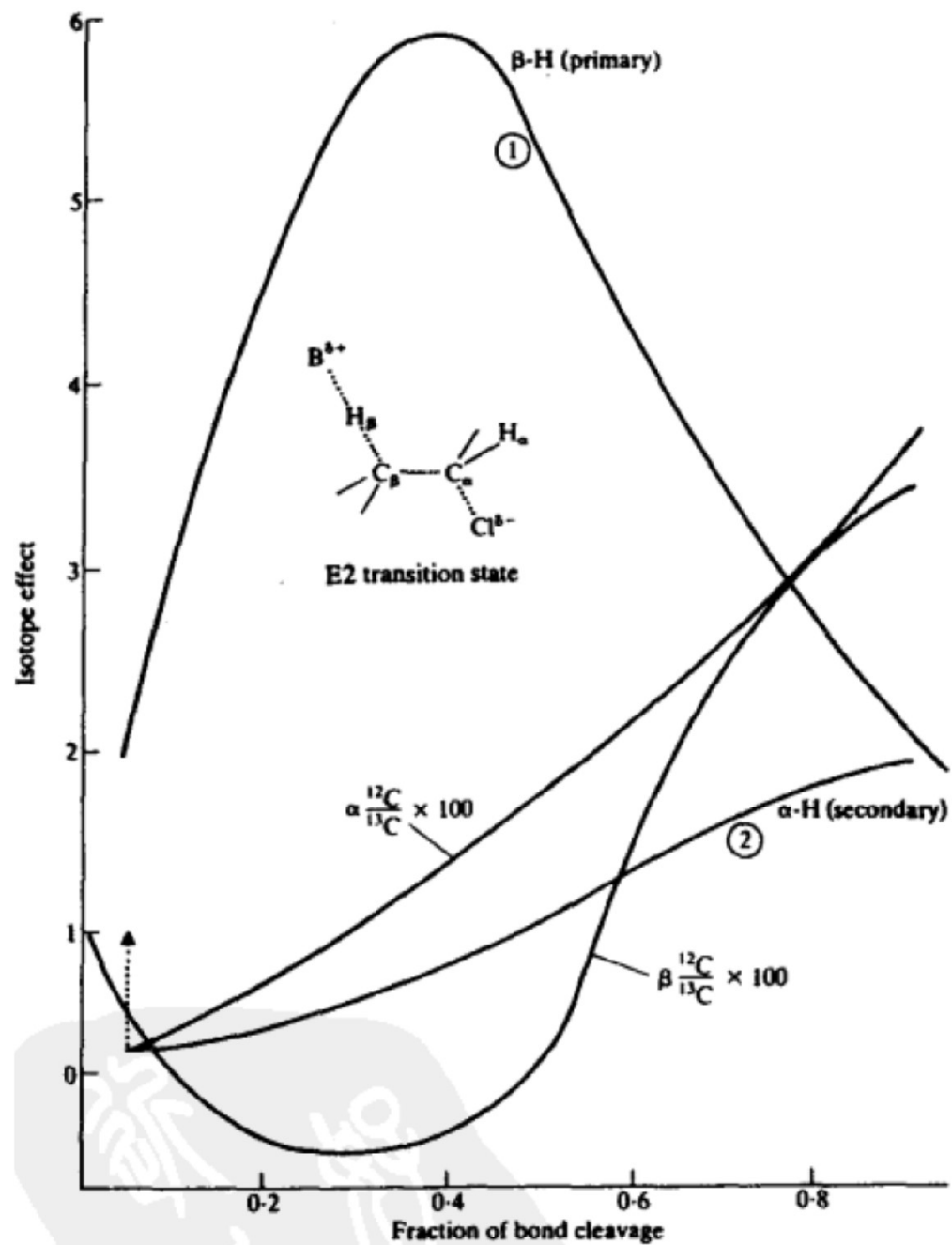


Fig. 7.3 Calculated curves showing the variation of the isotope effect with differing degrees of C-H bond-breaking in the E2-elimination transition state for the $\beta\text{-H}$ PKIE and for SKIEs at $\alpha\text{-H}$, $\alpha\text{-C}$ and $\beta\text{-C}$.

7.5 Solvent isotope effects

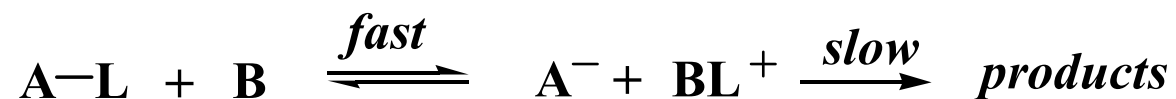
通过改变溶剂同位素，可进行反应机理的动力学研究，限于 $\text{H}_2\text{O}/\text{D}_2\text{O}$ ，有以下几种导致速率改变的原因：

1. 在决速步中，溶剂可能是反应试剂（溶剂解），可能与溶质连接，由此引起质子转移，有较大的动力学同位素效应。

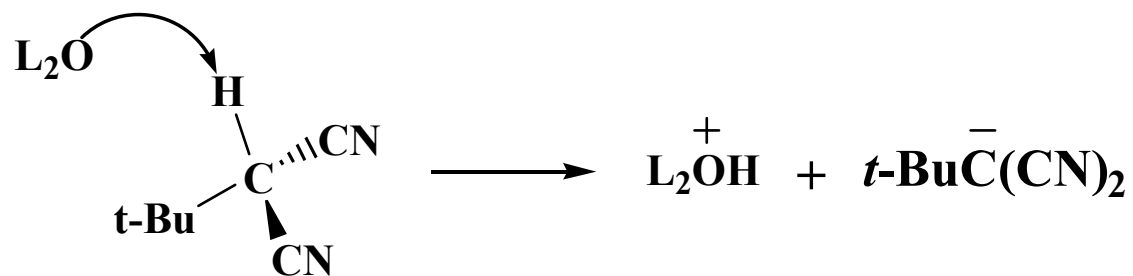
2. 质子溶剂可与溶质中酸性中心交换质子，以致溶质有不同的同位素，可能导致一级或二级同位素效应。

3. 质子溶剂的溶剂化性质，因同位素组成不同而不同，并影响溶质的化学势，尤其氢键能力的改变，又改变试剂的亲核能力。

酸碱催化反应的最初阶段，质子转移平衡：



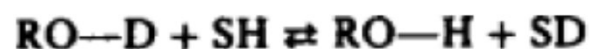
若没有连接质子的键断裂，同位素的改变将引起小的二级同位素效应。例如：溶剂水，O作为亲核中心



7.5.1 Fractionation factors (分馏系数)

溶剂从H₂O到D₂O改变引起的效应可以用 同位素分馏系数来预测

交换平衡:



分馏系数:

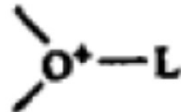

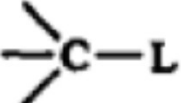
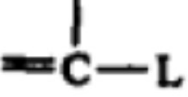
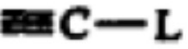
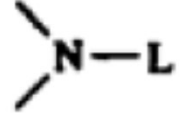
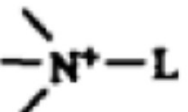
$$\phi = \frac{[\text{SD}][\text{RO-H}]}{[\text{SH}][\text{RO-D}]} = \frac{[\text{SD}]/[\text{SH}]}{[\text{RO-D}]/[\text{RO-H}]} \quad [7.13]$$

动力学同位素效应由下列方程来估算:

$$K_H/K_D = \frac{\prod_i^{\text{reactant sites}} \phi_i}{\prod_j^{\text{product sites}} \phi_j} \quad [7.14]$$

某元素的同位素在物理、化学、生物等反应过程中以不同比例分配于不同物质之中的现象称为同位素分馏 (isotopic fractionation)。

Table 7.5
H/D fractionation factors, ϕ ,
relative to water, for various
types of bond

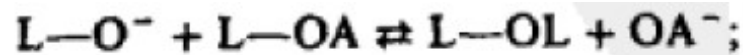
Bond type	ϕ
—O—L	1.0
—CO—OL	1.0
—O—OL	1.25
	0.69
	0.5
	0.84-1.18
	0.9
	0.69
	0.92
	0.97
—S—L	0.42
H—L	0.29

AOL (含氧酸) 在H₂O中比在D₂O中酸性强:



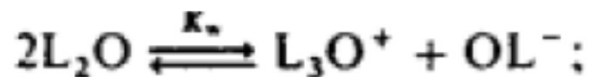
$$K_{\text{H}}/K_{\text{D}} = \phi_{\text{OL}}^2 \phi_{\text{OLA}} / \phi_{\text{O}^+\text{L}}^3 = (1/0.69^3) = 3.04. \quad [7.15]$$

OD⁻碱性比OH⁻强:



$$K_{\text{H}}/K_{\text{D}} = \frac{\phi_{\text{OL}^-} \cdot \phi_{\text{OLA}}}{\phi_{\text{OL}}^2} = 0.5/1 = 0.5. \quad [7.16]$$

H₂O比D₂O更易电离:

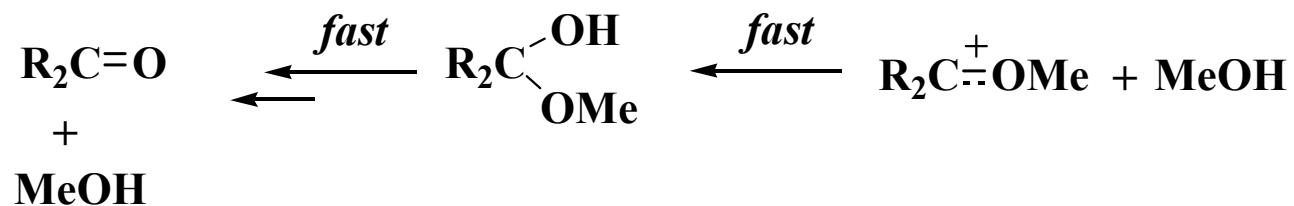
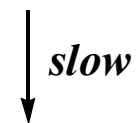
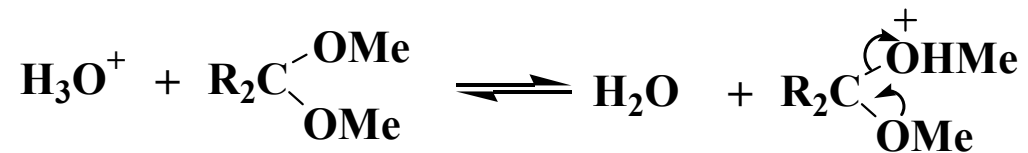
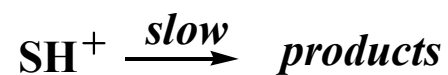


$$\begin{aligned} K_{\text{w}}(\text{H})/K_{\text{w}}(\text{D}) &= (\phi_{\text{OL}}^2 \phi_{\text{OLA}}) / (\phi_{\text{OL}^+}^3 \cdot \phi_{\text{OL}^-}) = 1/0.69^3 \times 0.5 \\ &= 6.1 \quad (\text{experimental value } 7). \end{aligned}$$

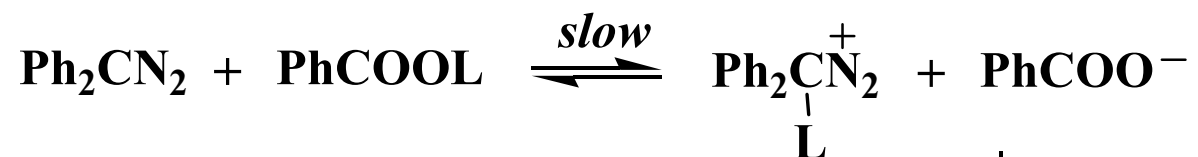
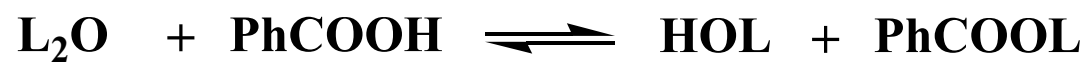
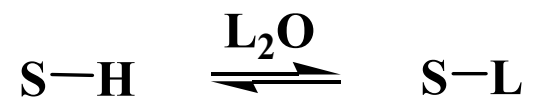
$$\text{Hence } \text{p}K_{\text{w}}(\text{D}) = 14.84,$$

7.5.2 溶剂同位素的例子

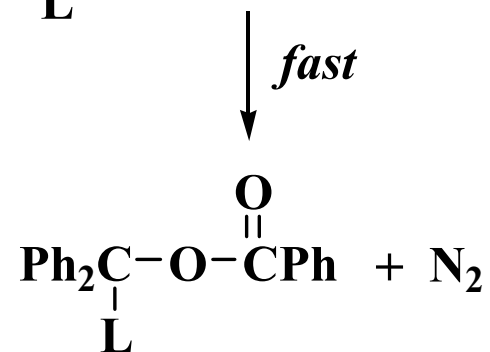
(a)



(b)



$$k_{\text{H}}/k_{\text{D}} = 7$$



本章内容

7.1 同位素效应：概述

1. 平衡同位素；2. 动力学同位素效应（KIE）：分为三类

7.2 一级动力学同位素效应的理论解释

7.3 过渡态结构对KIE的影响

7.4 二级动力学同位素效应

7.4.1 二级动力学同位素效应的来源：超共轭作用

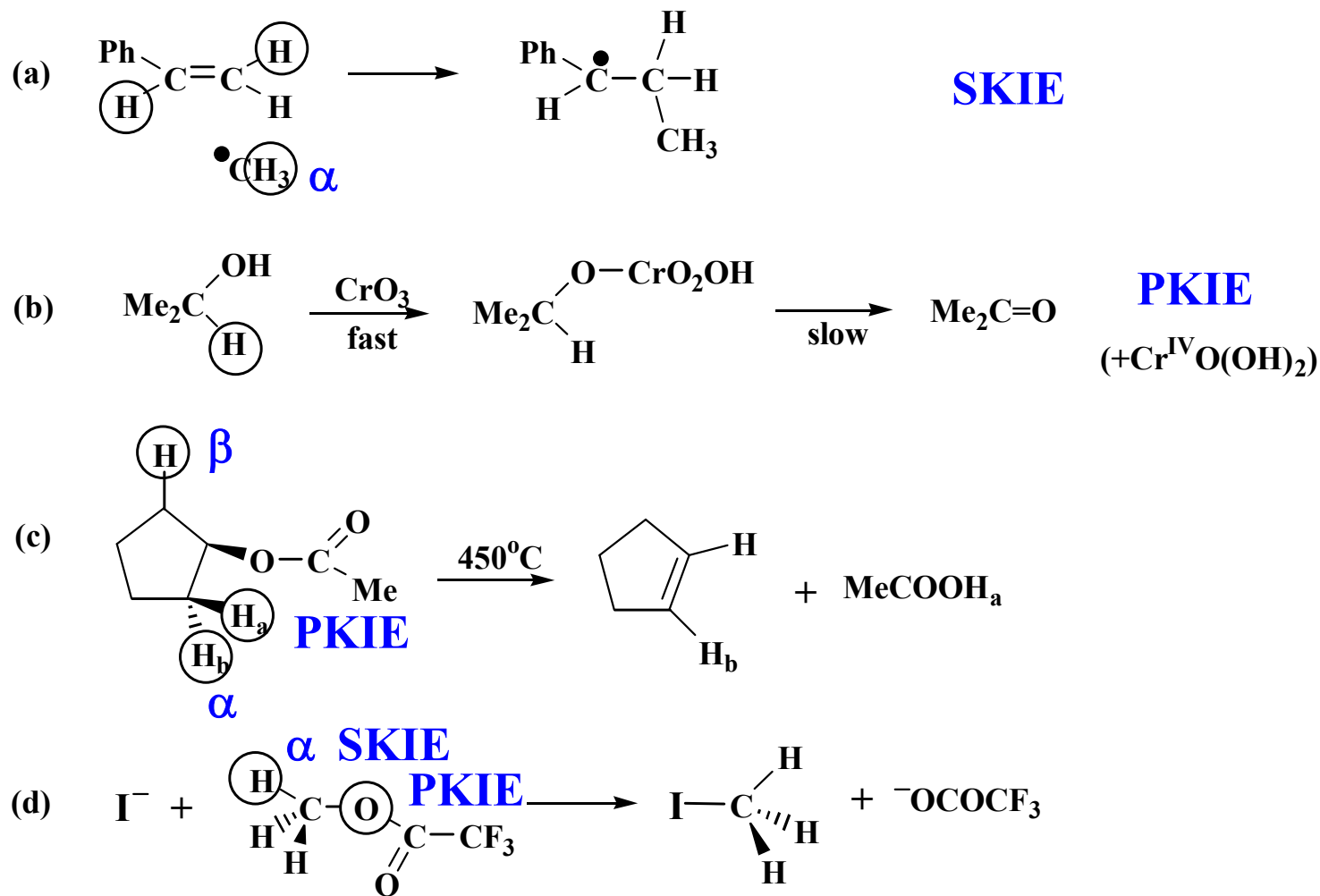
7.4.2 构象关系

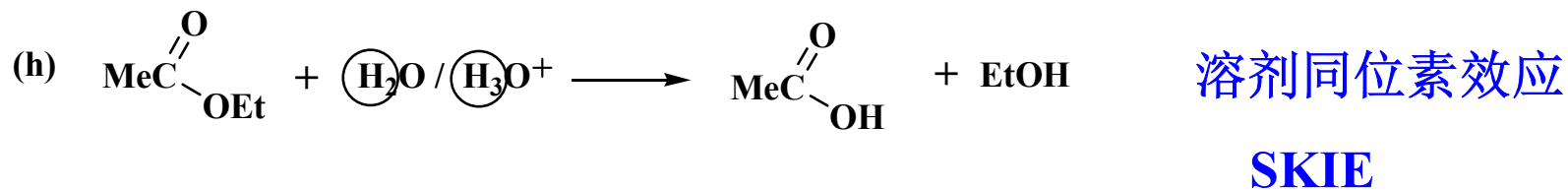
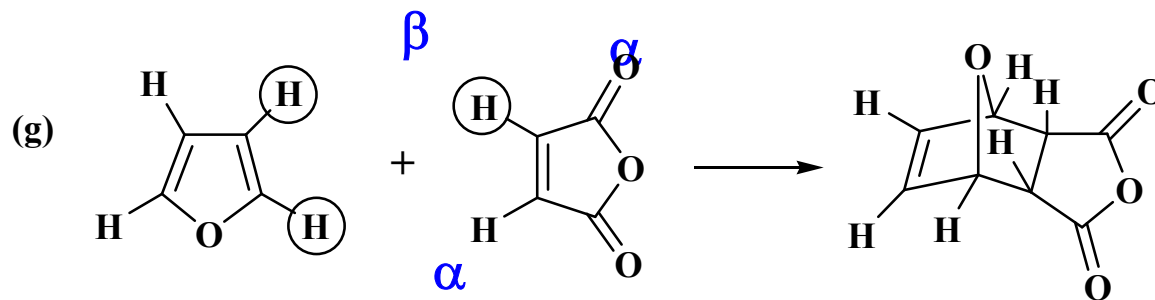
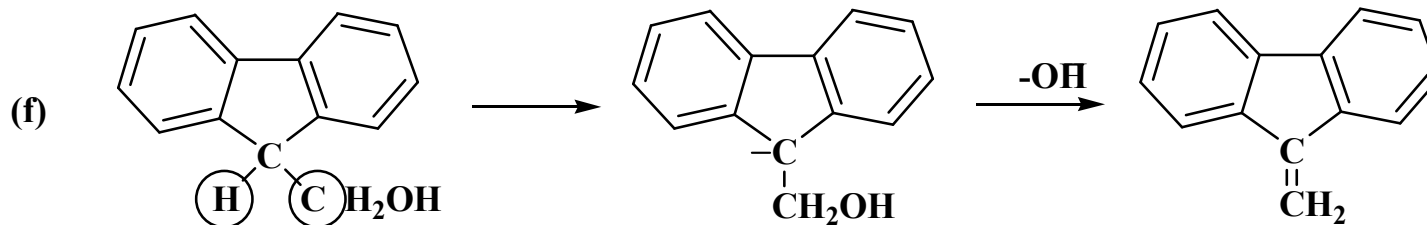
7.5 溶剂同位素效应

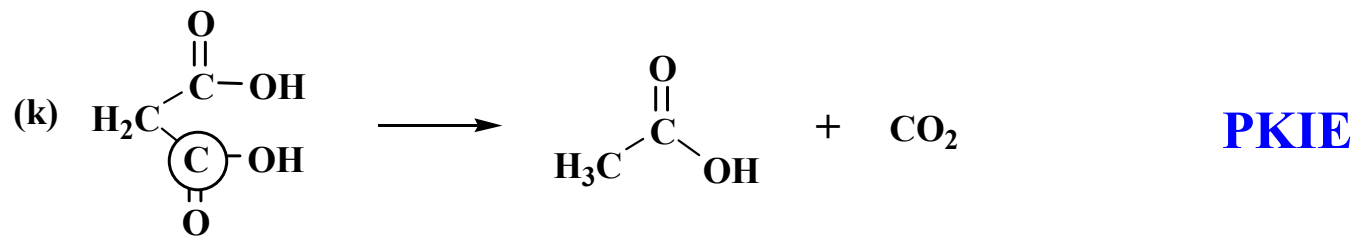
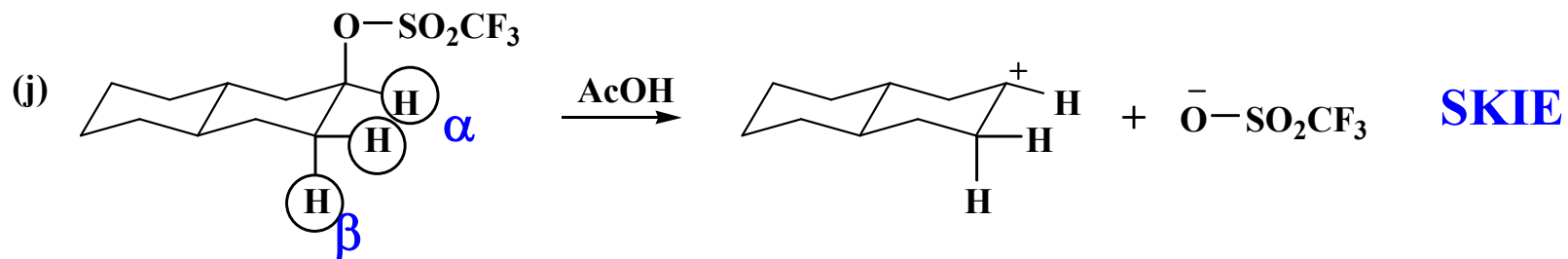
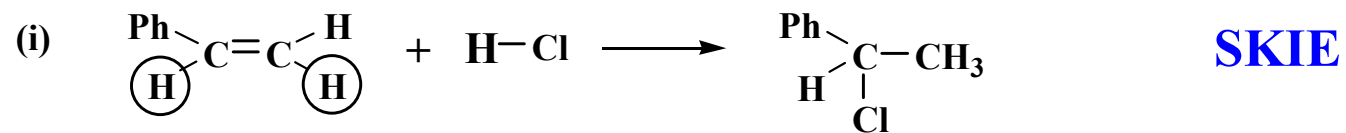
7.5.1 分馏系数

7.5.2 溶剂同位素的例子

Predict the type and magnitude of kinetic isotope effects associated with the atoms ringed (if two or more positions are ringed consider each separately):

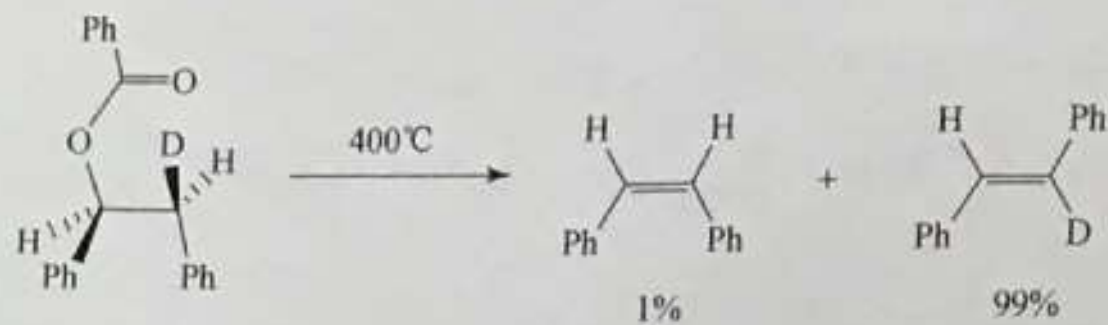
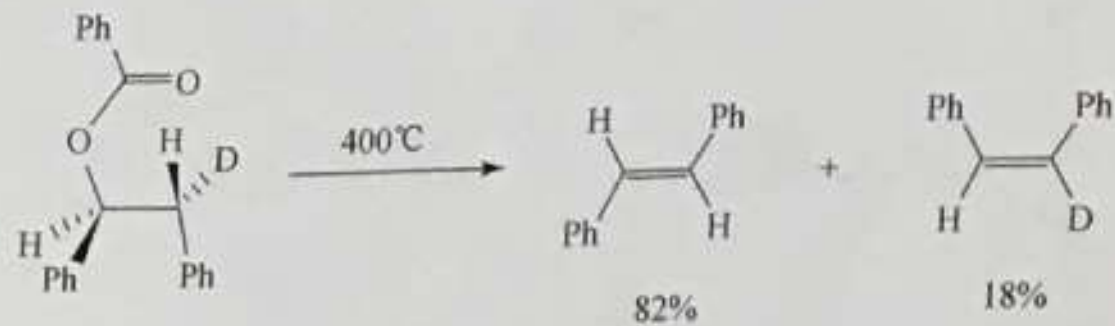






1-10 对于以下的同位素标记实验,请从反应机理的角度给予合理的解释(*J. Am. Chem.*

Soc. 1953, 75, 6011)。



@阅读:

参考书: 第7章