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Leibniz
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Gaich Seminar

The Hammett Correlation

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1. Introduction

2. Hammett Equation

- Variation of the Equation

3. Yukawa Tsuno Equation

4. Deviation from Hammett Correlation

Hammett Equation

- Describes a linear free energy relationship, relating reaction rates and equilibrium constants
 - Can be applied to many reactions involving benzoic acid derivatives with *m*- and *p*- substituents

$$\log \left(\frac{K_a(X)}{K_a(H)} \right) = \rho \sigma_x \quad \text{or} \quad \log \left(\frac{k_a(X)}{k_a(H)} \right) = \rho \sigma_x$$

↑ Reaction constant
 ↑ Hammett constant or substituent constant

Idea

- For any two reactions with two aromatic reactants only differing in the type of substituent, the change in free energy of activation is proportional to the change in Gibbs free energy

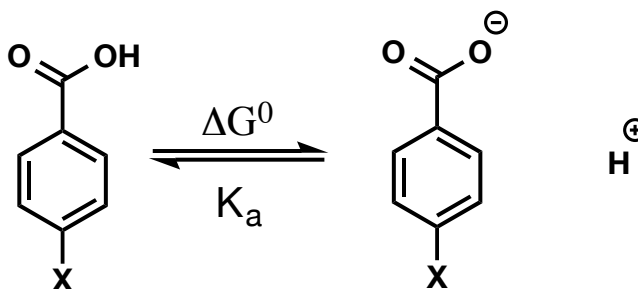
$K_a(H)$ is directly related to ΔG^0 via $\Delta G^0 = -2.303 \cdot RT \cdot \log K_a(H)$

$K_a(X)$ is directly related to ΔG^0 via $\Delta G^0 = -2.303 \cdot RT \cdot \log K_a(X)$

$$\sigma(X) = \log \frac{K_a(X)}{K_a(H)} = \frac{-\Delta\Delta G^0}{2.303RT}$$

Hammett Equation

- How do substituents affect the acidity?



	<i>p</i>		pK_a	K_a	ΔG^0
X=	NH₂	less acidic	4.86	1.4×10^{-5}	6.7 kcal/mol
	CH ₃		4.34	4.3×10^{-5}	
	H		4.20	6.3×10^{-5}	5.8 kcal/mol
	Cl		3.96	1.1×10^{-4}	
	NO₂	more acidic	3.42	3.8×10^{-4}	4.7 kcal/mol

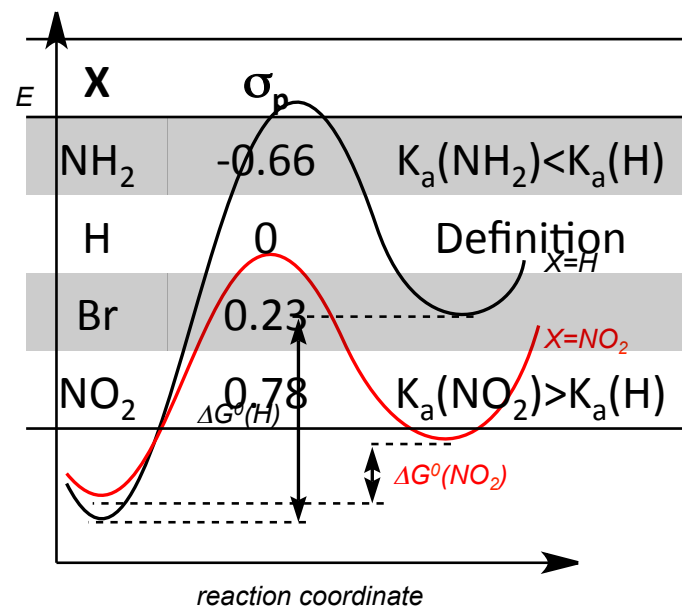
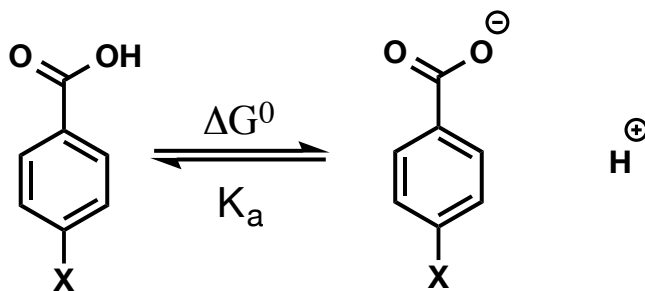
Hammett Equation

- *Hammett's Hypothesis*
 - *Each substituent X has a characteristic free-energy difference*

$$\log_{10} \frac{K_a(X)}{K_a(H)} = \frac{\Delta\Delta G^0(X)}{2.303RT} = \sigma(X)$$

Hammett
Parameter

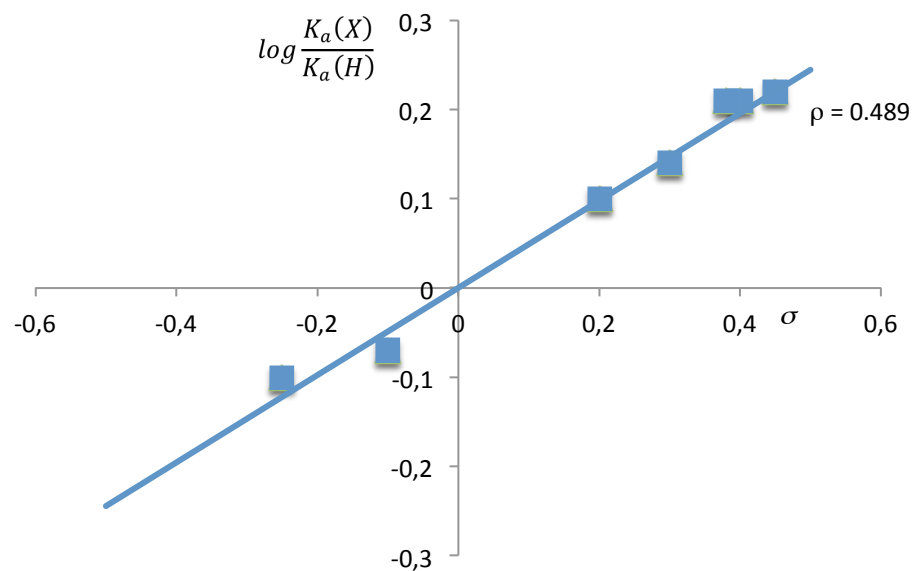
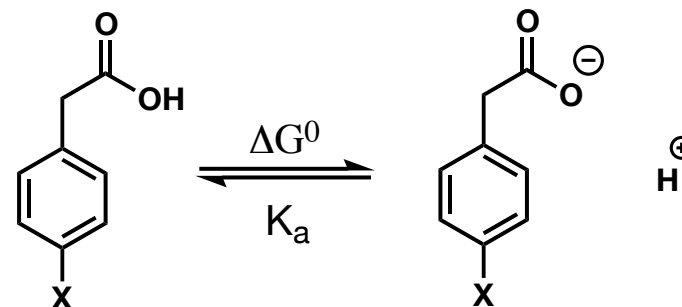
$$\Delta\Delta G^0(X) = \Delta G^0(X) - \Delta G^0(H)$$



Hammett Equation

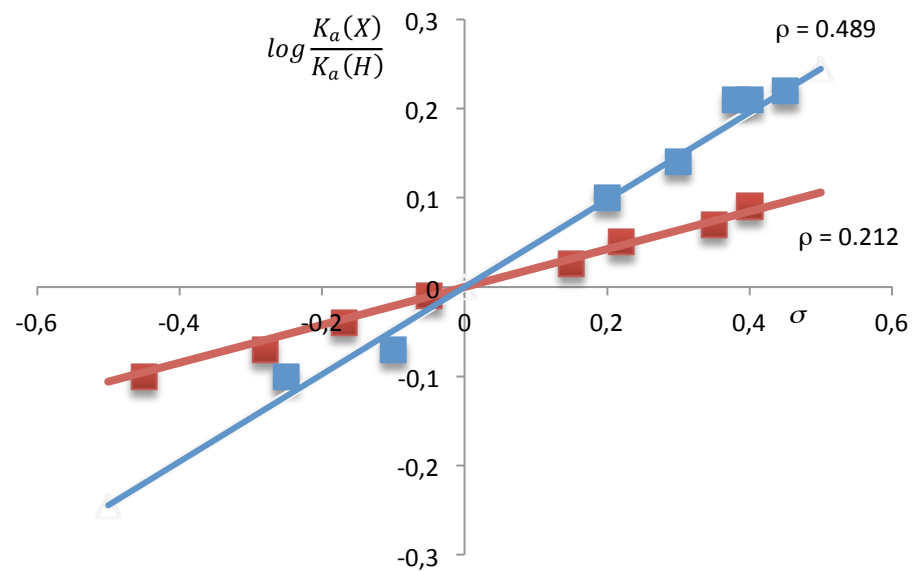
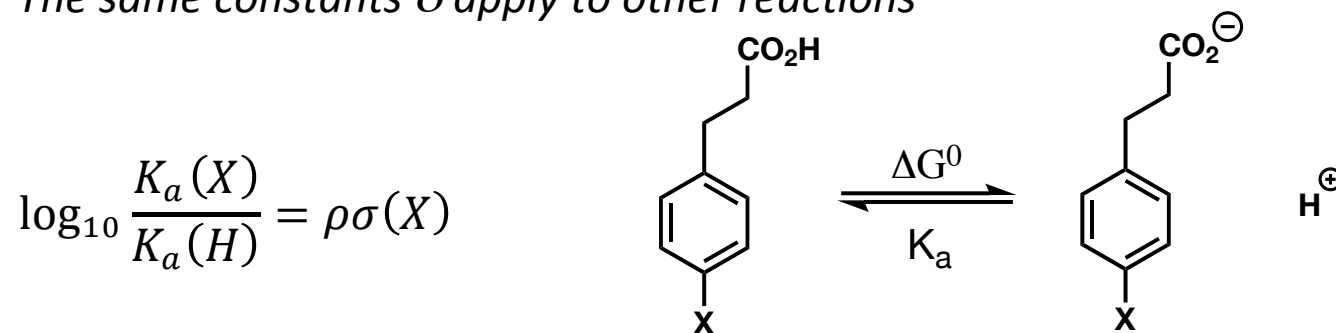
- *Hammett's Hypothesis*
 - *The same constants σ apply to other reactions*

$$\log_{10} \frac{K_a(X)}{K_a(H)} = \rho \sigma(X)$$



Hammett Equation

- *Hammett's Hypothesis*
 - *The same constants σ apply to other reactions*



Physical Meaning of σ and ρ

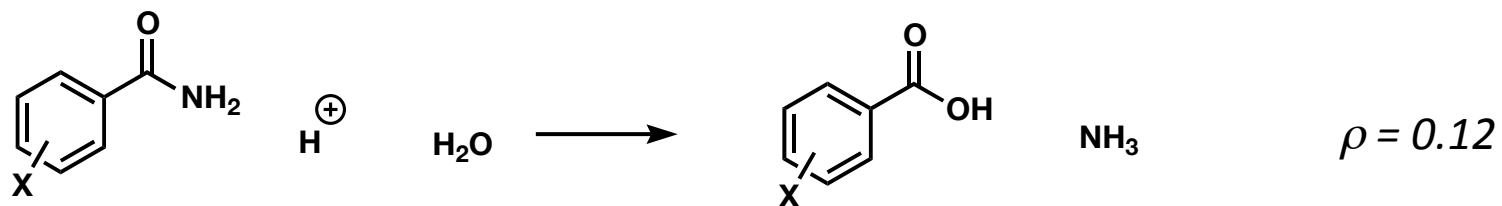
Reaction constant ρ

- *Is the slope of the line, correlating $\log k$ or $\log K$ with σ*
- *Sign is an indicator whether a reaction is suppressed or accelerated by the different substituents (EWG & EDG)*
 - *$\rho -$ indicates a suppression of the reaction by EWG*
 - *Positive charge is build up at the reaction center in the TS (rds)*
 - *$\rho +$ indicates an acceleration of the reaction by EWG*
 - *Negative charge is build at the reaction center in the TS (rds)*

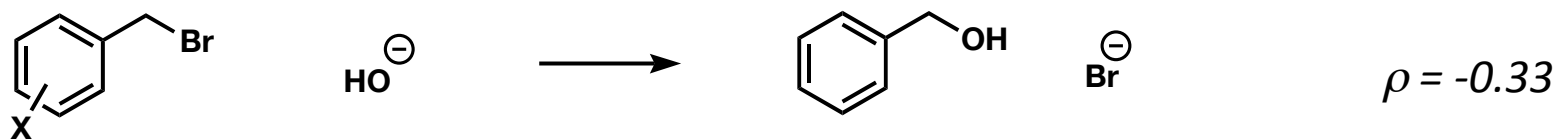
Substituent constant σ

- *Represents the electron attracting or repelling power of a substituent group*
- *quantitative measure of polar effects in any reaction given m- or p- substituents relative to **H***
 - *σ positiv: EWG (-I & -R)*
 - *σ negative: EDG (+I & +R)*

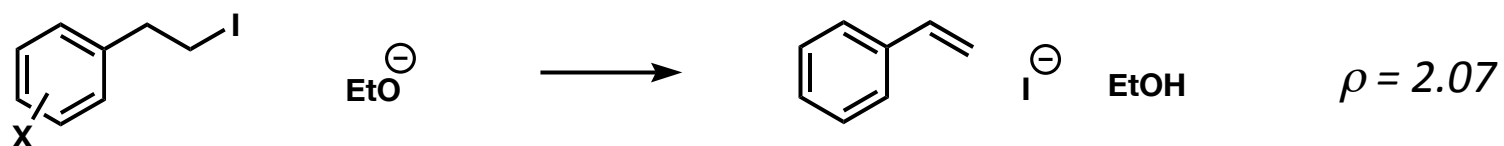
Further Meaning of ρ



Effects cancel each other out

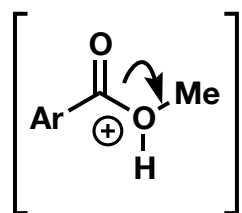
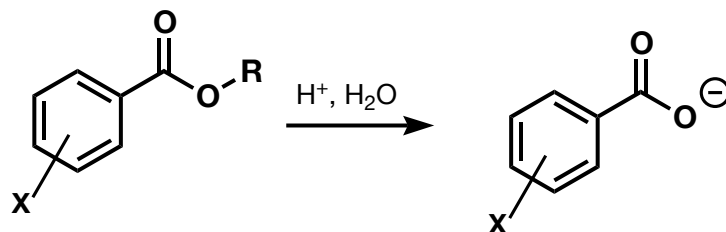


Effects cancel each other out



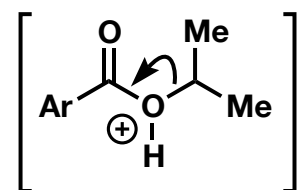
EWG Effects are superior compared to the EDG

ρ is an Indicator for Mechanism



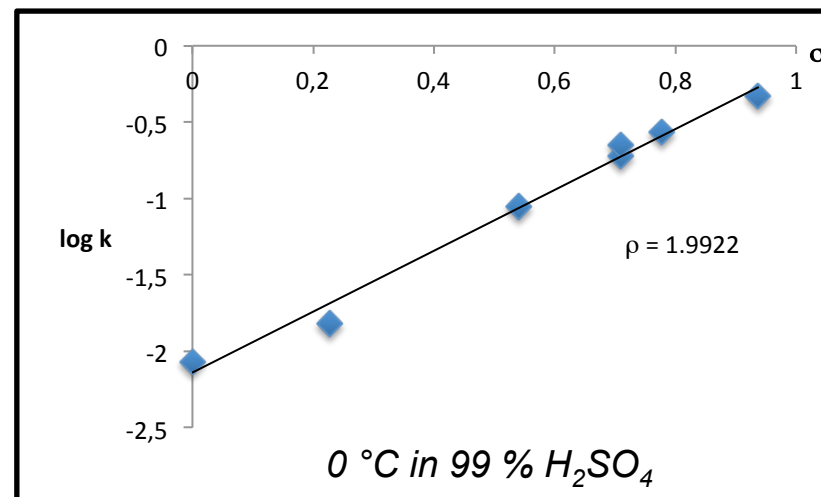
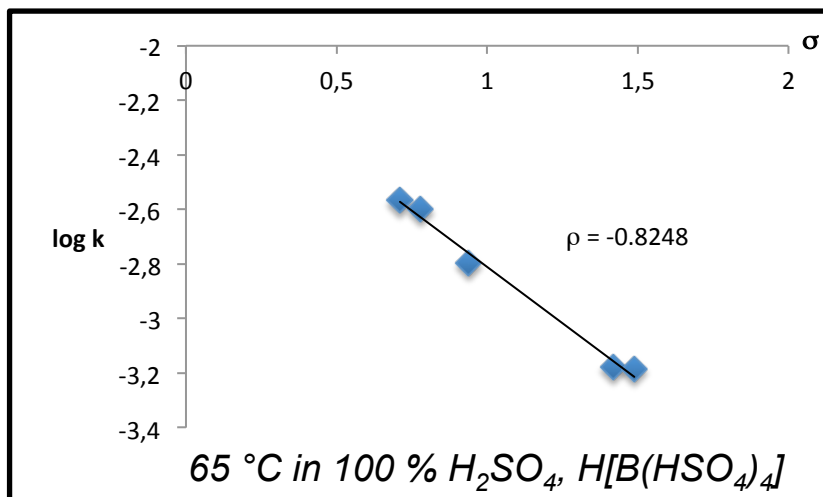
A_{Ac} mechanism

- e^- going away from arom
- Increased by EDG
- ρ is negative

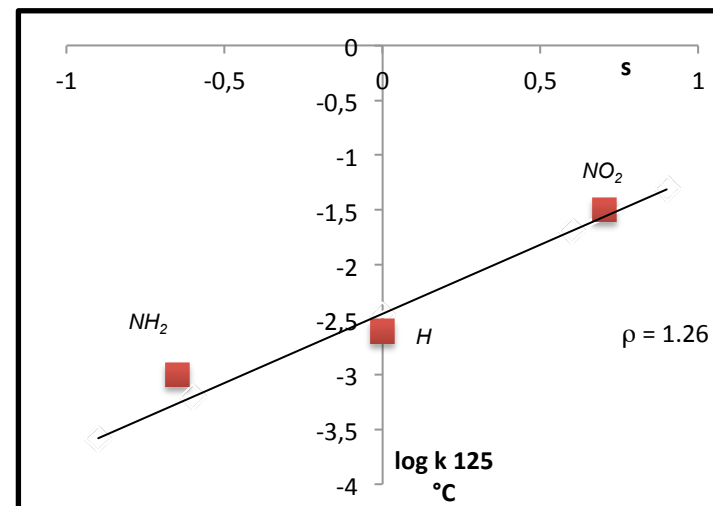
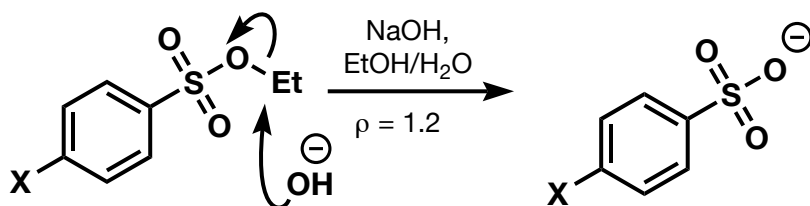
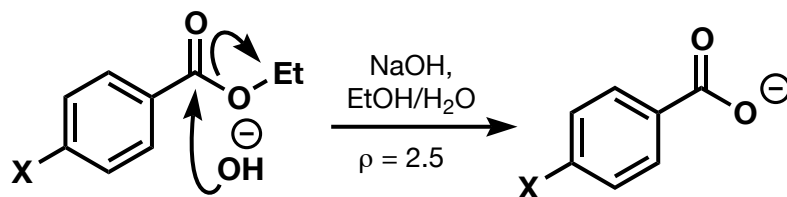
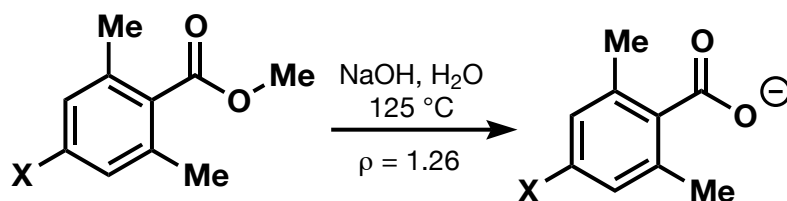


A_{A1} mechanism

- e^- going toward arom
- Increased by EWG
- ρ is positive



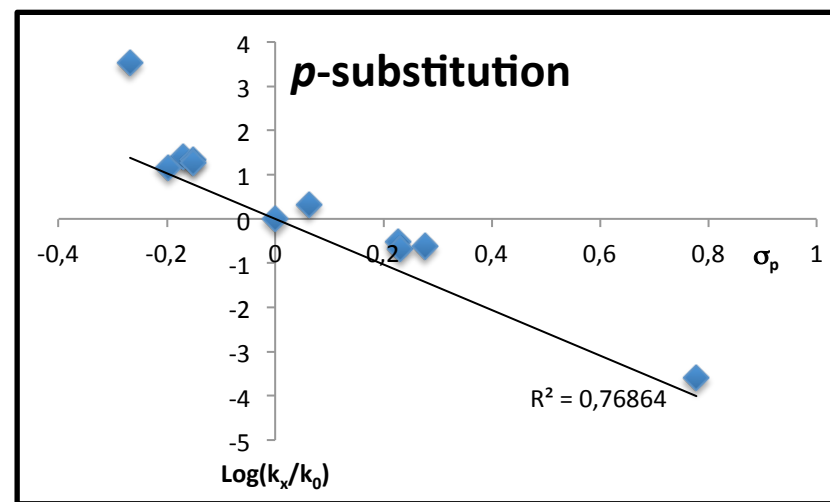
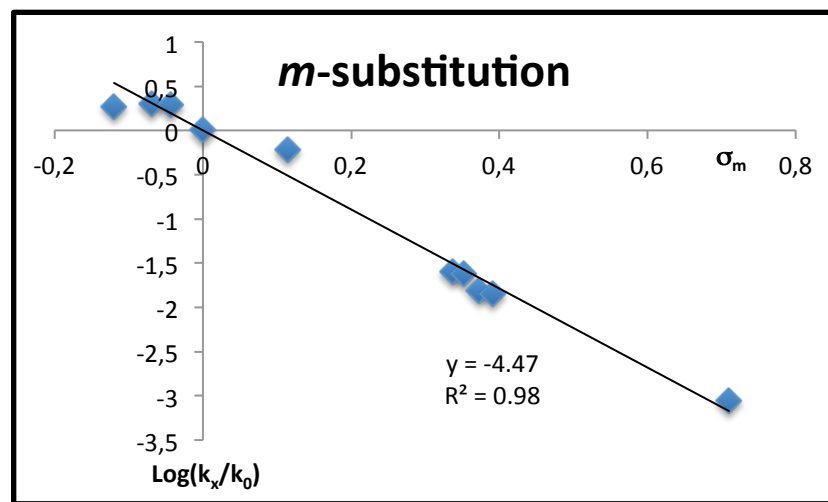
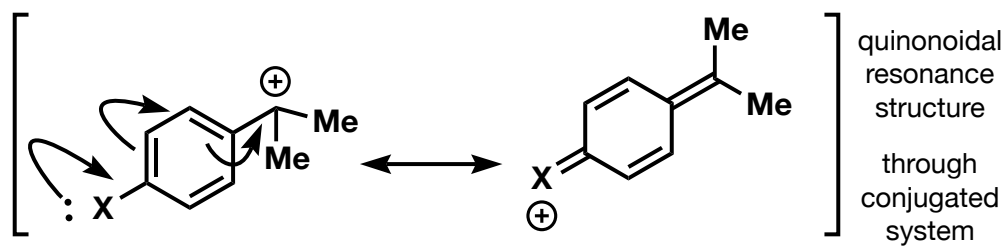
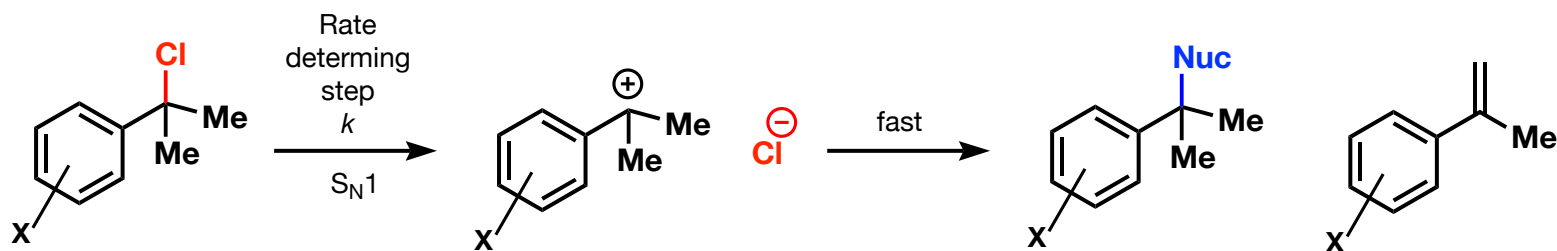
ρ is an Indicator for Mechanism



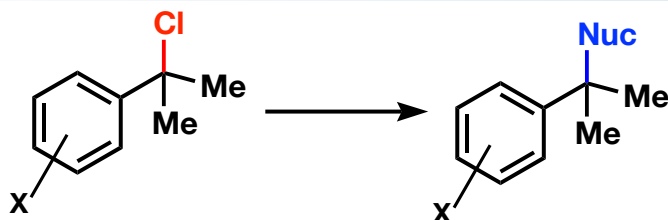
- ρ value is lower than in case of basic hydrolysis of unsubstituted esters
- Hydrolysis of sulfonic esters proceeds with alkyl-oxygen fission
 - ρ values of hydrolysis of 4X-2,6-dimethylbenzoate and benzyl-sulfonic esters are close to each other
 - Same mechanism proposed
 - Evidence via ^{18}O studies



Modification of the Equation



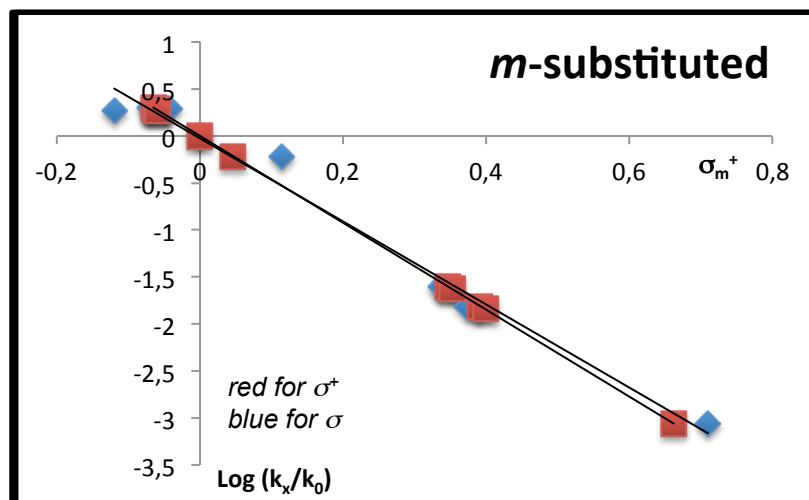
Modification of the Equation



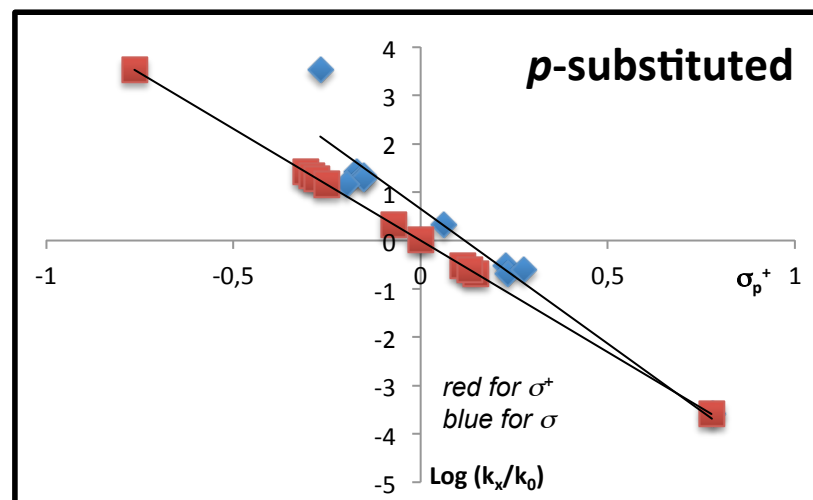
Hammett Equation
modified by Brown.

$$\log \frac{k_a(X)}{k_a(H)} = \rho^+ \sigma^+$$

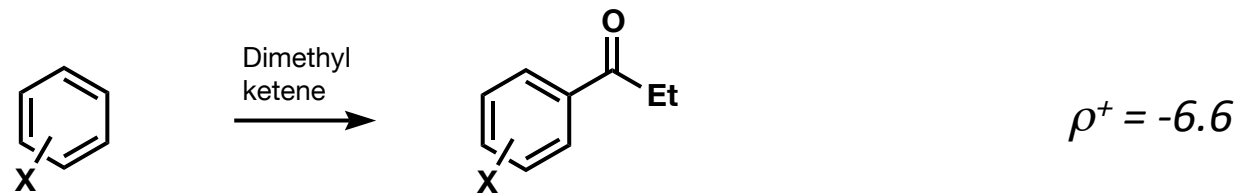
- σ_m^+ values close to Hammett σ values
 - Just inductive effects of substituents
- σ_p^+ values for EDG show a great difference to Hammett σ_p values due to through conjugation
- σ^+ is applied to reactions where a cation is developed



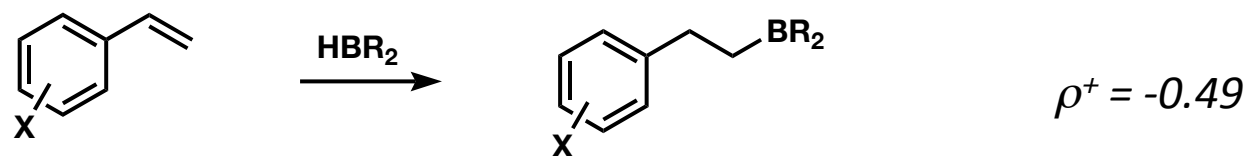
The slopes are made from calculated values



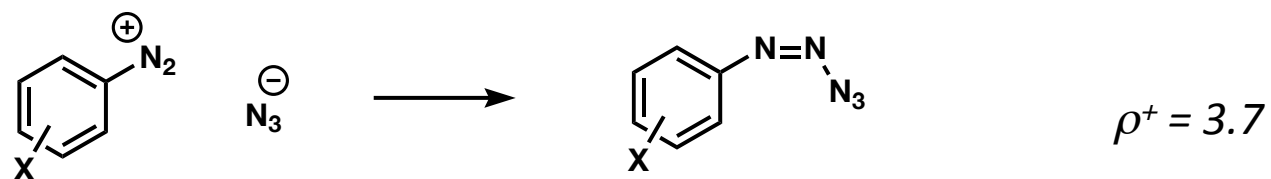
Meaning of ρ^+



Reaction center is on the ring

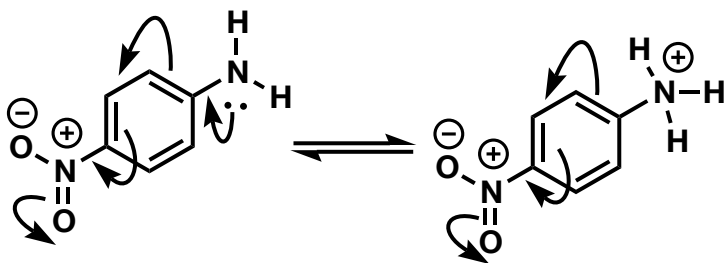


Effects cancel out each other



Cationic intermediate causes a positive value

Modification of the Equation



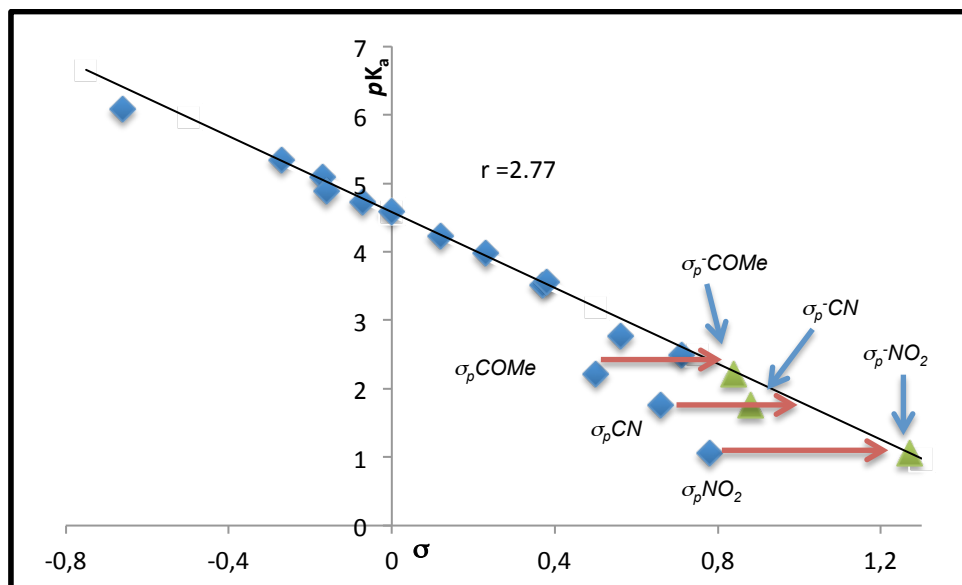
$$\rho \cdot \sigma_{pNO_2} = 2.77 \cdot 0.78 = 2.16 \text{ calculated}$$

3.52 observed.

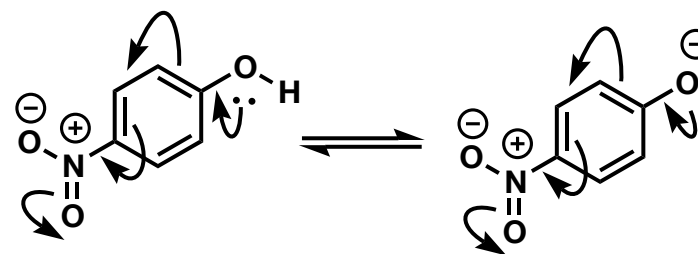
$$\sigma^-_{pNO_2} = 3.52 \cdot 2.77^{-1} = 1.27$$

Modification of the Hammett equation

$$\log \frac{k_x}{k_0} = \rho^- \sigma^-$$



pK_a values of phenols also fit to σ^- because with phenolate anion appears a much greater through conjugation

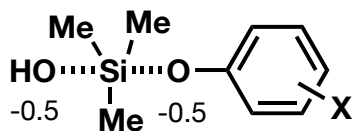
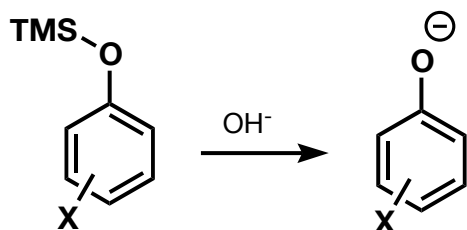


Yukawa-Tsuno equation

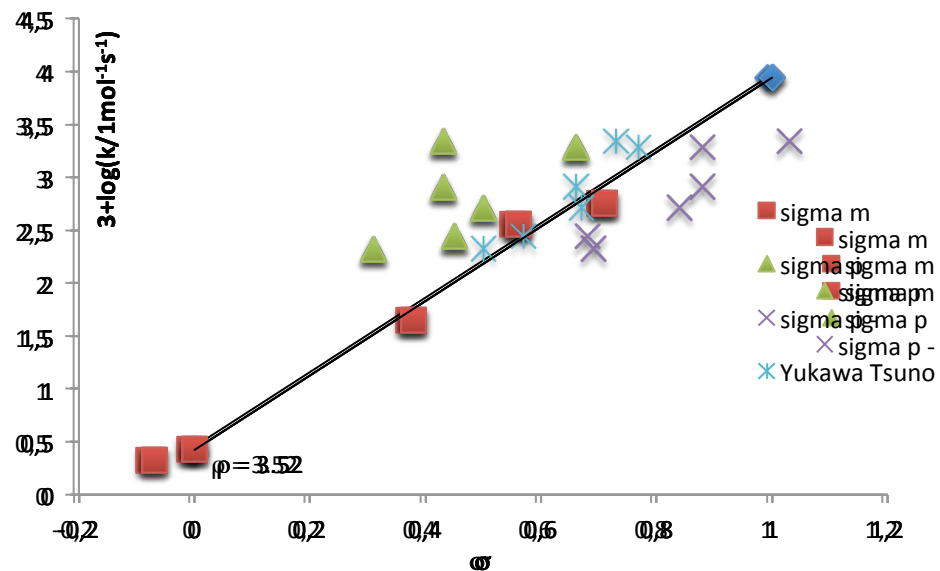
Yukawa Tsuno Equation

$$\log \frac{k_x}{k_0} = \rho \cdot (\sigma + r[\sigma^- - \sigma])$$

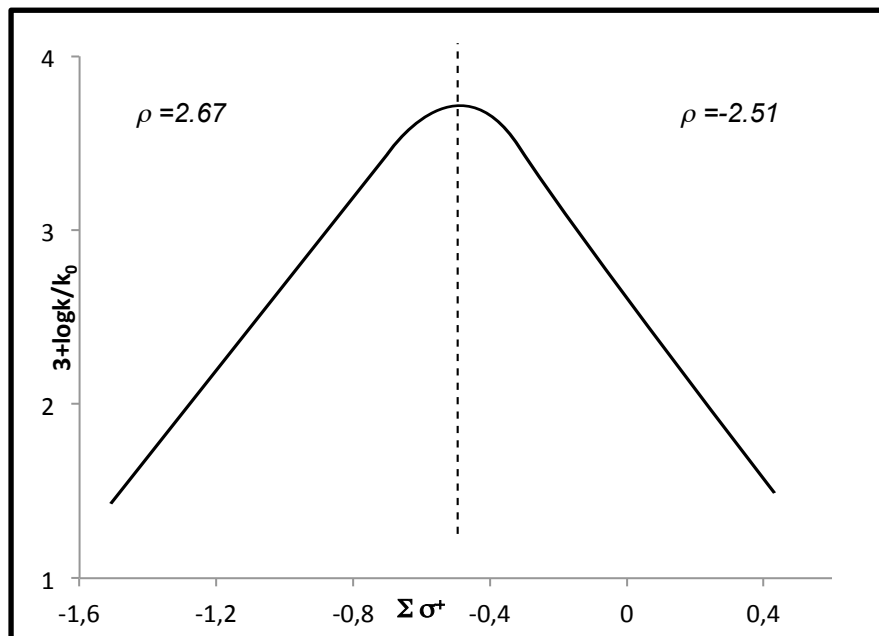
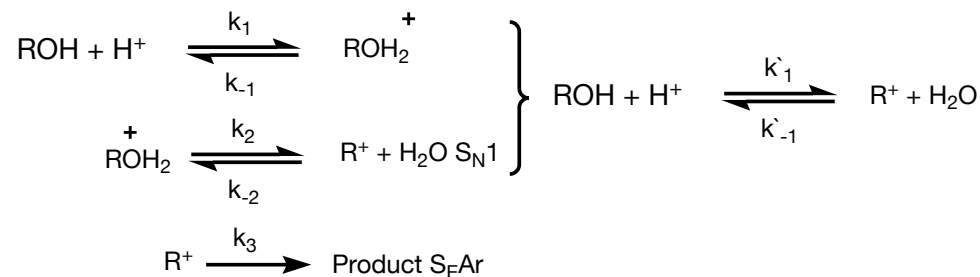
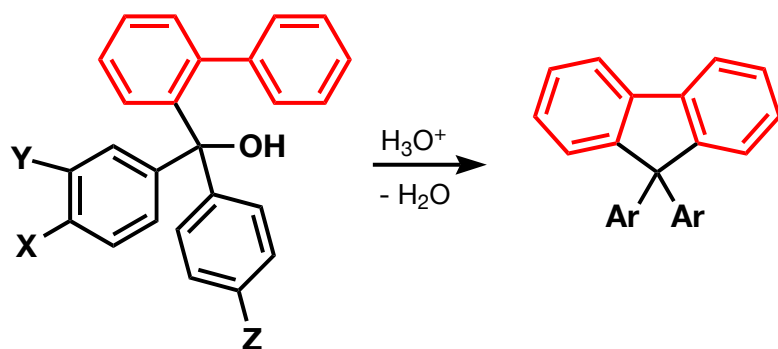
- *separating influence of induction and resonance on a reaction (distinguish normal from enhanced resonance effects)*



$r \rightarrow$ *enhanced resonance parameter*
 $r > 0 \rightarrow$ *more sensitive to resonance effects*
 $r < 0 \rightarrow$ *less sensitive to resonance effects*

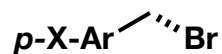
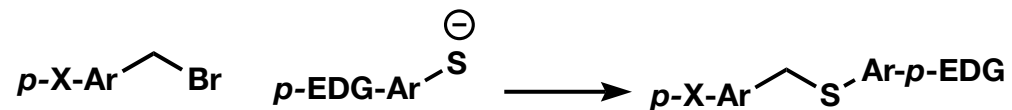


Cyclodehydration of 2-phenyltriarylcarbinols



1. X, Y, Z are different substituents
2. left side: EDG can stabilize the carbo cation via resonance and/or inductive effects, so k_3 is the rds.
3. right side: EWG promote the electrophilic aromatic substitution, so k_2 is the rds.
4. σ^+ values because cation is the reactant

Elucidation of Reaction Mechanisms

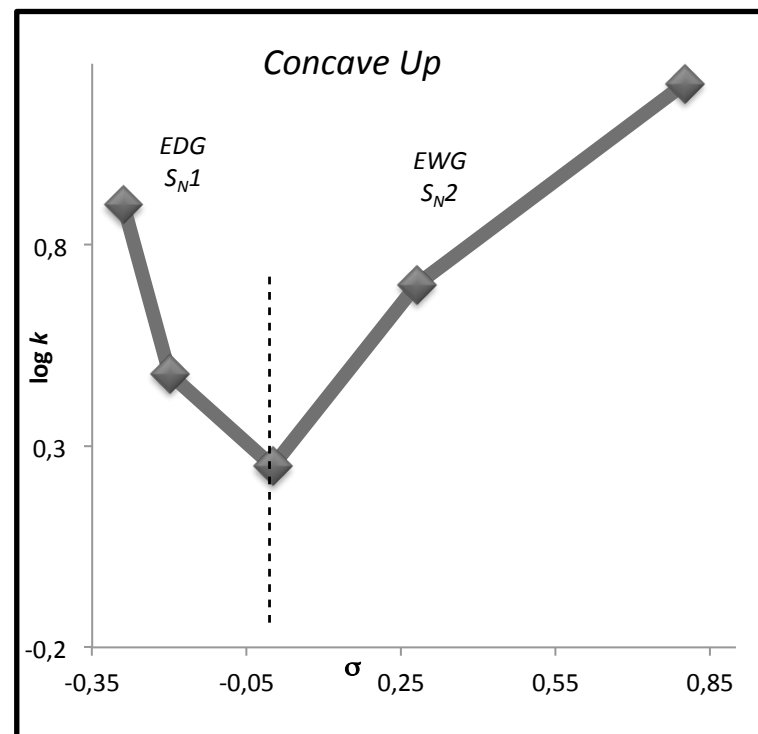
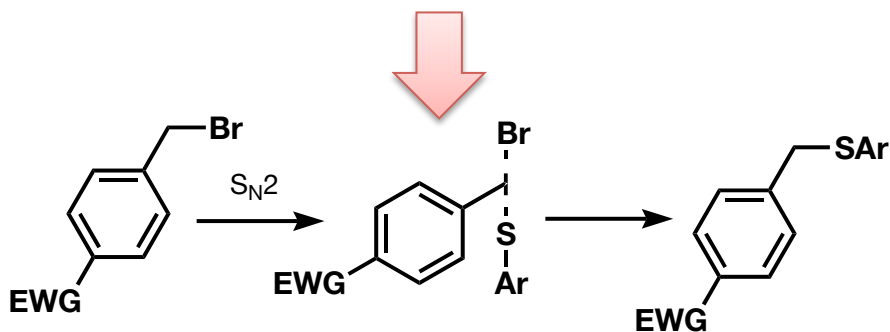
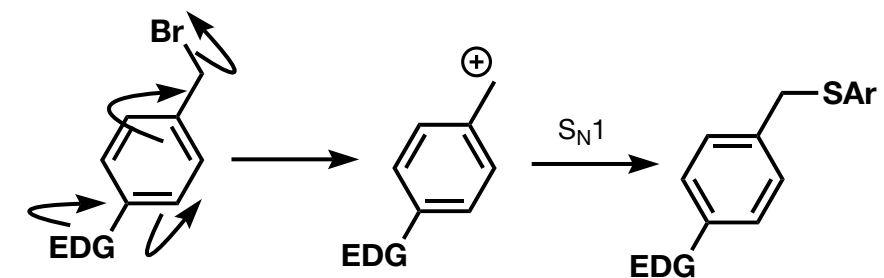


Substrate like
TS

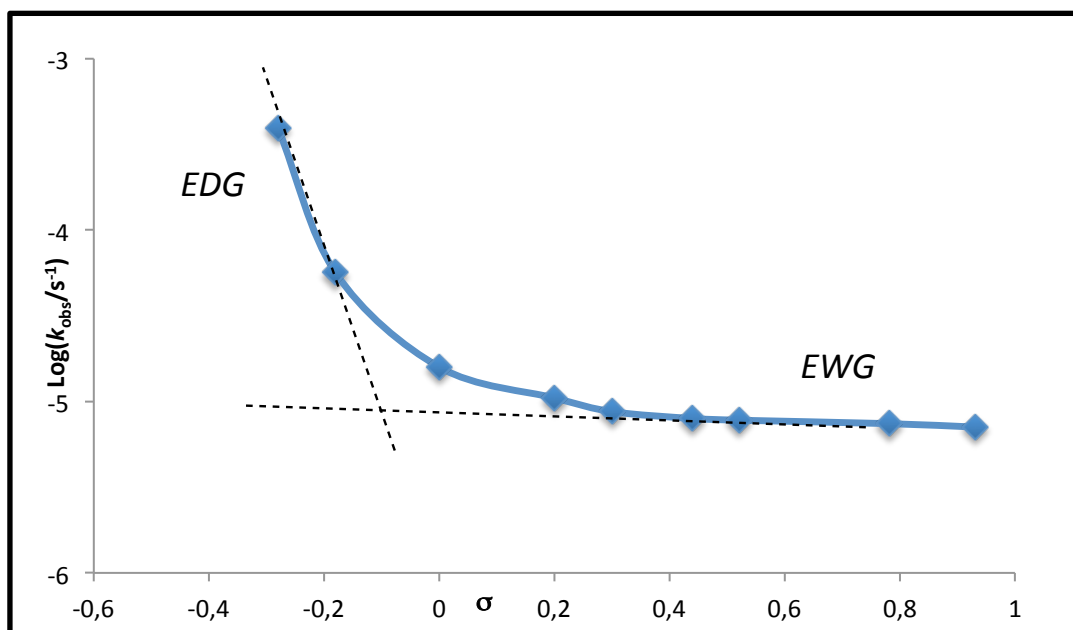
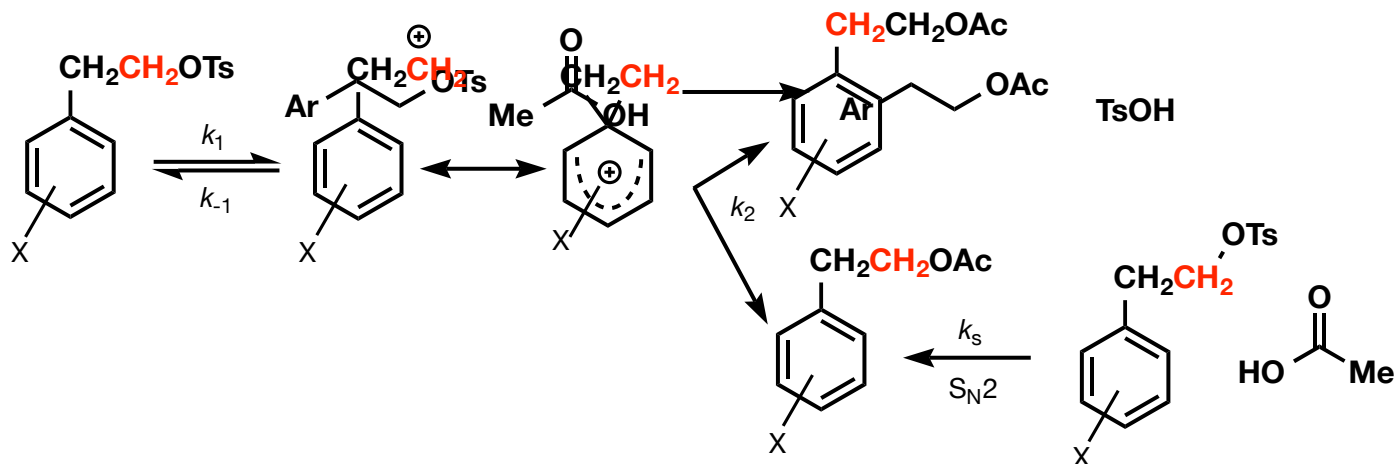


Product like
TS

Mechanism changes



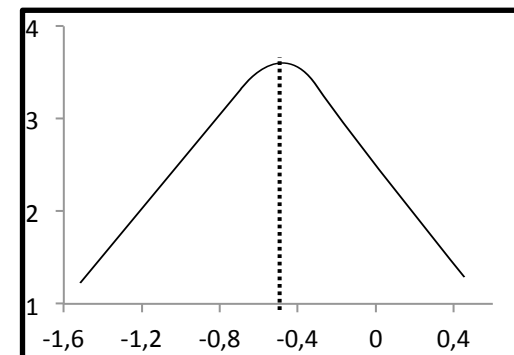
Elucidation of Reaction Mechanisms



- *EWG support S_N2 mechanism since cations can not be stabilized*
- *EDG promote the S_N1 mechanism*
- *No Elimination product due to "internal return"*

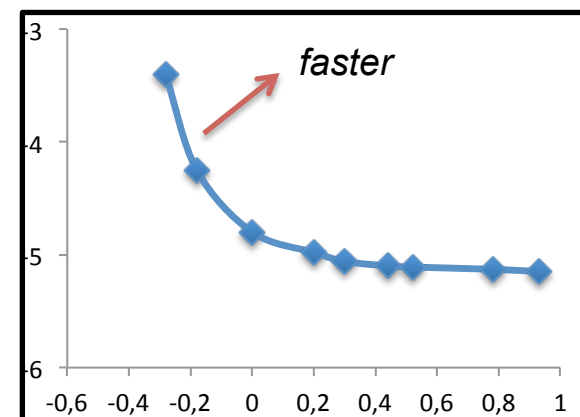
Concave downwards:

- *Indicator for change in rate determining step*
 - *Mechanism is not influenced*



Concave upwards:

- *Indicator for change in mechanism*
 - *The new pathway must be faster than the original, otherwise the original pathway stays dominant*
 - *The faster pathway causes an upward curving deviation*



Thank you for your attention