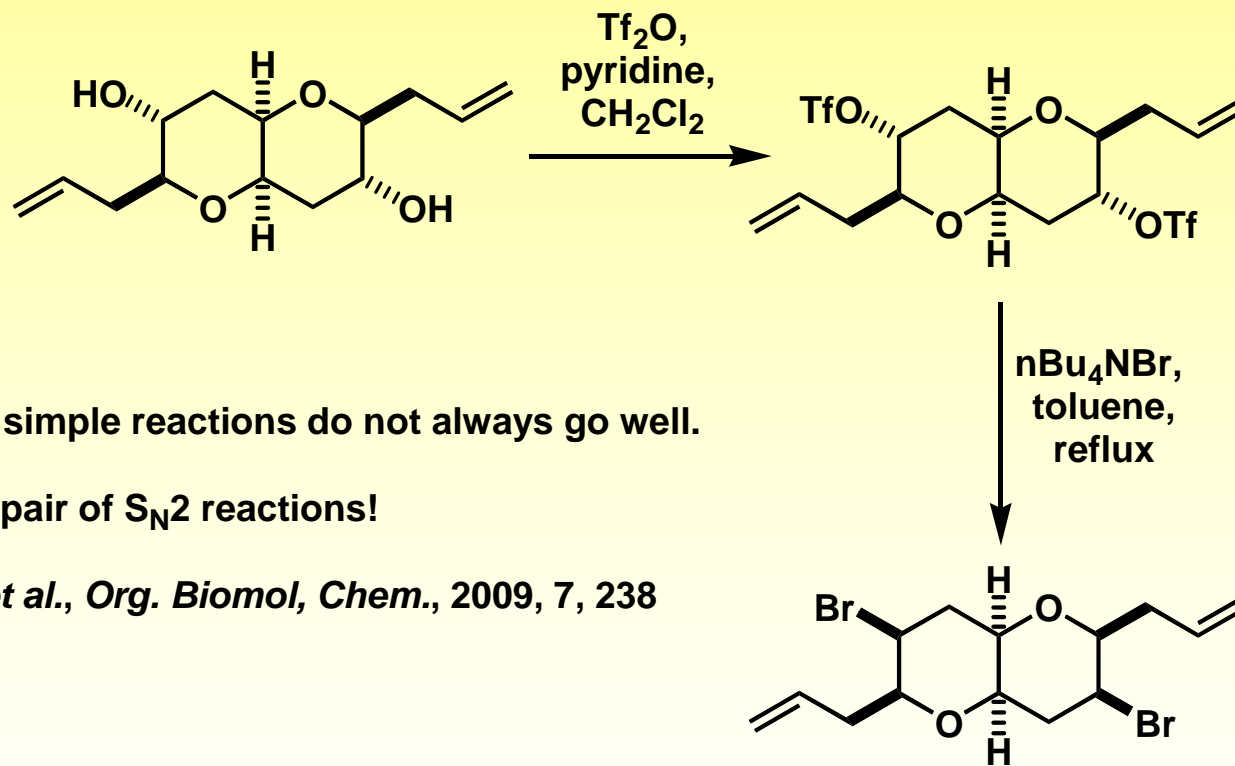


Introduction to Kinetics I

Contents

- Rate expressions
- Single-step reactions
- Transition state theory
- Transition state molecularity
- Two-step reactions
- Rate determining steps
- Integrating simple rate expressions
- Changes in R.D.S.

Substitution reactions



Even seemingly simple reactions do not always go well.

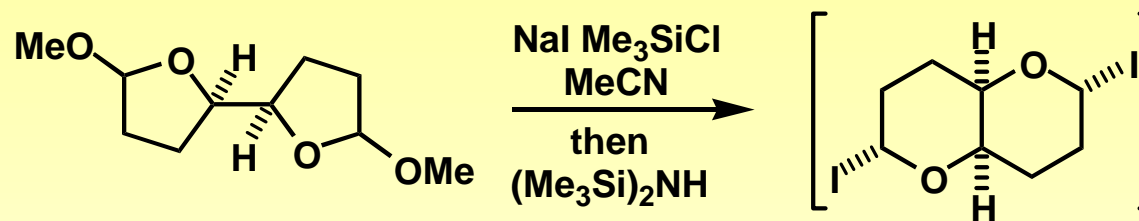
But not an easy pair of $\text{S}_{\text{N}}2$ reactions!

See Sheldrake *et al.*, *Org. Biomol. Chem.*, 2009, 7, 238

19 % over 2 steps

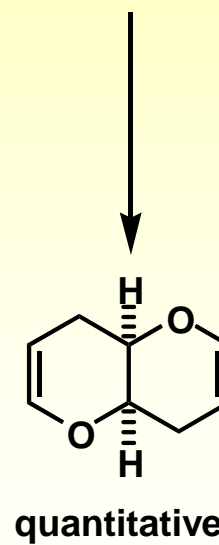
(8 other methods failed!)

Substitution reactions

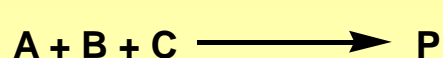


But other more complicated reactions go very well!

See Sheldrake *et al.*, *Org. Biomol. Chem.*, 2009, 7, 238



Reaction orders and rate laws



What is the mechanism?
Not just curly arrows but timing!

Rate of a reaction is defined as $\frac{d[P]}{dt}$ where

$$\frac{d[P]}{dt} = k [A]^a [B]^b [C]^c$$

where a, b and c are the ORDERS of the reaction with respect to the concentrations of A, B and C. k is a constant.

Remember

- a) a, b or c can be zero.
- b) orders for simple processes are often integers.

$$\frac{d[P]}{dt} = k [A]$$

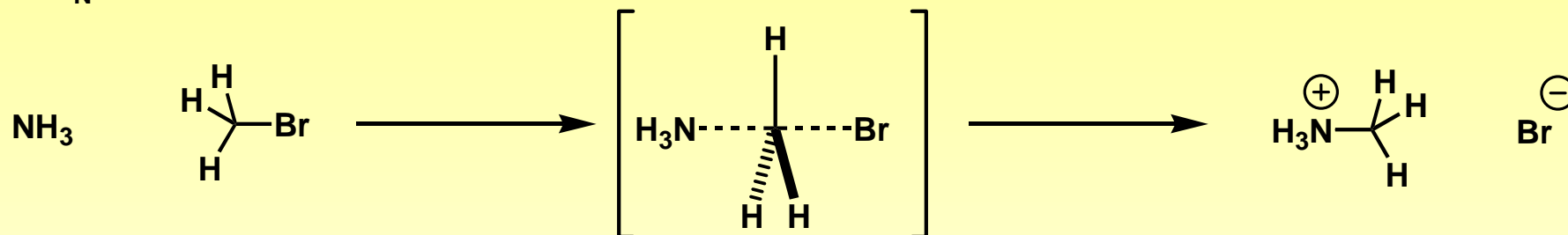
Simple unimolecular kinetics

$$\frac{d[P]}{dt} = k [A]^2 \text{ or } k [A] [B]$$

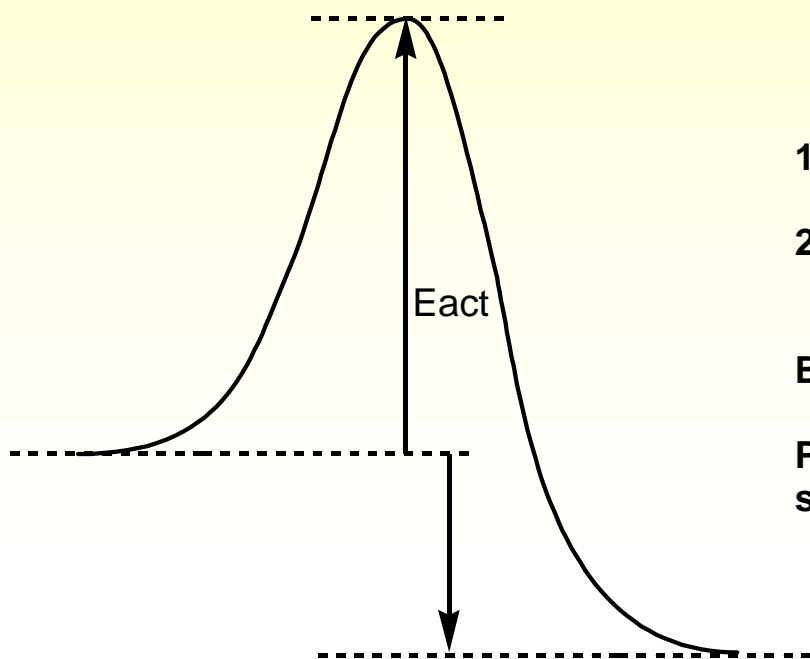
Simple bimolecular kinetics

What do we want to know?

The S_N2 reaction:



Transition state -
an energy maximum point along the reaction path



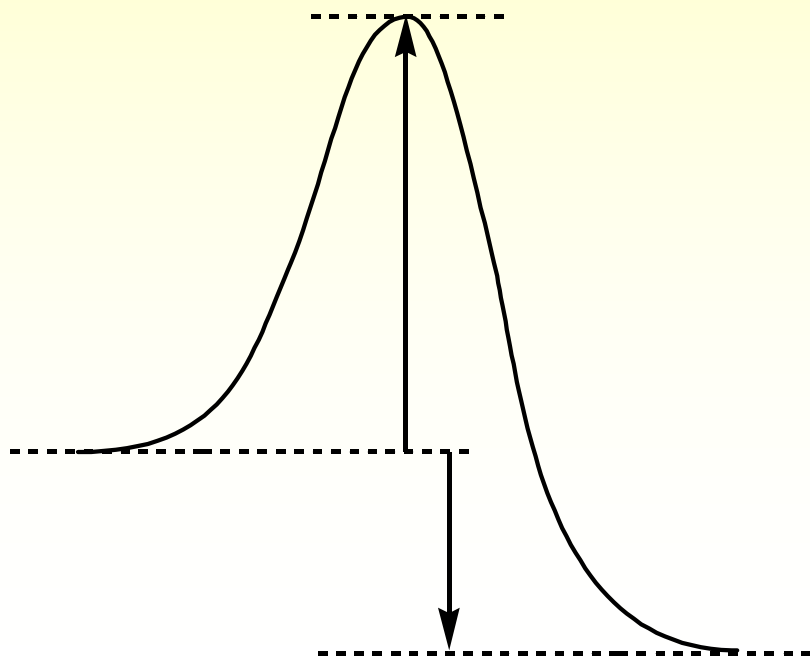
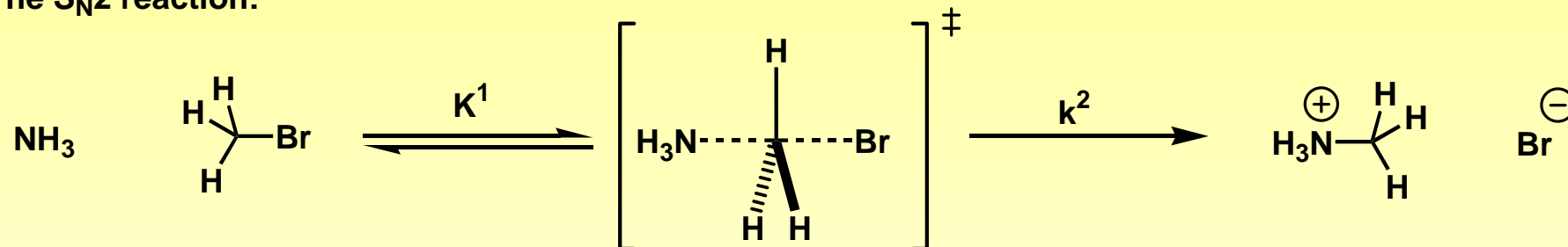
- 1) What is the structure of the transition state?
- 2) What is the energy of the transition state?

BIG problem:

Population of the transition state is effectively zero so we have to use indirect methods to study it.

What does TS theory say?

The S_N2 reaction:



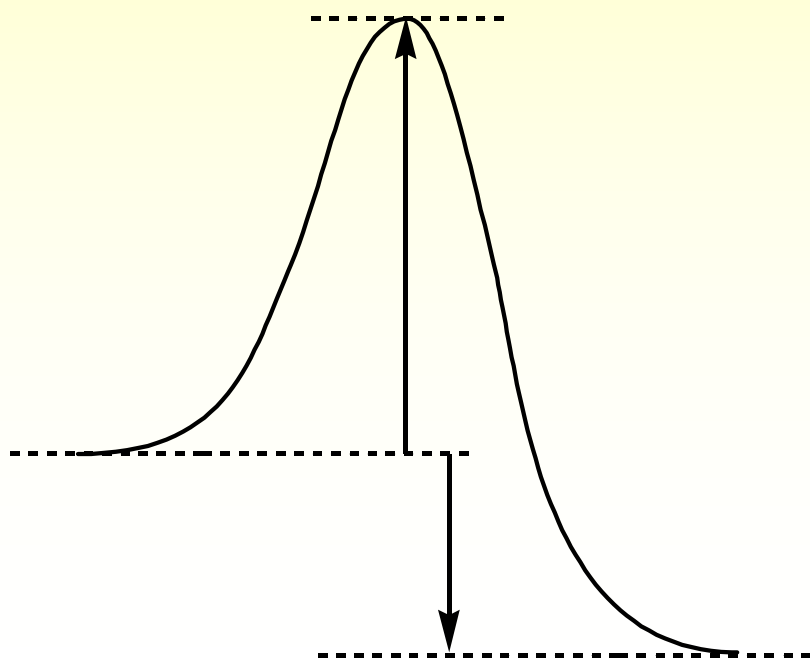
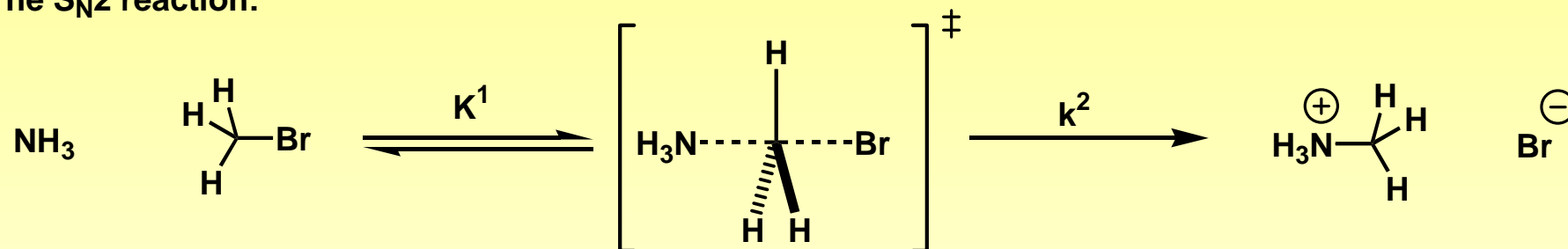
Some assumptions:

- 1) The reaction is defined as a two-step process
- 2) Starting materials are in equilibrium with the TS
- 3) the rate of the "second step" is defined by statistical mechanics:

$$k^2 = \frac{k_B T}{h}$$

What does TS theory say?

The S_N2 reaction:



given that $\frac{d[\text{prod}]}{dt} = k^2 [\text{T.S.}]$

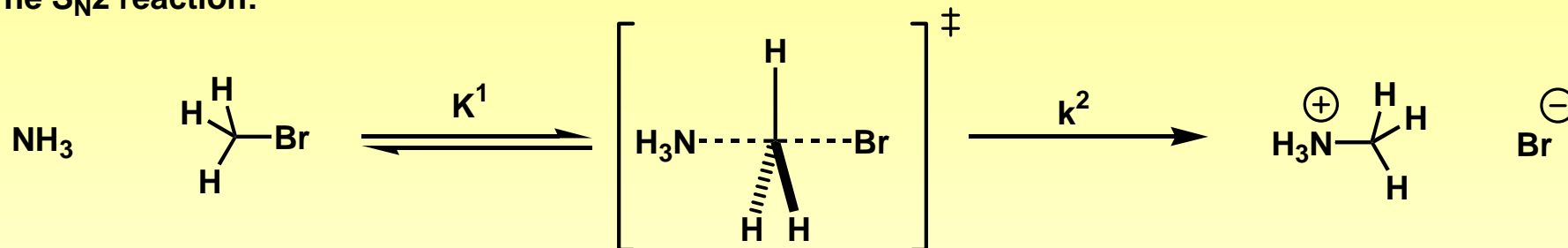
and $K^1 = \frac{[\text{T.S.}]}{[\text{NH}_3][\text{CH}_3\text{Br}]}$

$$[\text{T.S.}] = K^1 [\text{NH}_3][\text{CH}_3\text{Br}]$$

$$\frac{d[\text{prod}]}{dt} = k^2 K^1 [\text{NH}_3][\text{CH}_3\text{Br}]$$

What does TS theory say?

The S_N2 reaction:



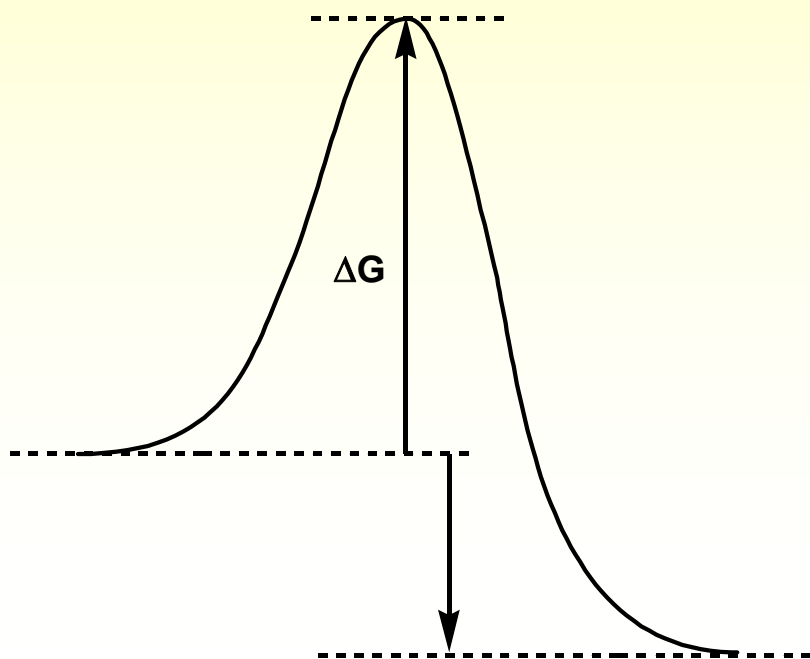
$$\frac{d[\text{prod}]}{dt} = k^2 K^1 [\text{NH}_3] [\text{CH}_3\text{Br}]$$

$$[\text{T.S.}] = K^1 [\text{NH}_3] [\text{CH}_3\text{Br}]$$

$$\Delta G = -RT \ln K^1$$

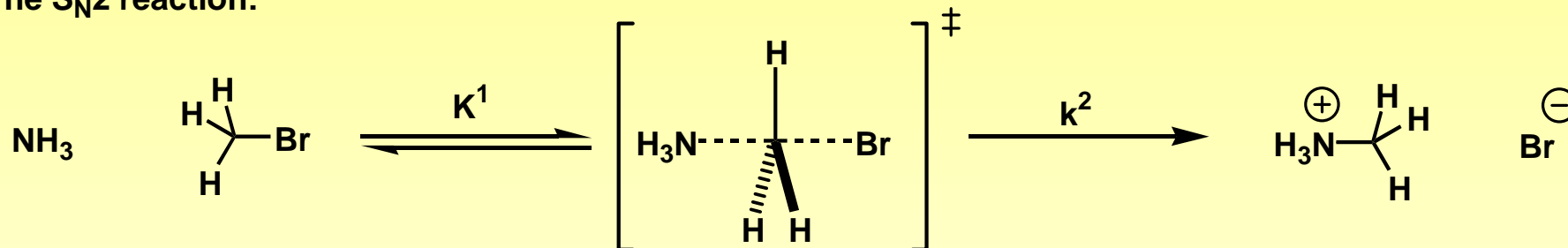
Therefore we know

- 1) Which (and how many) starting materials are needed to make the T.S.
- 2) How much higher in energy is the TS than the starting materials.



What does TS theory say?

The S_N2 reaction:



We know

1) Which (and how many) starting materials are needed to make the T.S. of the rate determining step.

Therefore, we know what concentrations to adjust to make the reaction faster.

2) How much higher in energy is the T.S. than the starting materials.

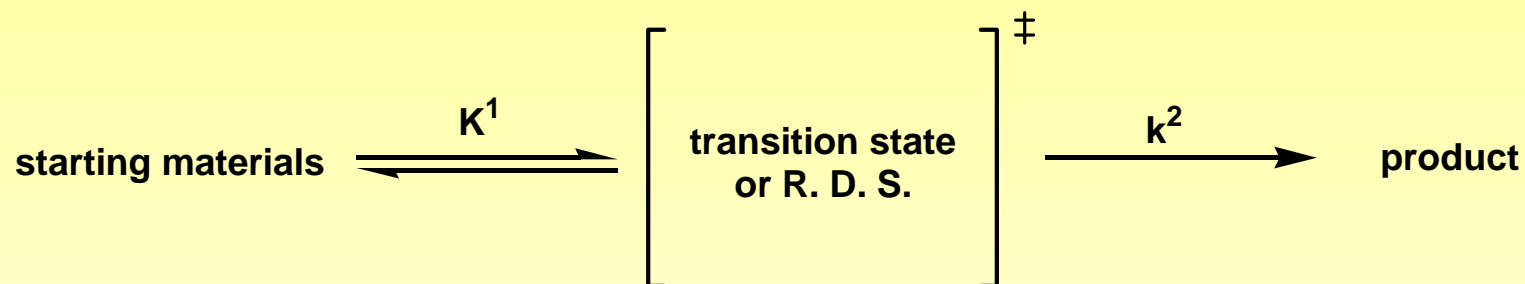
Therefore we have some initial ideas about the structure of the T.S.

BUT

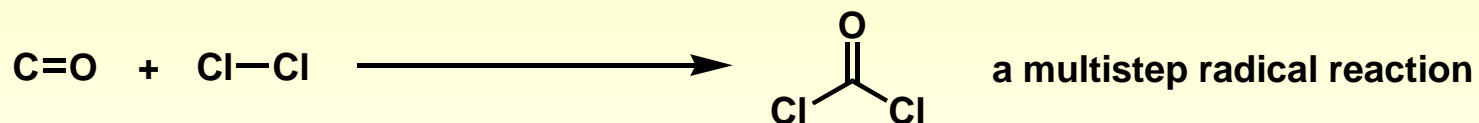
3) What about the making and breaking of bonds?

There are some methods useful for working out the difference in BONDING between the starting materials and the T.S. e.g. kinetic isotope effects and free energy relationships. These measure how broken or formed a bond is.

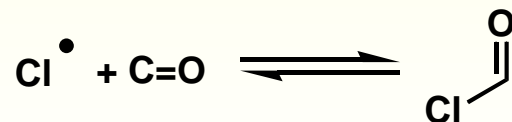
Reaction orders and the molecularity of the R.D.S.



Reaction orders tell us which (and how many) starting materials are needed to make the T.S. of the R.D.S.



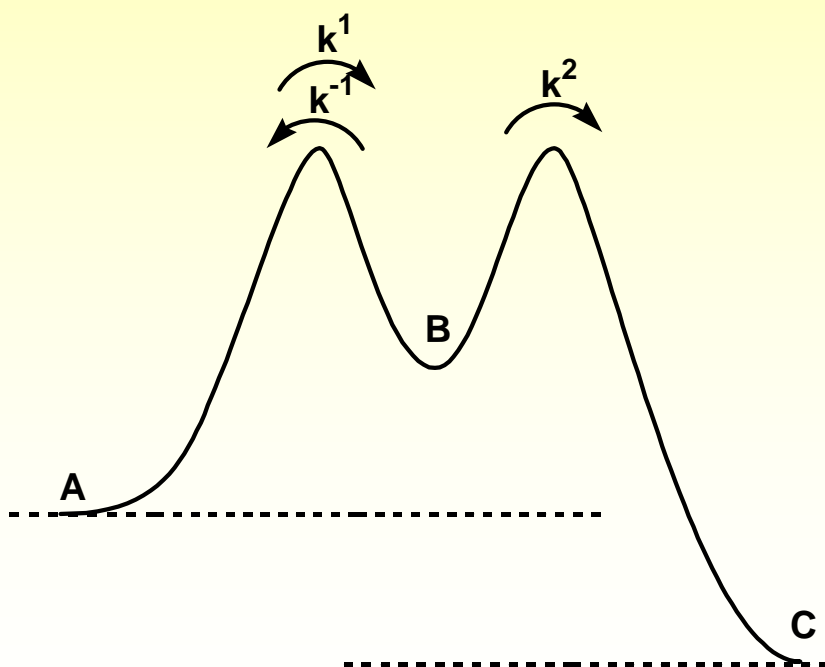
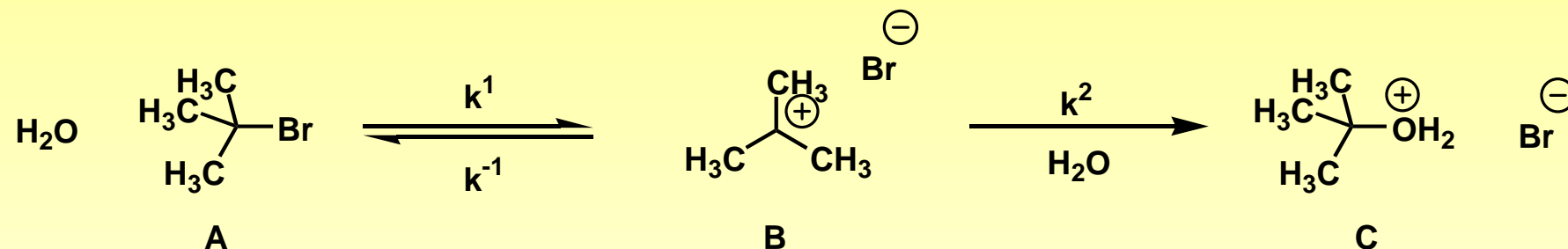
A possible mechanism



from experiment $\frac{d[\text{COCl}_2]}{dt} = k [\text{CO}] [\text{Cl}_2]^{1.5}$

This tells us that in the T.S. of the R.D.S. there is one CO molecule and 1.5 Cl_2 molecules.

Stepwise reactions



Can we predict the rate expression for a two step process?

Let us assume that [B] is v low during the reaction, and that it reacts as fast as it is made.

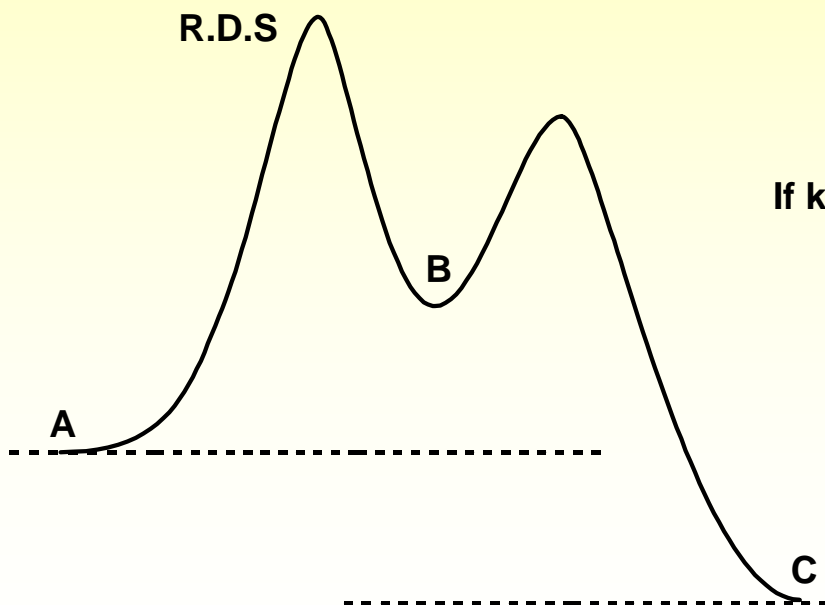
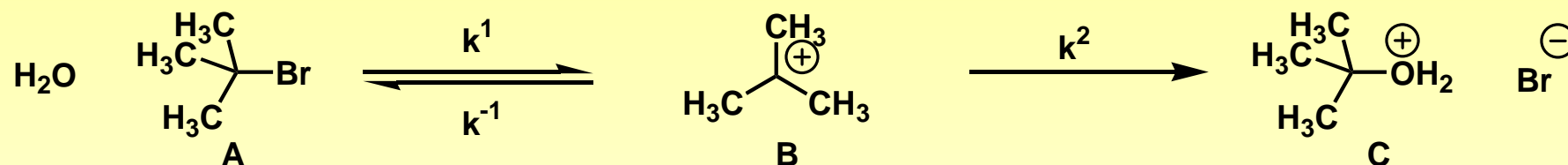
$$\frac{d[\text{B}]}{dt} = 0$$

$$\frac{d[\text{B}]}{dt} = k^1[\text{A}] - k^{-1}[\text{B}][\text{Br}^-] - k^2[\text{B}][\text{H}_2\text{O}] = 0$$

$$[\text{B}] = \frac{k^1[\text{A}]}{k^{-1}[\text{Br}^-] + k^2[\text{H}_2\text{O}]}$$

$$\frac{d[\text{C}]}{dt} = k^2[\text{B}][\text{H}_2\text{O}] = \frac{k^1 k^2 [\text{H}_2\text{O}][\text{A}]}{k^{-1}[\text{Br}^-] + k^2[\text{H}_2\text{O}]}$$

First step is R.D.S.



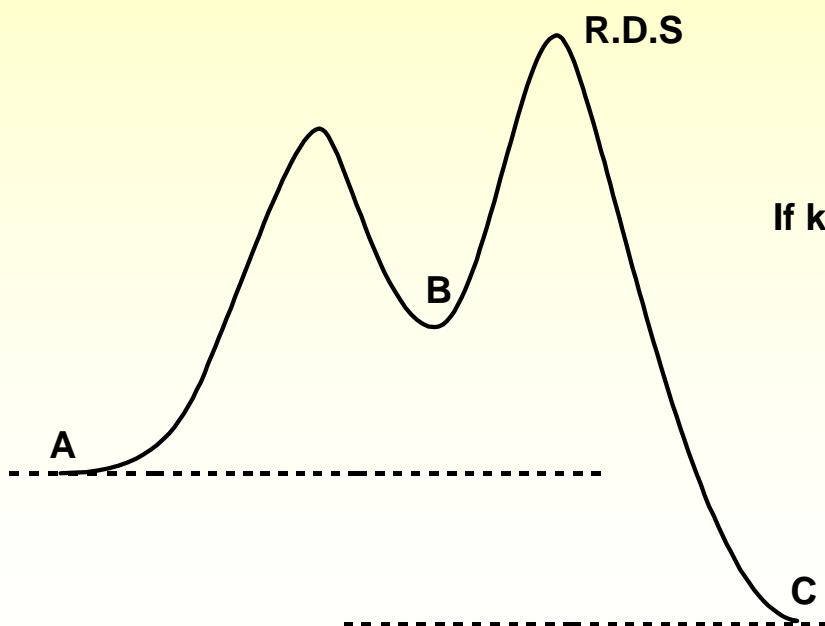
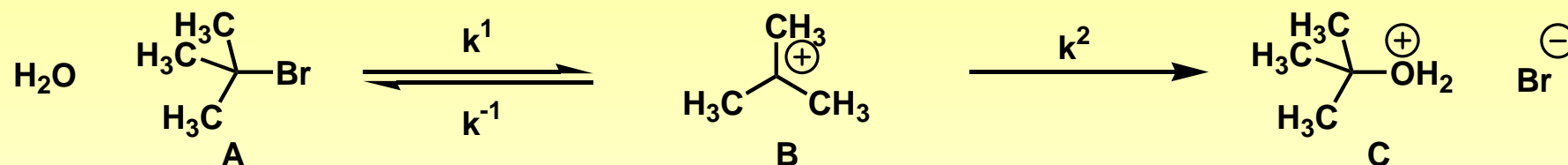
global rate $\frac{d[\text{C}]}{dt} = \frac{k^1 k^2 [\text{H}_2\text{O}][\text{A}]}{k^{-1}[\text{Br}^-] + k^2[\text{H}_2\text{O}]}$

If $k^2[\text{H}_2\text{O}] \gg k^{-1}[\text{Br}^-]$

$$\frac{d[\text{C}]}{dt} = \frac{k^1 k^2 [\text{H}_2\text{O}][\text{A}]}{k^2[\text{H}_2\text{O}]} = k^1[\text{A}]$$

The $\text{S}_{\text{N}}1$ reaction !

Second step is R.D.S.



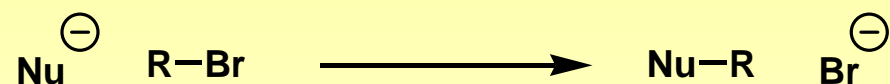
global rate $\frac{d[\text{C}]}{dt} = \frac{k^1 k^2 [\text{H}_2\text{O}][\text{A}]}{k^{-1} [\text{Br}^-] + k^2 [\text{H}_2\text{O}]}$

If $k^{-1} [\text{Br}^-] \gg k^2 [\text{H}_2\text{O}]$

$$\frac{d[\text{C}]}{dt} = \frac{k^1 k^2 [\text{H}_2\text{O}][\text{A}]}{k^{-1} [\text{Br}^-]}$$

The $\text{S}_{\text{N}}1$ reaction but with inhibition by bromide. If you add more bromide rate falls. The common ion effect

Various types of S_N reaction



1) A bimolecular S_N2 reaction

$$\frac{d[\text{NuR}]}{dt} = k [\text{Nu}^{\ominus}][\text{RBr}]$$

2) A unimolecular S_N1 reaction

$$\frac{d[\text{NuR}]}{dt} = k [\text{RBr}]$$

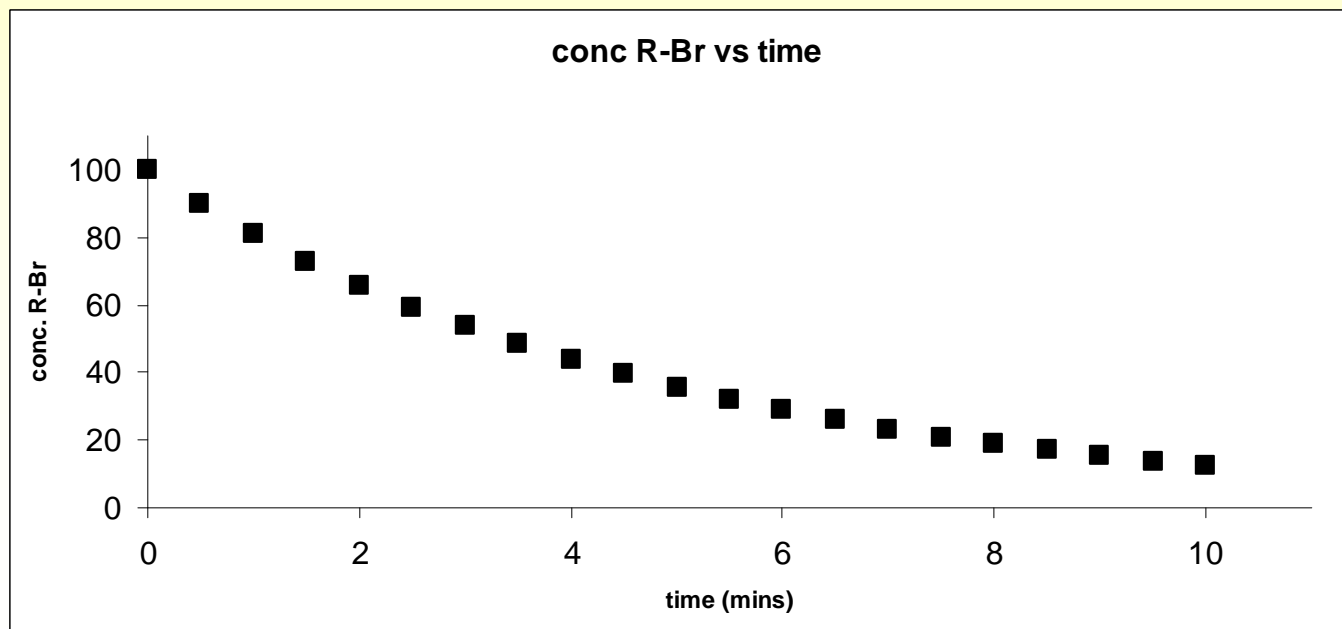
3) A complex S_N reaction with inverse order kinetics

$$\frac{d[\text{NuR}]}{dt} = \frac{k^1 k^2 [\text{Nu}^{\ominus}][\text{RBr}]}{k^{-1}[\text{Br}^{\ominus}]}$$

How does this relate to experiment?



Data from sample reaction 1:



First order kinetics



$$\frac{d[\text{RBr}]}{dt} = -k [\text{RBr}]$$

$$\int_{[\text{RBr}]_0}^{[\text{RBr}]_t} \frac{d[\text{RBr}]}{[\text{R-Br}]} = -k \int_0^t dt$$

$$\ln[\text{RBr}]_t - \ln[\text{RBr}]_0 = -kt$$

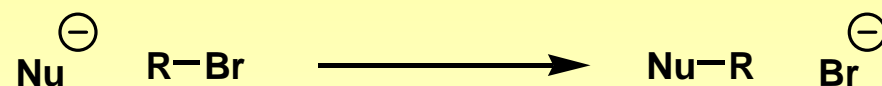
$$\ln[\text{RBr}]_t = -kt + \ln[\text{RBr}]_0$$

A straight line

or

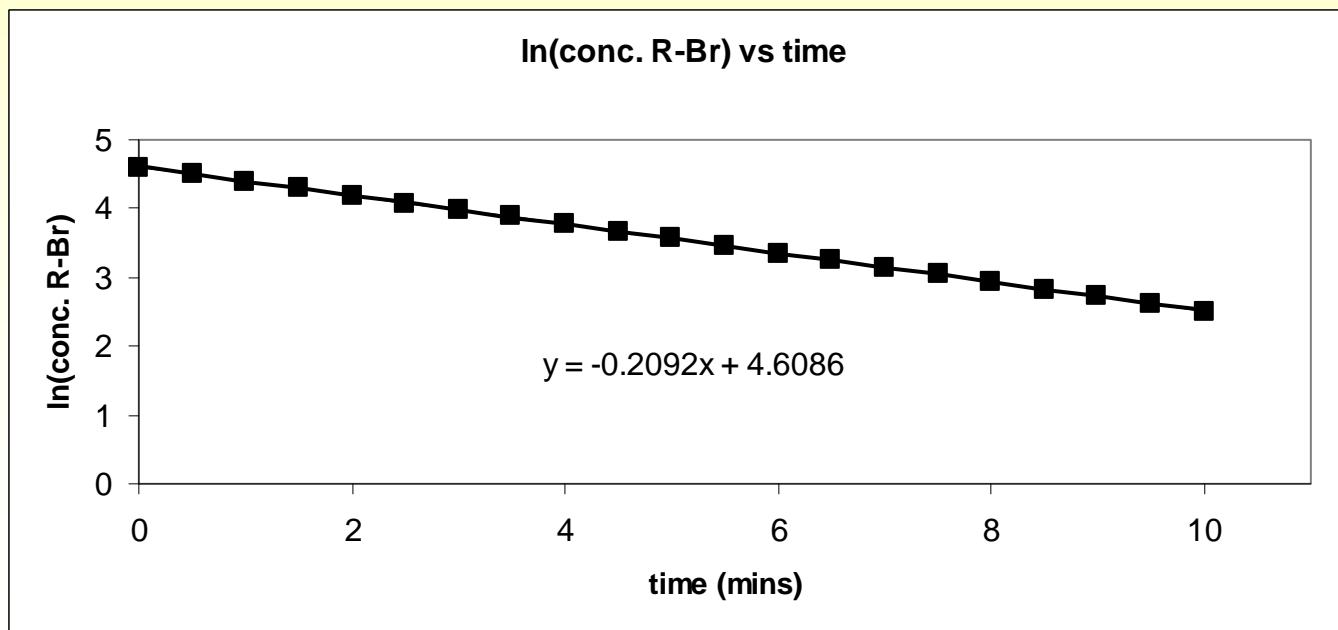
$$[\text{RBr}]_t = [\text{RBr}]_0 e^{(-kt)}$$

How does this relate to experiment?



$$\ln[\text{RBr}]_t = -kt + \ln[\text{RBr}]_0$$

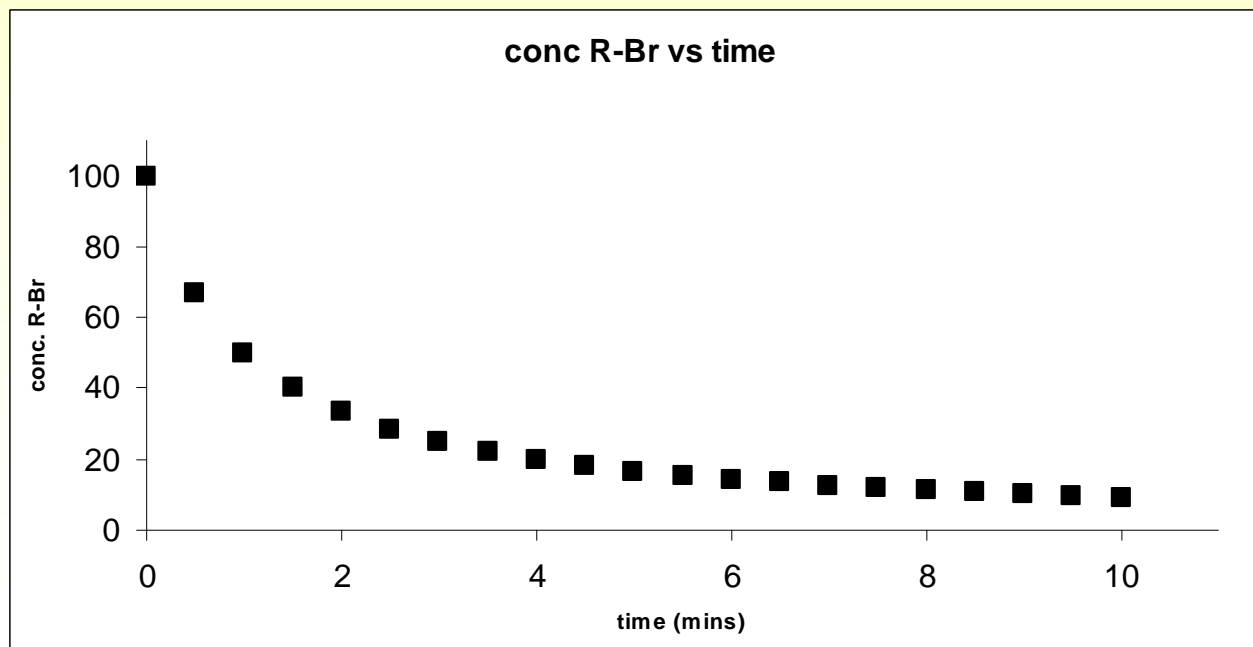
A first order reaction. Could be $\text{S}_{\text{N}}1$ or $\text{S}_{\text{N}}2$ if $[\text{Nu}^{\ominus}]$ is constant.



How does this relate to experiment?



Data from sample reaction 2:



Second order kinetics



$$\frac{d[\text{RBr}]}{dt} = -k [\text{RBr}] [\text{Nu}^{\ominus}]$$

if $[\text{RBr}] = [\text{Nu}^{\ominus}]$

$$\frac{d[\text{RBr}]}{dt} = -k [\text{RBr}]^2$$

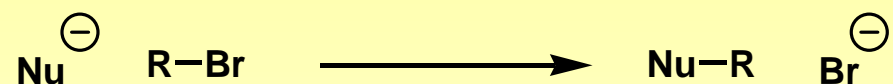
$$\int x^n dx = \frac{1}{n+1} x^{n+1}$$

$$\int_{[\text{RBr}]_0}^{[\text{RBr}]_t} \frac{d[\text{RBr}]}{[\text{R-Br}]^2} = -k \int_0^t dt$$

$$\frac{1}{[\text{RBr}]_t} = kt + \frac{1}{[\text{RBr}]_0}$$

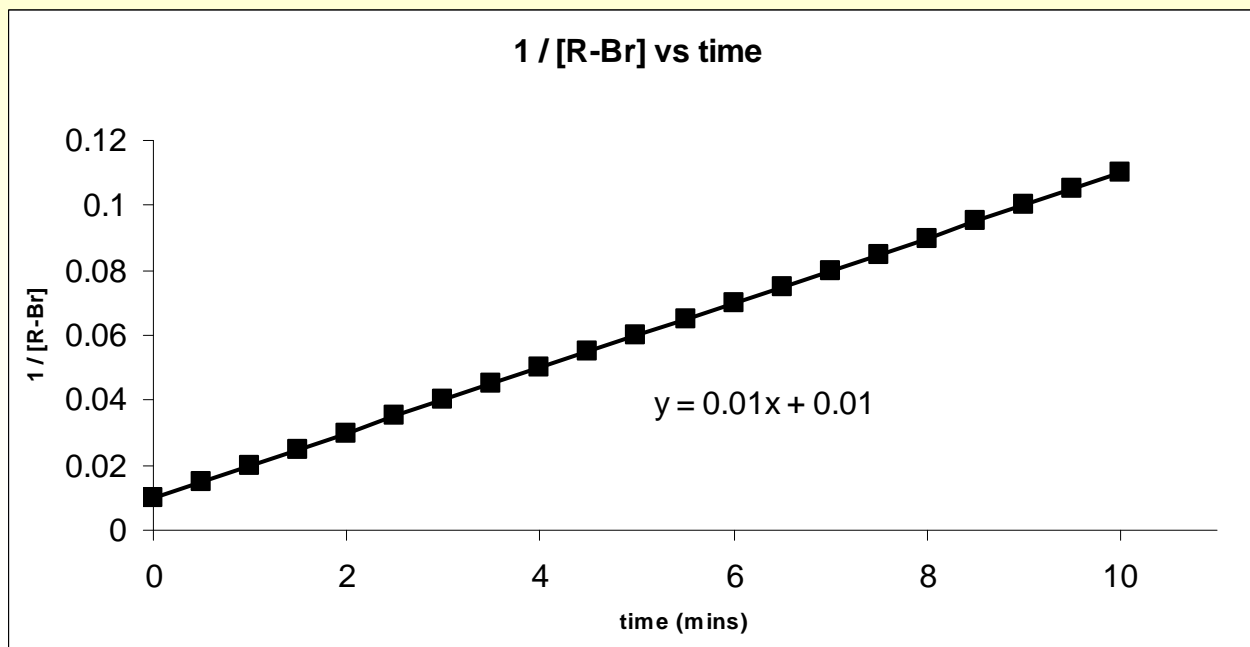
A straight line

How does this relate to experiment?

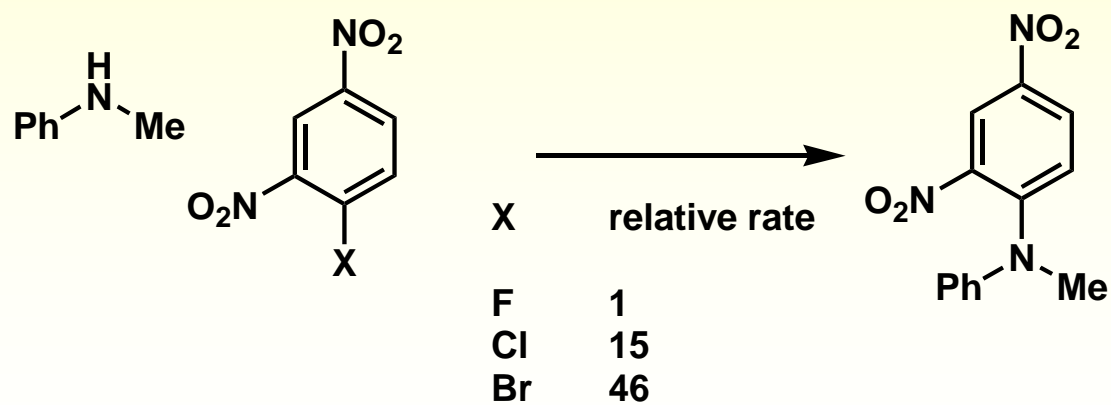
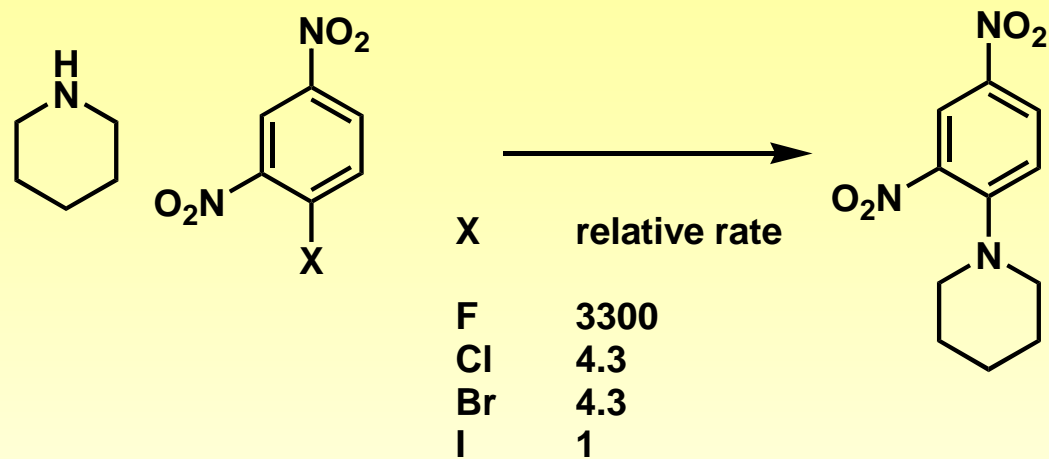


$$\frac{1}{[\text{RBr}]_t} = kt + \frac{1}{[\text{RBr}]_0}$$

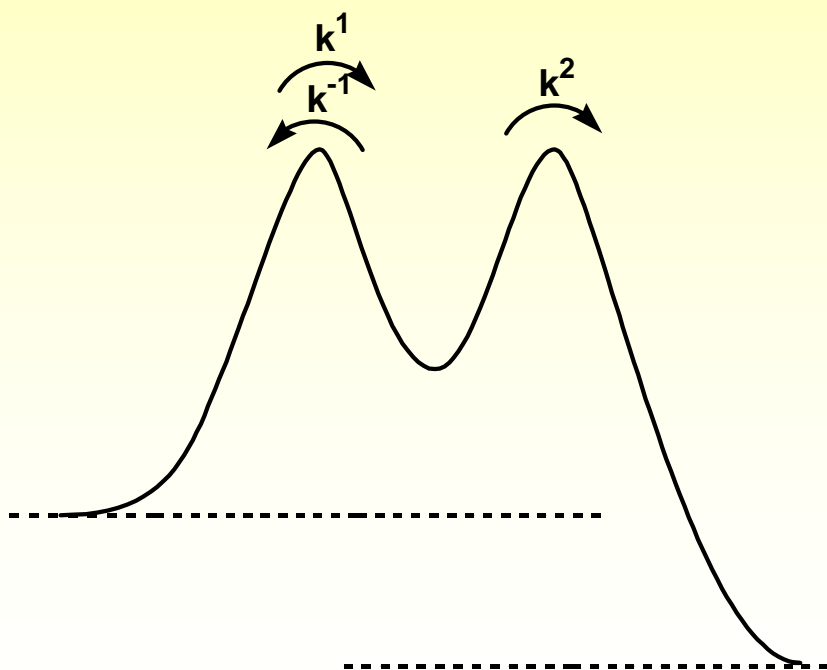
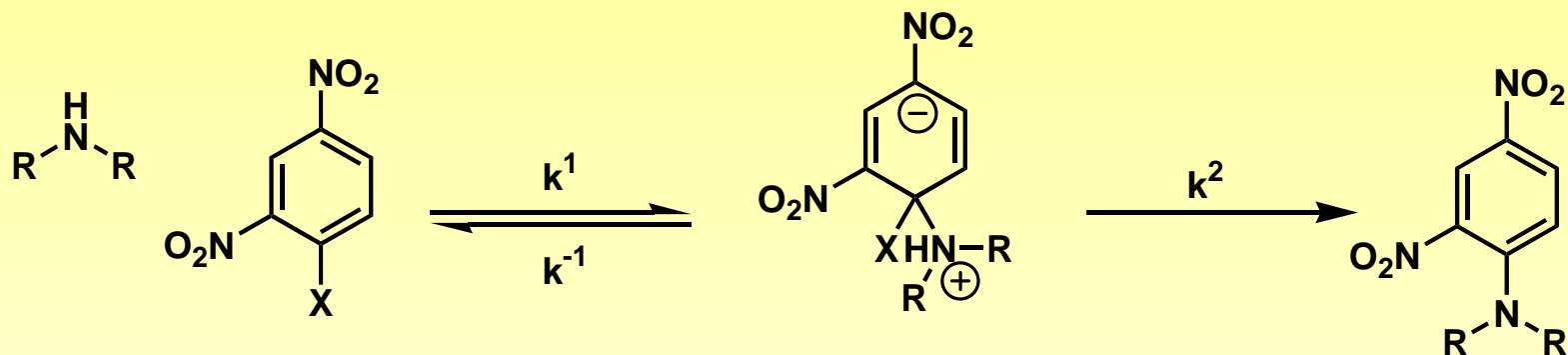
Overall second order kinetics so possibly $\text{S}_{\text{N}}2$



Stepwise S_NAr reactions

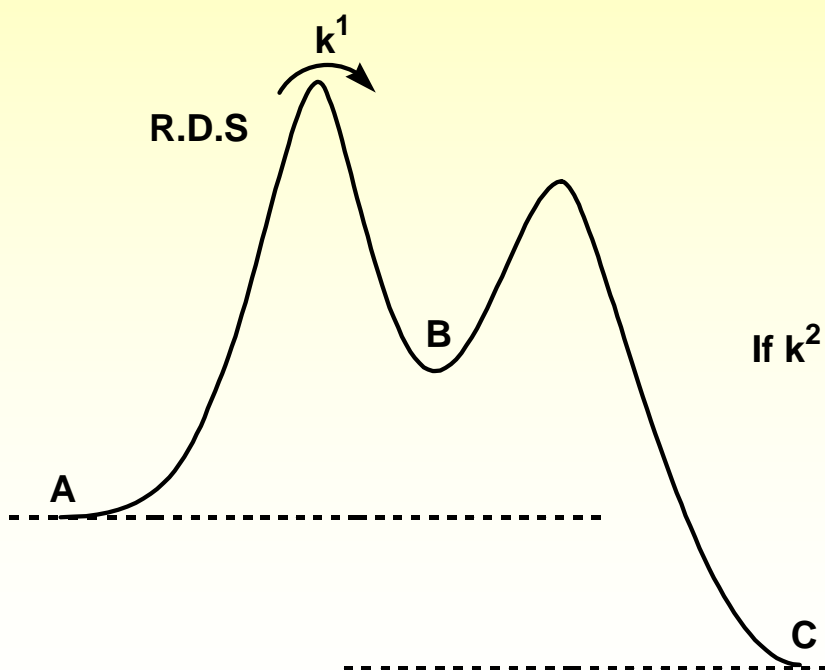
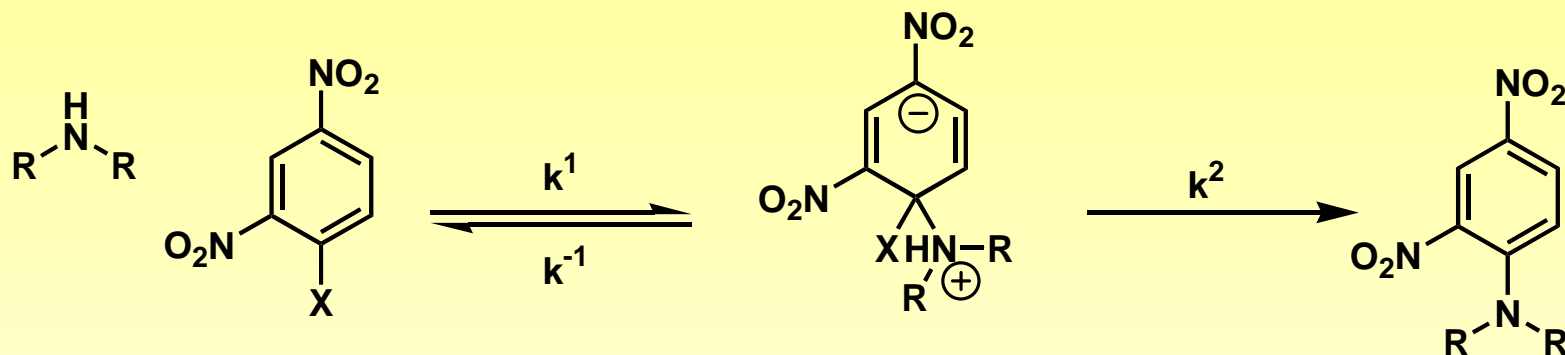


Stepwise reaction kinetics



$$\frac{d[\text{prod}]}{dt} = \frac{k^1 k^2 [\text{pip}][\text{ArX}]}{k^{-1} + k^2}$$

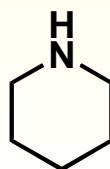
Stepwise reaction kinetics



$$\frac{d[\text{prod}]}{dt} = \frac{k^1 k^2 [R_2NH][ArX]}{k^{-1} + k^2}$$

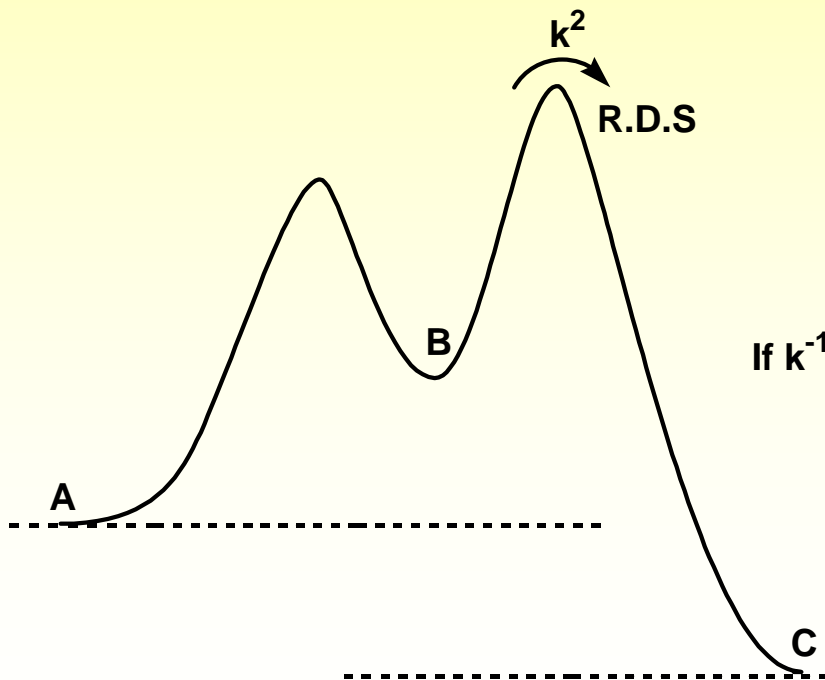
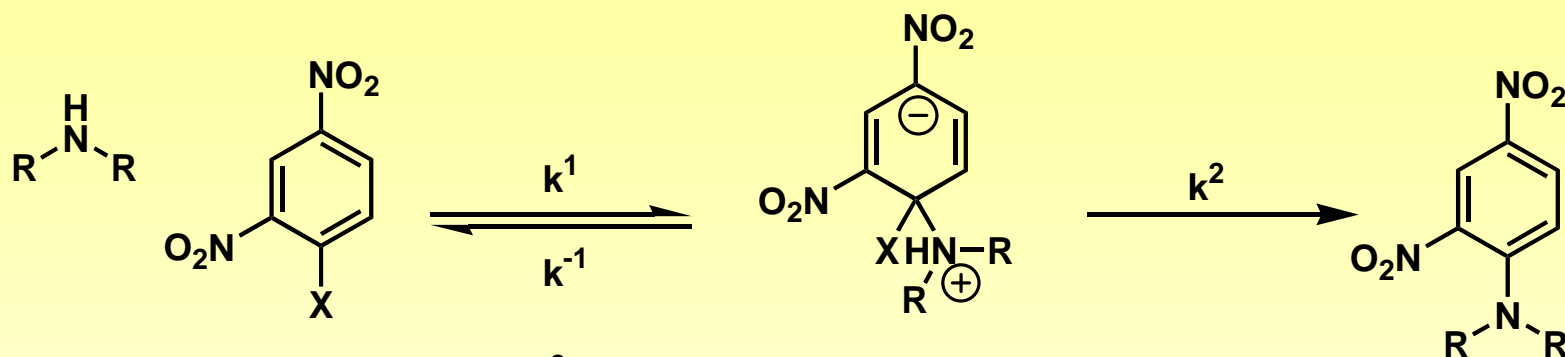
If $k^2 \gg k^{-1}$

$$\frac{d[\text{prod}]}{dt} = \frac{k^1 k^2 [R_2NH][ArX]}{k^2} = k^1 [R_2NH][ArX]$$



is a relatively poor leaving group, so k^1 dominates, so ArF is fastest

Stepwise reaction kinetics



$$\frac{d[\text{prod}]}{dt} = \frac{k^1 k^2 [R_2NH][ArX]}{k^{-1} + k^2}$$

If $k^{-1} \gg k^2$

$$\frac{d[\text{prod}]}{dt} = \frac{k^1 k^2 [R_2NH][ArX]}{k^{-1}}$$

$\text{Ph}-\text{N}(\text{H})\text{Me}$ is a relatively good leaving group, so k^2 dominates, so ArBr is fastest