

# Elementary collision and transport processes in plasma

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# Summary

Collision types

Cross section

Collision details

Transport processes

# Electron collisions I

▶ **elastic collision**



▶ excitation



▶ de-excitation (superelastic collision)



▶ ionization by electron collision (electron has to be energetic)



▶ dissociative ionization

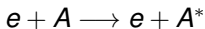


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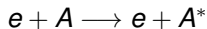


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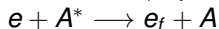
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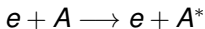


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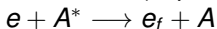
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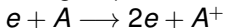
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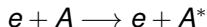


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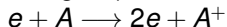
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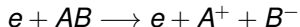
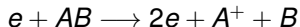
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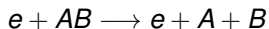


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# Electron collisions II

- ▶ dissociation



- ▶ dissociative attachment



- ▶ radiative attachment



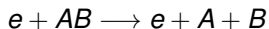
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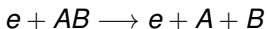


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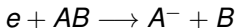


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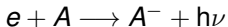
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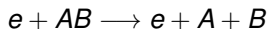


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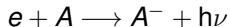
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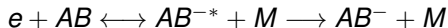
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- ▶ de-excitation



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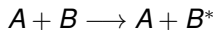


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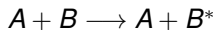


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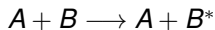


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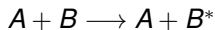


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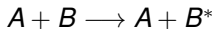


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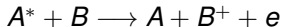
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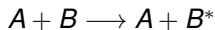


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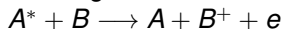
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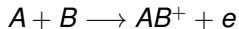
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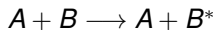


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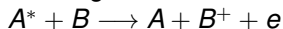
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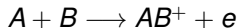
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# Ion collisions

▶ elastic collision



▶ excitation



▶ ionization



▶ resonant charge transfer



▶ positive-negative ion recombination



▶ dissociative recombination



▶ recombination in ternary collision



▶ ion-molecule reaction

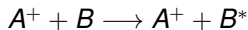


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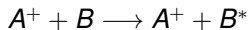


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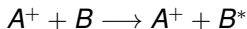


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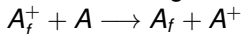
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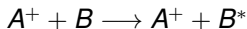


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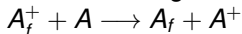
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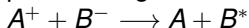
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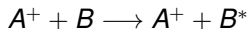


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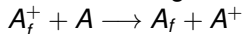
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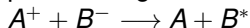
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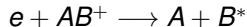
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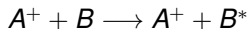


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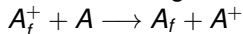
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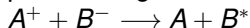
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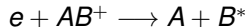
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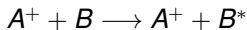


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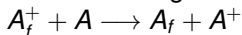
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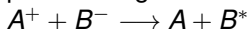
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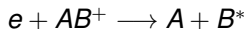
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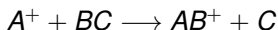
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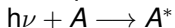


- ▶ ion-molecule reaction



# Photon collisions

- ▶ absorption



- ▶ emission



- ▶ stimulated emission



- ▶ photo-ionization

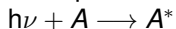


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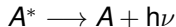


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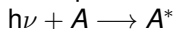


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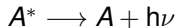


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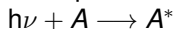


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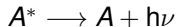


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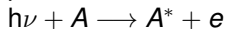
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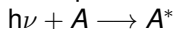


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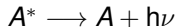


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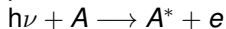
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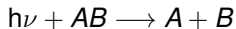
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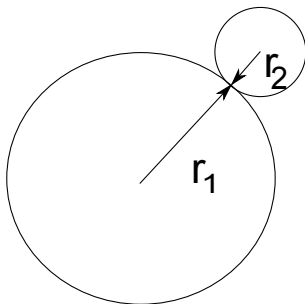
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# Cross Section I

- ▶ (microscopic) cross section —  $\sigma$  [ $\text{m}^2$ ]
- ▶ expresses the likelihood of interaction of incoming particle with target particle
- ▶ when particles in a beam are thrown against a foil made of a certain substance, the cross section  $\sigma$  is a hypothetical area measure around the target particles of the substance (usually its atoms) that represents a surface
- ▶ if a particle of the beam crosses this surface, there will be some kind of interaction
- ▶ for hard sphere model  $\sigma = \pi \cdot R^2$ , where  $R = r_1 + r_2$



# Cross Section II

## Differential cross section

- ▶  $\frac{d\sigma}{d\Omega}, \sigma_d$  [ $\text{m}^2\text{srad}^{-1}$ ]
- ▶ expresses the likelihood of scattering of particles under specific angle

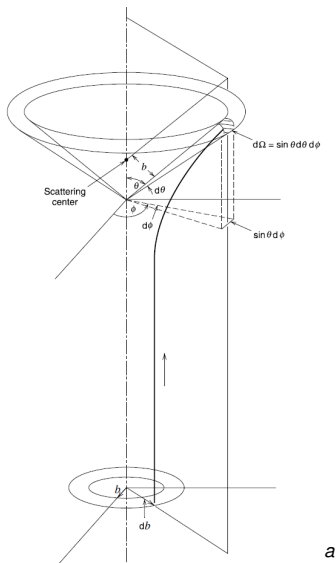
Macroscopic cross section  $\Sigma = n\sigma$

Mean free path (the distance over which the uncollided flux decreases to 1/e of its initial value)  $\lambda = \frac{1}{n\sigma}$

Collision frequency  $\nu = n\sigma v$

# Differential cross section

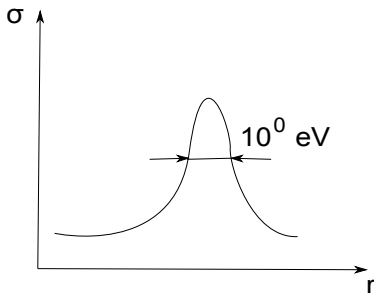
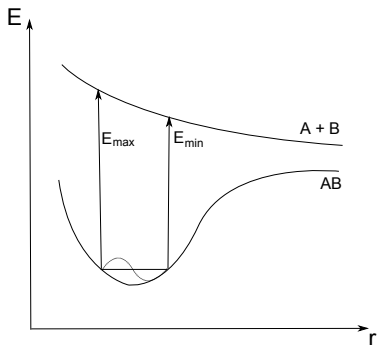
- ▶  $\sigma = \int \frac{d\sigma}{d\Omega} d\Omega$
- ▶  $\sigma^{(k)} = 2\pi \int_0^\pi (1 - \cos \theta)^k \frac{d\sigma(\theta)}{d\Omega} \sin \theta d\theta$
- ▶  $\sigma^{(1)}$  ... cross section for momentum transfer  $\equiv \sigma_m$
- ▶  $\sigma^{(2)}$  ... cross section for energy transfer  $\equiv \sigma_E$



<sup>a</sup>Liebermann, M.A., Lichtenberg, A.J.  
*Principles of Plasma Discharges and  
Materials Processing*

# Dissociation

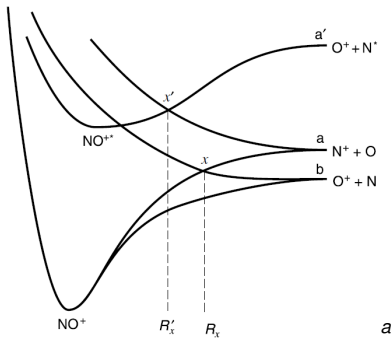
- ▶ Franck-Condon principle
- ▶ interaction time  
 $\sim 10^{-16} - 10^{-15} \text{ s}$
- ▶ vibration period  
 $\sim 10^{-14} - 10^{-13} \text{ s}$
- ▶ radiation time  
 $\sim 10^{-9} - 10^{-8} \text{ s}$



- ▶ rotational states  $\sim 0.01$  eV
- ▶ vibrational states  $\sim 0.1$  eV
- ▶ electronic states  $\sim 1$  eV
- ▶ an electron can transfer only  $\frac{2m}{M} E_e$ , which is low energy – higher vibrational states through some unstable  $AB^*$

# Resonant and nonresonant charge transfer

- ▶ resonant charge transfer  
 $A_f^+ + A \longrightarrow A_f + A^+$
- ▶ nonresonant charge transfer  
 $A^+ + B \longrightarrow A + B^+$
- ▶ separated  $N^+ + O$  level is 0.92 eV higher than the  $N + O^+$
- ▶ at the crossing separation  $R_x$  a change of state corresponding to a transfer of charge can occur

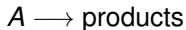


<sup>a</sup>Liebermann, M.A., Lichtenberg, A.J.  
*Principles of Plasma Discharges and  
 Materials Processing*

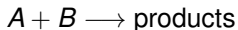
# Elementary chemical reaction

3 types:

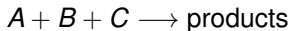
1. unimolecular



2. bimolecular



3. termolecular



reaction rate  $R = \frac{1}{\alpha_j} \frac{dn_j}{dt}$   $\alpha_j$  ... stoichiometric coefficient,  
 $n_j$  ... volume density [ $\text{m}^{-3}$ ]

# Rate constants

- ▶  $A \longrightarrow$  products

$$R = -\frac{dn_A}{dt} = k_1 n_a$$

$k_1$  ... first order rate constant [ $k_1$ ] =  $s^{-1}$

- ▶  $A + A \longrightarrow$  products

$$R = -\frac{1}{2} \frac{dn_A}{dt} = k_2 n_a^2$$

$k_2$  ... second order rate constant [ $k_2$ ] =  $cm^3 s^{-1}$

- ▶  $A + B \longrightarrow$  products

$$R = -\frac{dn_A}{dt} = -\frac{dn_B}{dt} = k_2 n_a n_b$$

- ▶  $A + A + A \longrightarrow$  products

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$k_3$  ... third order rate constant [ $k_3$ ] =  $cm^6 s^{-1}$

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# Free diffusion

- ▶ diffusion without electric fields
- ▶ Fick's law  $\vec{j} = -D\nabla n$
- ▶  $\vec{j}$  ... flux,  $D$  ... diffusion constant,  $n$  ... density
- ▶  $-\frac{dN}{dt} = -\int_{\vec{S}} \vec{j} d\vec{S}$
- ▶  $\frac{\partial n}{\partial t} + \text{div}\vec{j} = 0$
- ▶  $\frac{\partial n}{\partial t} = -\nabla \cdot (D\nabla n) = D\Delta n$
  
- ▶ self-diffusion constant  $D = \frac{1}{3} v_a \lambda [m^2 s^{-1}]$ , where  $v_a$  is the mean free path and  $\lambda$  is the collision frequency
- ▶  $D \sim \frac{T^{\frac{3}{2}}}{d^2 p \sqrt{m_0}}$

- ▶ mutual diffusion

- ▶  $D_{ab} = D_{ba} = D_a \frac{n_a}{n_a + n_b} + D_b \frac{n_b}{n_a + n_b} [m^2 s^{-1}]$

Self-diffusion constant

gas	H <sub>2</sub>	He	H <sub>2</sub> O	N <sub>2</sub>	CO <sub>2</sub>	Hg
D[10 <sup>-4</sup> m <sup>2</sup> s <sup>-1</sup> ]	1.27	1.25	0.14	0.18	0.1	0.025

## Mutual diffusion constant

gas	$D_{ab}[10^{-4} m^2 s^{-1}]$ in air	$D_{ab}[10^{-4} m^2 s^{-1}]$ in H <sub>2</sub>
H <sub>2</sub>	0.66	1.27
He	0.57	1.25
air	0.18	1.66
CO	0.175	0.64
CO <sub>2</sub>	0.135	0.54



# Ambipolar diffusion

- ▶ in electric field; electrons and ions both taken into account
- ▶ in the steady state we make the congruence assumption that the flux of electrons and ions out of any region must be equal, such that charge does not build up
- ▶ since the electrons are lighter, and would tend to flow out faster (in an unmagnetized plasma), an electric field must spring up to maintain the local flux balance
- ▶ a few more electrons than ions initially leave the plasma region to set up a charge imbalance and consequently an electric field
- ▶  $\frac{\partial n}{\partial t} - D_a \Delta n = G - L$ , with G and L the volume source and sink
- ▶ in a weakly ionized discharge and using the Einstein relation  $D_a \approx D_i \left(1 + \frac{T_e}{T_i}\right)$
- ▶ ambipolar diffusion is tied to the slower species, in this case the ions
- ▶ in the usual case in weakly ionized plasmas, in which  $T_e \gg T_i$ , the ions and electrons both diffuse at a rate that greatly exceeds the ion free diffusion rate