EE 403/503
Introduction to Plasma Processing

The kinetic Theory of Gases

(Elestic & Inelastic Collisions)

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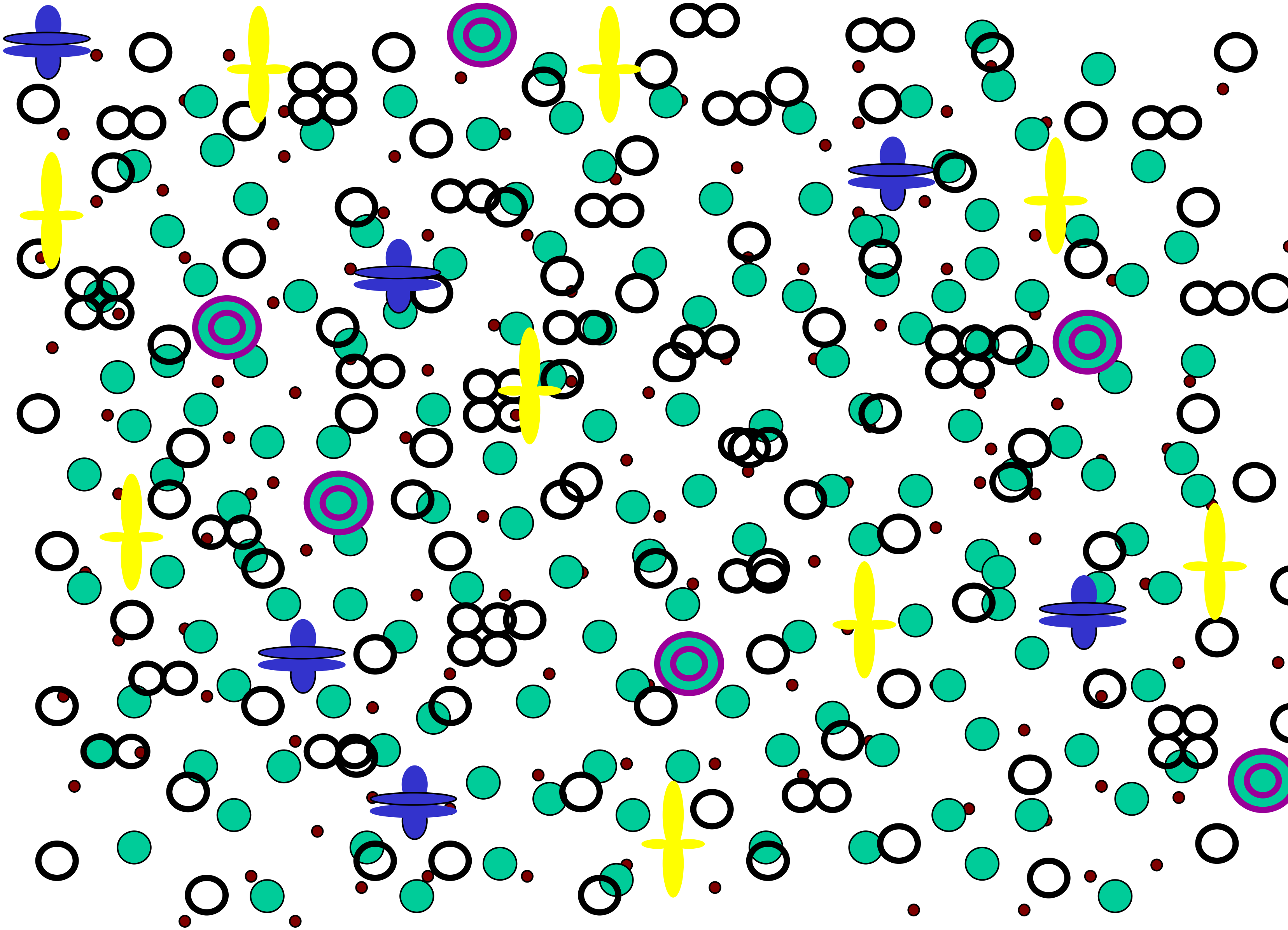
Lecture Notes on Principles of Plasma Processing

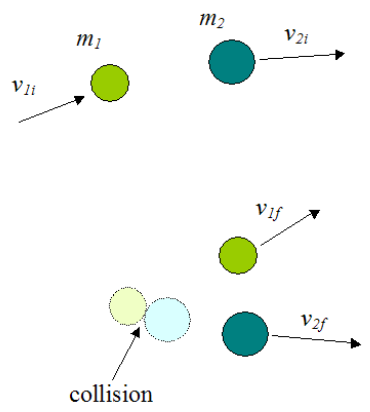
Handbook of Advanced Plasma Processing Techniques

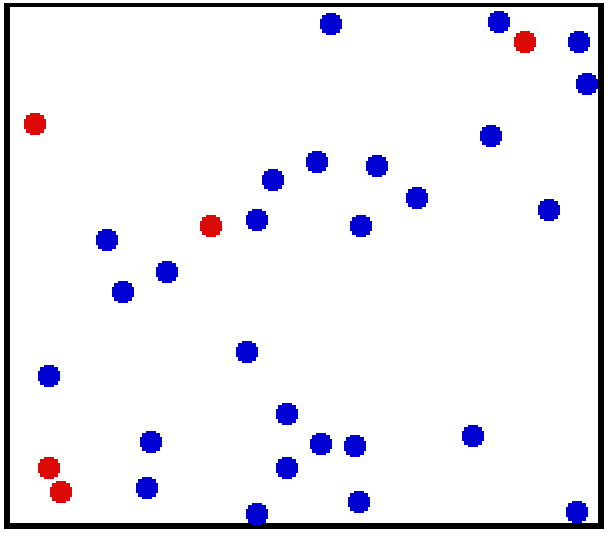


Definition

Collision means the action of bodies striking or coming together (touching). When two particle pass each other and some measurable change in their path occurs, collision has taken place

Collisions involve forces (there is a change in velocity). Collisions can be *elastic*, meaning they conserve energy and momentum, *inelastic*, meaning they conserve momentum but not energy





1- Type of Collisions

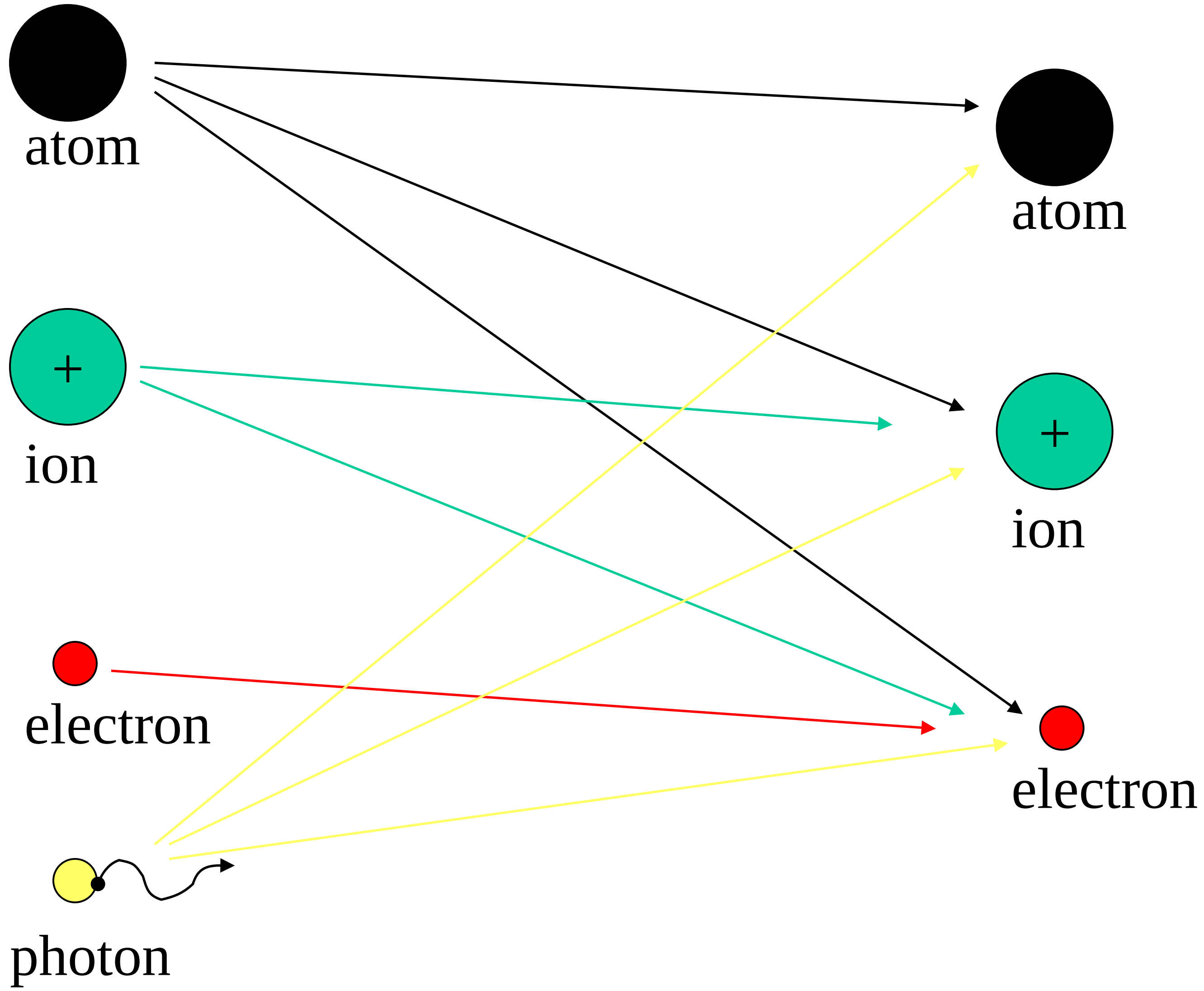
a- Elastic Collisions

b- Inelastic Collisions

2- Collision Parameters

3- A Simple Example

Binary Collisions



Major Types of Atomic Processes

(see the handout)

Particle Type	Symbol
Photon	o
Electron	e
Ground State atom or molecule	0
Electronically excited-one electron	0’
two electrons	0”
metastable state	0^m
Vibrationally excited molecules	0^v
Rotationally excited molecules	0^r
Positive ion ; singly, doubly, …	1, 2, …
Negative ion	$\overline{1}$

Examples:

$A^+ + B \rightarrow A + B^+$

10/01 Charge Transfer

$\Phi + AB \rightarrow A + B^* \rightarrow A + B + \Phi$

o(00)/00’/00o

Photo Dissociation

Principal Kinds of Collision

Electrons

$e + A \rightarrow A^{+} + 2e$	Ionization
$e + A \rightarrow A^{*} \rightarrow e + A + h\nu$	Excitation
$e + A^{*} \rightarrow 2e + A^{+}$	Penning Ionization
$e + A \rightarrow e + A$	Elastic Scattering
$e + AB \rightarrow e + A + B$	Dissociation
$e + AB \rightarrow 2e + A^{+} + B$	Dissociative Ionixation
$e + AB \rightarrow A^{-} + B$	Dissociative Attachment
$e + A^{+} + B \rightarrow A + B$	Recombination

Ions

$A^+ + B \rightarrow A + B^+$	Charge Exchange
$A^+ + B \rightarrow A^+ + B$	Elastic Scattering
$A^+ + B \rightarrow A^+ + B^+ + e$	Ionization
$A^+ + B \rightarrow A^+ + B^* \rightarrow A^+ B + \Phi$	Excitation
$A^+ + e + B \rightarrow A + B$	Recombination
$A^+ + BC \rightarrow A^+ + B + C$	Dissociation
$A + BC \rightarrow C + AB$	Chemical Reaction

Photons

$\Phi + A \rightarrow A^*$ — Photo Excitation

$\Phi + AB \rightarrow A + B$ — Photo Dissociation

$\Phi + A \rightarrow A^+ + e$ — Photo Ionization

Atoms

$A + B \rightarrow A + B$ — Elastic Scattering

$A + B \rightarrow A + B^+ + e$ — Ionization

$A + BC \rightarrow A + B + B$ — Dissociation

$A^* \rightarrow A + \Phi$ — Photo Emission

Energy [eV]

Ionization energy:

$$e + N_2 = N_2^+ + e + e \qquad 15.6$$

$$e + H_2 = H_2^+ + e + e \qquad 15.4$$

$$e + SiH_4 = SiH_4^+ + e + e \qquad 11.4$$

$$e + H = H^+ + e + e \qquad 13.6$$

Electron Affinity:

$$H^- = H + e \qquad 0.75$$

$$OH^- = OH + e \qquad 18$$

$$O_3^- = O_3 + e \qquad 2.0$$

$$O_2^- = O_2 + e \qquad 0.44$$

$$O^- = O + e \qquad 1.5$$

$$SiH_3^- = SiH_3 + e \qquad 2.7$$

Formation of multicharged negative ions is much less possible

See: "Plasma Physics and Engineering; Chapter 2 & 3; pp. 15-155

Particle Type	Symbol
Photon	o
Electron	e
Ground State atom or molecule Electronically excited-one electron two electrons metastable state Vibrationally excited molecules Rotationally excited molecules	0 0' 0" 0^m 0^v 0^r
Positive ion ; singly, doubly, …	1, 2, …
Negative ion	

Examples:

e(00)'/e0'0' Electron impact dissociation

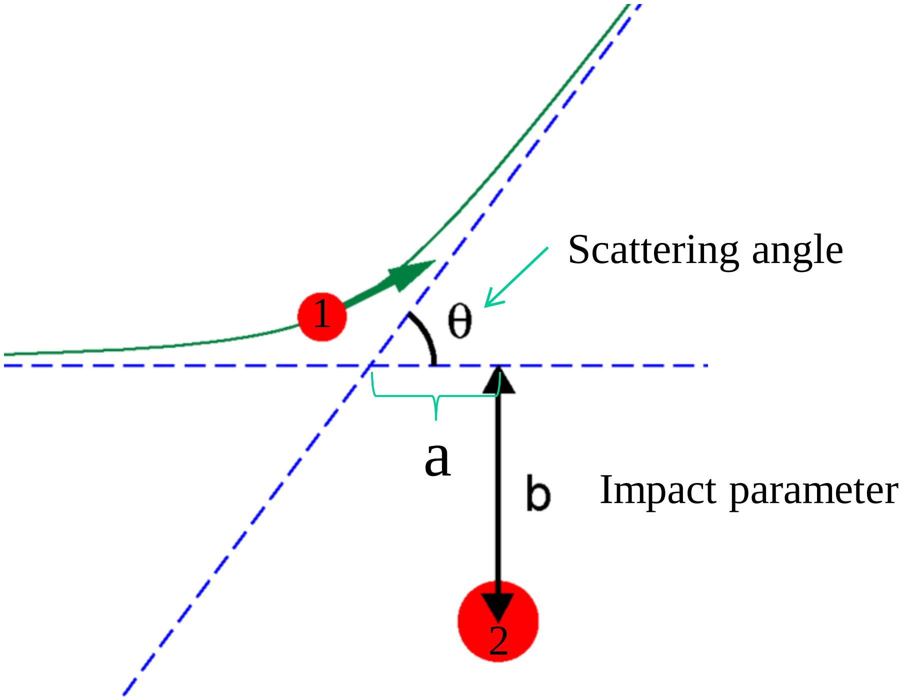
e1/e1Φ **Bremsstrahlung, or free-free emission**

$0^v0/00^v$ Vibrational excitation exchange

e(01)/ee11 **Electron impact dissociative ionization**

<u>Collision Parameters</u>

1- Impact Parameter (b):

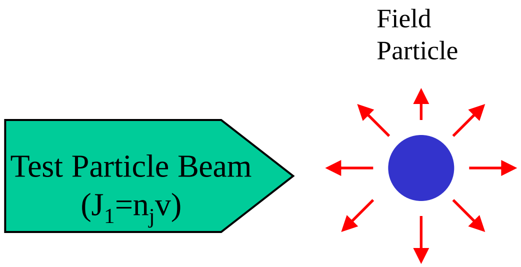


$$\theta = \pi - 2b \int_{r_{\min}}^{\infty} \frac{dr}{r^2 \sqrt{1 - (b/r)^2 - 2U/mv_{\infty}^2}}$$

$$\tan\left(\frac{\theta}{2}\right) = \frac{a}{b}$$

2- Total Collision Cross Section $Q_{12}(v)$:

$$Q_{12}(v) = \frac{\text{Number of test particles colliding with the field particles per unit time}}{\text{Flux Density } J_1}$$



$$Q_{12} = Q_{12}^{elastic} + Q_{12}^{nonelastic}$$

Elastic Collision: no changes in internal energy

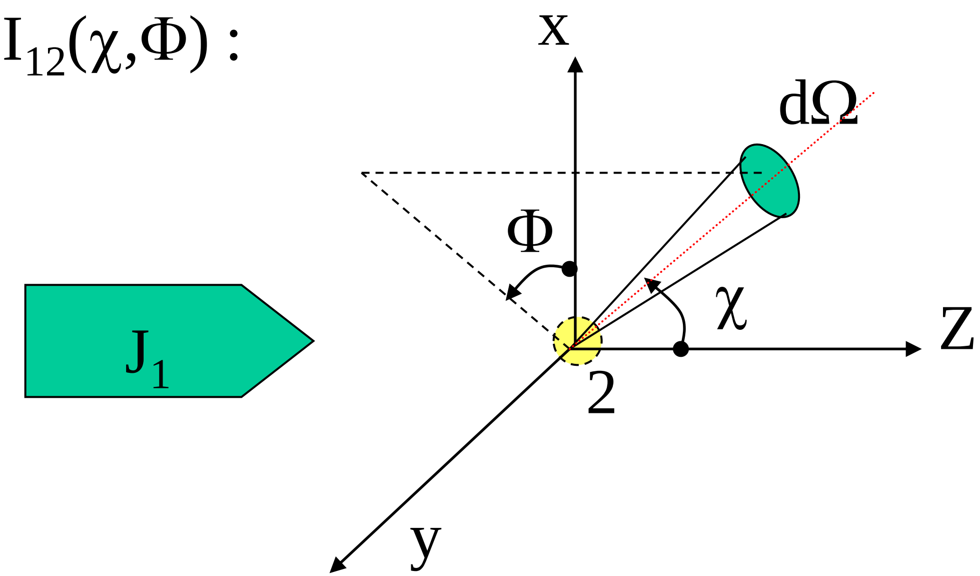
Inelastic Collision: with internal energy exchange

3- Nonelastic Collision Cross Section $Q_{12}(v)$:

$$Q_{12}^{(1\rightarrow 2)}(v) = \frac{\text{Number of test particles causing a } (1\rightarrow 2) \text{ excitation of the field particles per unit time}}{\text{Flux Density } J_1}$$

In an electron atom collision, kinetic energy of the electron needs to be above the energy of the first excited level in order to have an inelastic collision.

4- Differential Cross Sections $I_{12}(\chi,\Phi)$:

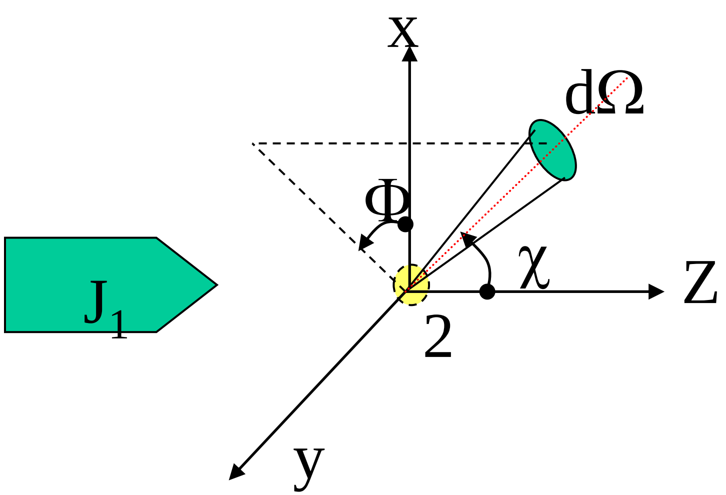


$$\mathbf{I_{12}(\chi,\Phi)\, d\Omega} = \frac{\text{Number of test particles scattered by the field particles into the solid angle } d\Omega \text{ per unit time}}{J_1}$$

$$\mathbf{Q_{12} = \int_{4\pi} I_{12}(\chi,\Phi) d\Omega}$$

Total Cross Section

5- Cross section for momentum transfer $Q_{12}^{m}(v)$:

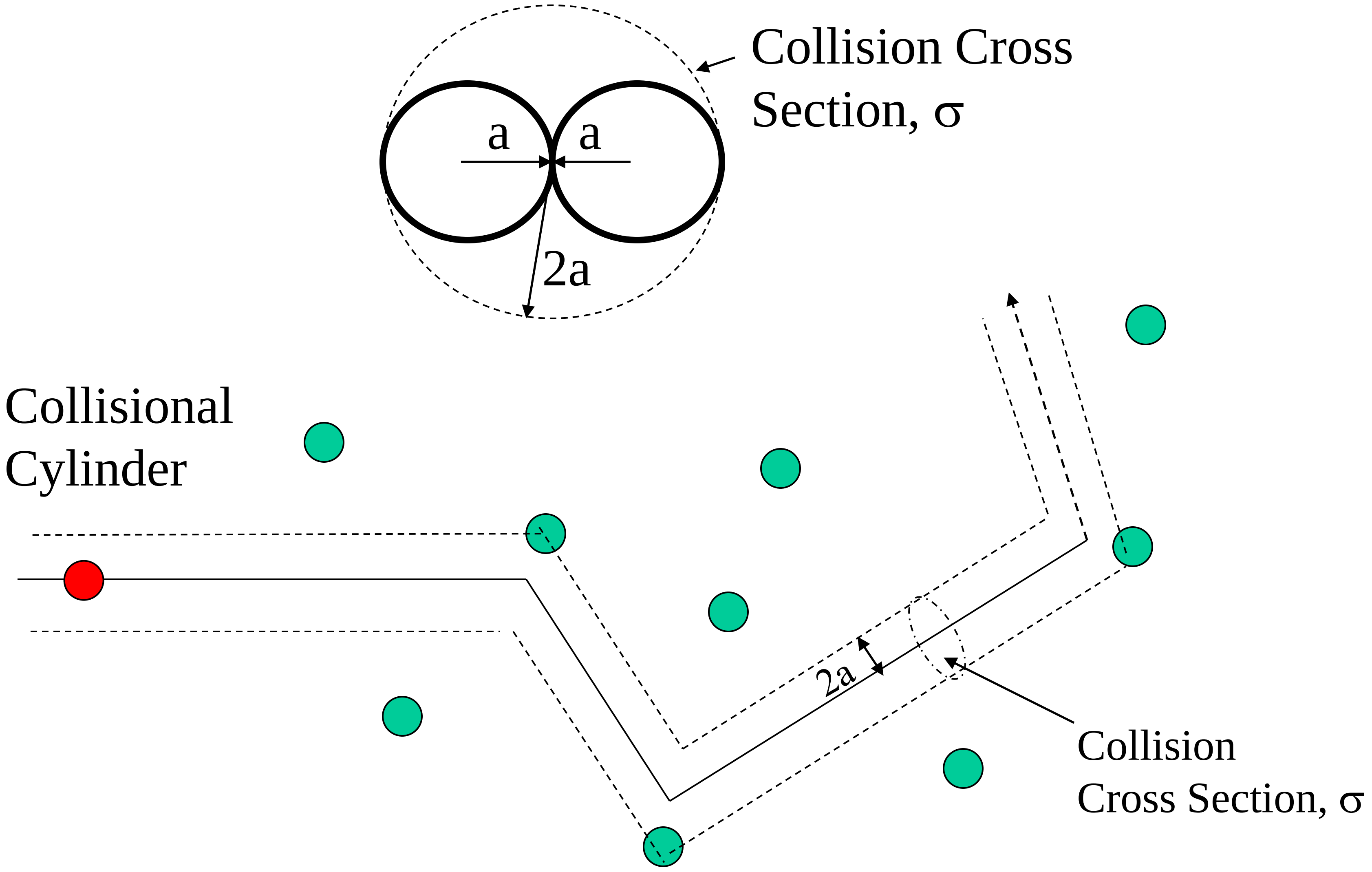


$$Q_{12}^{m}(v) \equiv \int_{4\pi} (1-\cos\chi) I_{12}^{elastic}(\chi,\Phi) d\Omega$$

$(m_1 v J_1) Q_{12}^{m}(v)$ is the total loss in the z-component of momentum of the beam per unit time

$Q_{12}^{m}/Q_{12}^{elastic}$ the average fraction of momentum lost by the test particle in elastic collisions.

Binary Hard-sphere Collision



Number of Collisions = n . σ . v . t

Reaction Rate Coefficient:

Reaction: A + B → C

Collision Cross Section

Velocity

Velocity distribution function

$$\langle \sigma v \rangle = \frac{1}{n} \int_{-\infty}^{\infty} \sigma(v) v f(v) dv$$

Collision Frequency

Density of the target

$$\nu_c = n \langle \sigma v \rangle$$

Interaction Rate

Density of the beam

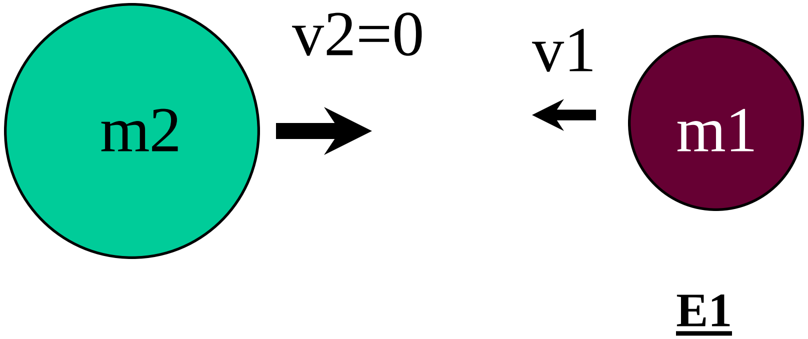
$$R = n^* v_c = n^* n \langle \sigma v \rangle$$

Mean Free Path

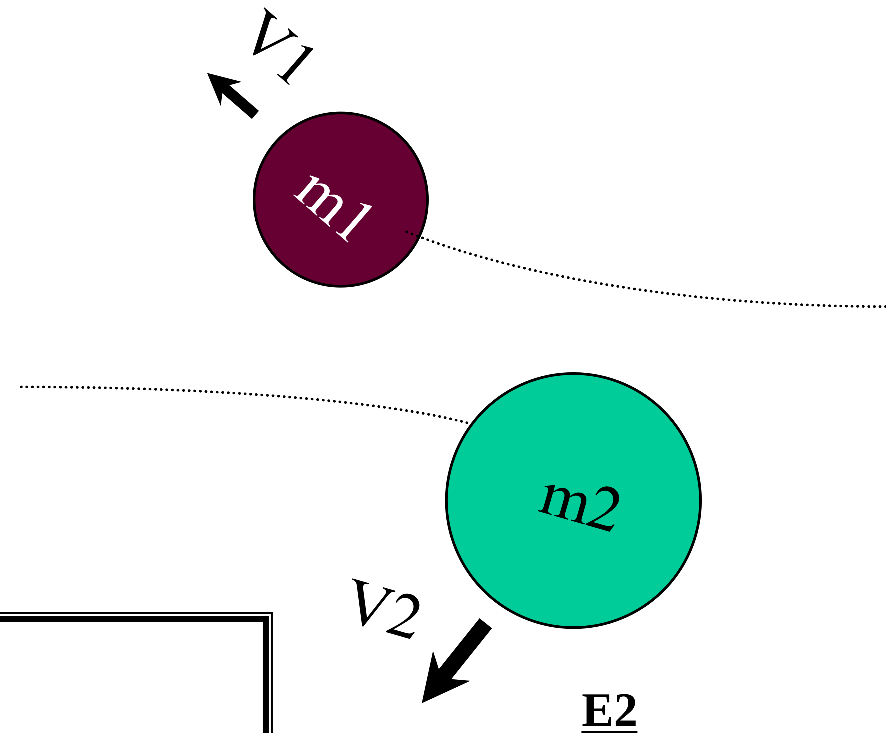
Average distance covered by a particle (photon, atom or molecule) between successive impacts. Distance at which the intensity of particles drops by 1/e.

$$\lambda = \frac{\bar{v}}{n\langle \sigma v \rangle} \cong \frac{1}{\langle n\sigma \rangle}$$

Before the collision



After the collision

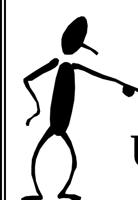


Conservation of Momentum:

$$m_1 v_1 = m_1 V_1 + m_2 V_2$$

Conservation of energy:

$$\frac{m_1 v_1^2}{2} = \frac{m_1 V_1^2}{2} + \frac{m_2 V_2^2}{2} + U$$

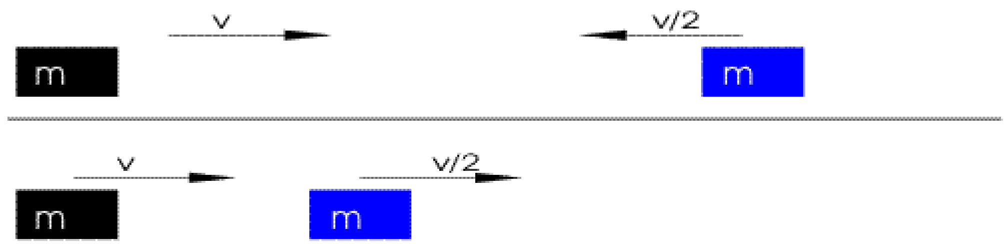


U=0 elastic collision

$U \neq 0$ inelastic collision

Elastic Collision (U=0)

Elastic collision of equal masses



Elastic collision of masses in a system with a moving frame of reference

Elastic collision of unequal masses

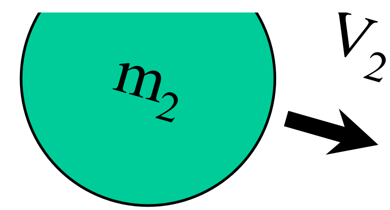
Elastic Collision (U=0)

$$m_1 v_1 = m_1 V_1 + m_2 V_2$$

$$\frac{m_1 v_1^2}{2} = \frac{m_1 V_1^2}{2} + \frac{m_2 V_1^2}{2}$$

Fraction of energy transferred in an elastic collision

$$\frac{E_2}{E_1} = ?$$



E2

Answer:

$$\frac{E_2}{E_1} = \frac{4 \times m_1 \times m_2}{(m_1 + m_2)^2}$$

E2

Inelastic Collision (U≠0)

Elastic Collision (U=0)

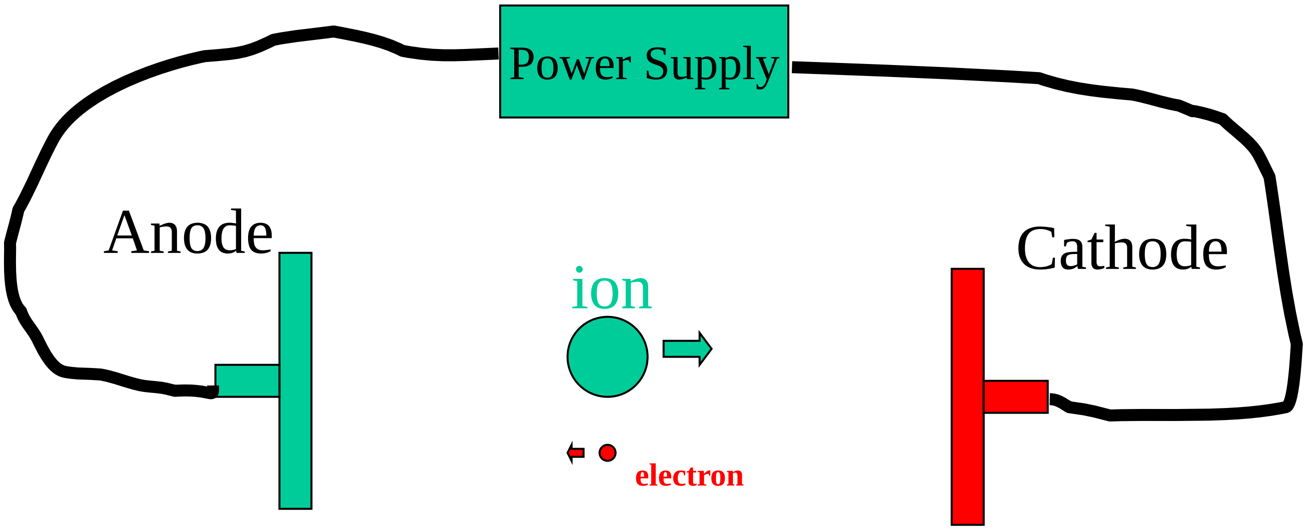
Inelastic Collision (U=0)

$$\frac{E_2}{E_1} = \frac{4 \times m_1 \times m_2}{(m_1 + m_2)^2}$$

$$U_{Max} = \frac{m_2}{m_1 + m_2} \times E_1$$

Case 1- $m_1=m_2$ $\begin{cases} m_1=m_2= m_e \\ m_1=m_2=m_a \text{ or } m_i \end{cases}$ → $E_1 = E_2$ U_{max}~$0.5E_1$

Case 2- $m_2 >> m_1$ $\begin{cases} m_1= m_e \\ m_2= m_a \text{ or } m_i \end{cases}$ → E_2~0 U_{max}~E_1



Lorentz Force → $F=eE$ → $F_i = F_e$

$\left\{ \begin{array}{l} F=ma \\ m_i >> m_e \end{array} \right.$ → $a_e >> a_i$ → Electrons accelerate faster and travel longer distances

$F_i=F_e$ and electrons travel longer distances

Energy=Force x Distance → Electrons pick up more energy from the power source

Electrons pick up energy from the power supply

↓

Electrons transfer energy to ions because of large collision cross sections (Coulomb interaction) compared to the atoms

↓

Ions transfer energy to the neutral because of their approximately equal mass

Project

- Every week at the end of my lecture, we will discuss for ½ hour about the project.

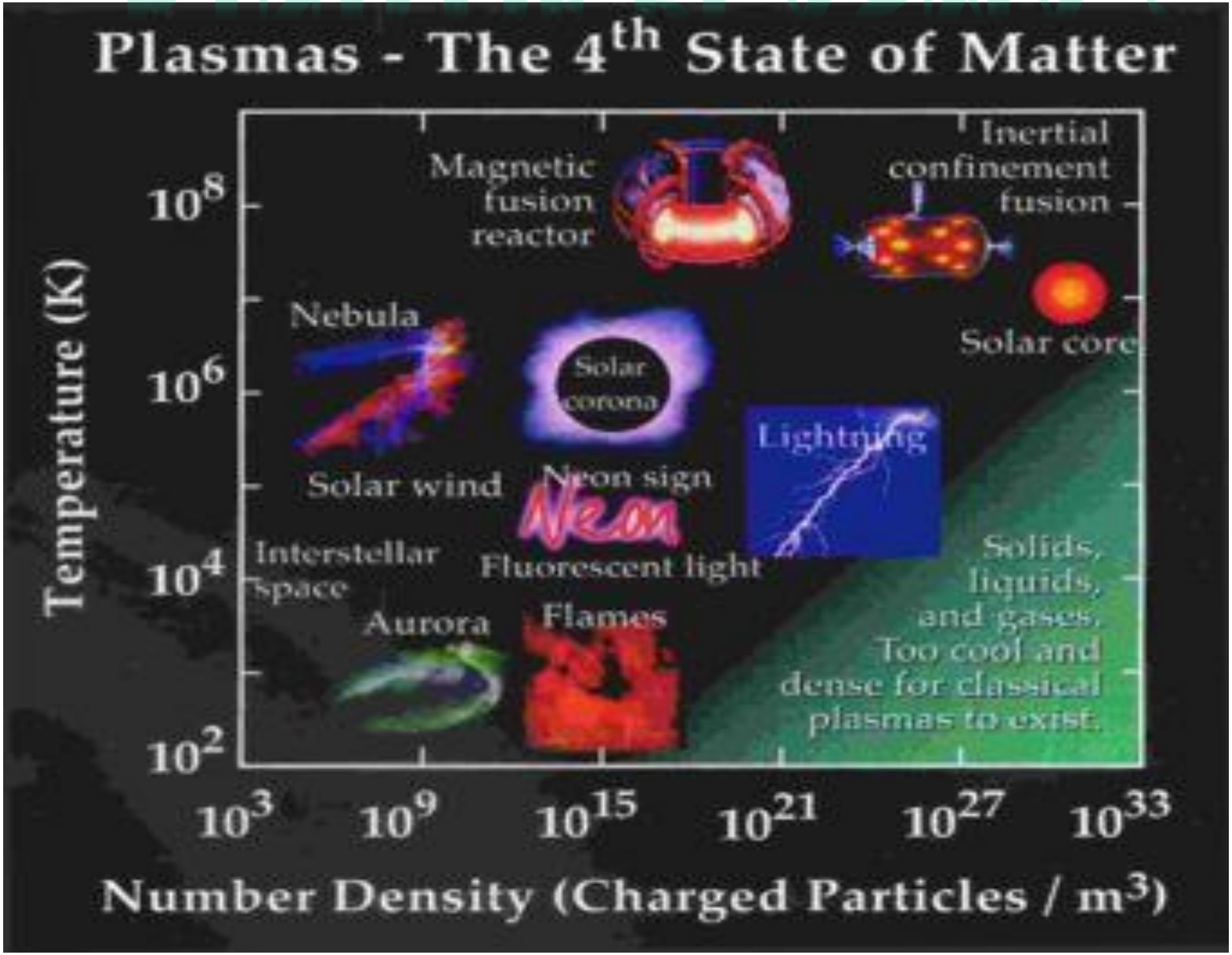
- You will be randomly asked to present your most recent project activities and you will be graded.

This week's task:

1-The objective (or importance) of your plasma application

2- At least two recent (max 1 year) activities (such as publication, Links to other research activities, …) in your project area.

KIND OF PLASMA ?



HOW DOES YOUR PLASMA DEVICE WORK?

Man-Made Plasmas

Coupling

Breakdown

Maintenance

DC, AC, RF, MW Power Supplies

Capacitors

Focused Laser Beam

Electron and ion beams

Solid (e.g. iron, copper, …)

Liquid (Mercury, …)

Gas (Ar, H_2, SF_6, …)

Man-Made Plasmas