Federal University of Santa Catarina
Graduate Program in Engineering and Mechanical Sciences

Plasmas and electrical discharges in gases

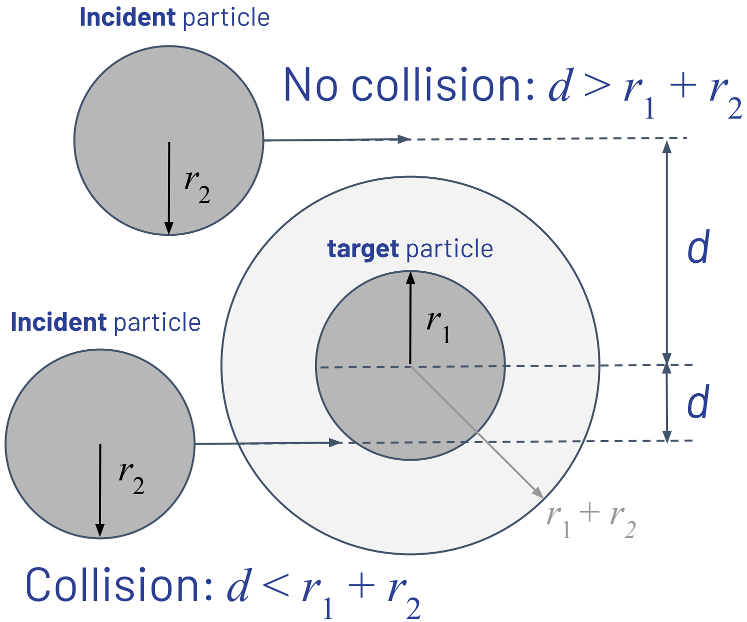
(ECM410054)

Diego Alexandre Duarte
Laboratory of Surface Treatments

SUMMARY
Plasmas and electrical discharge in gases

- Kinetic theory of gases
- Atomic structure
- Ionization
- Deionization
- Electron emission
- Behavior of charged particles in a gas in electric fields of low E/p
- Behavior of charged particles in a gas in electric fields of high E/p
- Glow discharges
- Plasmas

IONIZATION
Cross section



- For collisions between neutral particles:

$$d < r_1 + r_2$$

- The area blocked by one gas particle is:

$$\pi(r_1 + r_2)^2$$

that is defined as the **cross section** (Å^2 or 10^{-20} m^2 or πa_0). The **total projected target area** (effective cross section per volume unit or number of collisions per unit length; m^{-1}) is:

$$N\sigma = \pi(r_1 + r_2)^2 = \frac{1}{\lambda}$$

where N is the gas density. If the projectile and target particles are electrons and molecules respectively:

$$\lambda_e = \frac{1}{\pi r_1^2 N} = \frac{k_B T}{\pi r_1^2 p} = 5.66\lambda = 357 \text{ nm}$$

which is larger than the previous mean free path calculated for gas molecules (63 nm).

- The collision between two particles (charged or not) is quite complex due to the interaction between their electric and magnetic fields; for convenience, mechanics can be used for ideal gases, but cannot be ignored for electrical discharges.

IONIZATION
Cross section

- Consider a monoenergetic beam of electrons of density n (m^{-3}) moving through a gas with a velocity v. The number of electrons undergoing collisions per unit area per second in a distance dx is given by:

$$dn = -\sigma n dx$$

where σ is the collisional cross section. Since $v = dx/dt$, we get:

$$n(x) = n_0 e^{-\sigma x}$$

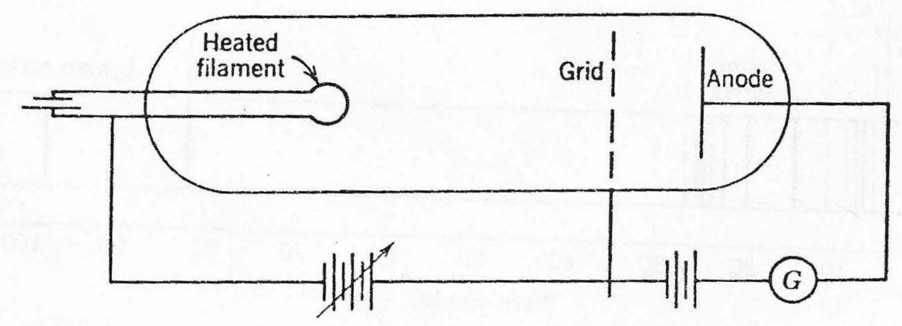


Fig. 2.3 Schematic diagram of apparatus for measuring the excitation energies of gases.

where n_0 is initial density of the electronic beam. Multiplying both sides by the fundamental charge, we get the current density i (A/m^2):

$$i(x) = i_0 e^{-\sigma x}$$

Either of the above equations can be used to measure σ. <u>The same experiment is applied for photoionization</u>.

E. Nasser, Fundamentals of Gaseous Ionization and Plasma Electronics, New York: Wiley, 1971.

IONIZATION
Cross section

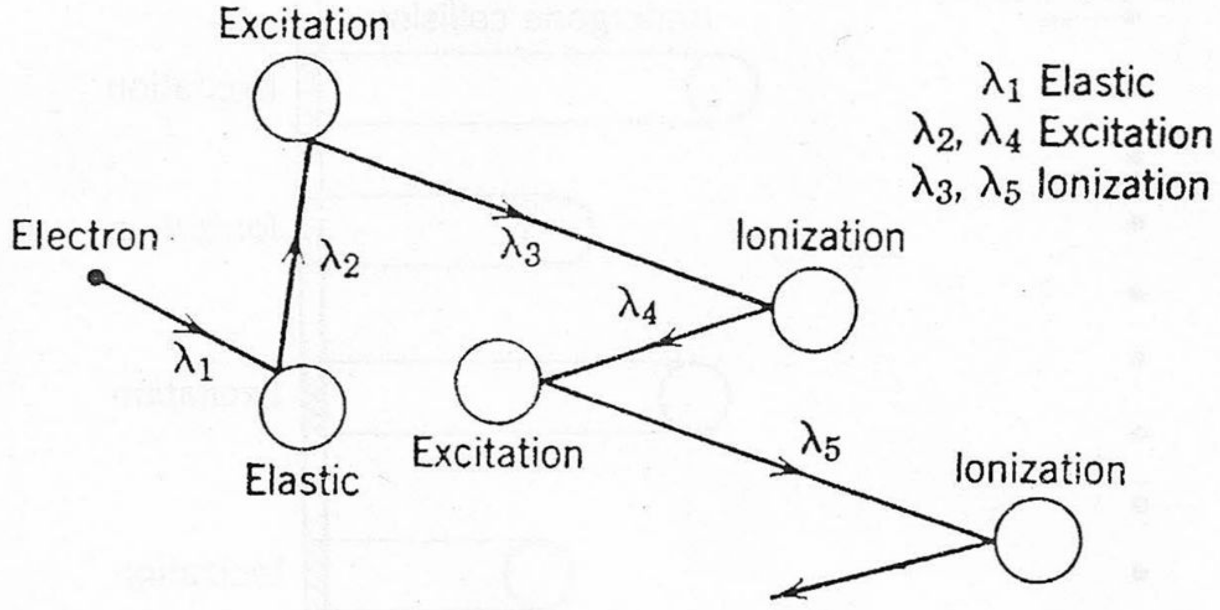


Fig. 3.4 The various kinds of collision product and the respective cross sections and free paths.

IONIZATION
Probability of ionization

- The probability of ionization P_{ion} ie defined as the ratio:

$$P_{\text{ion}} = \frac{N\sigma_{\text{ion}}}{N\sigma} = \frac{\sigma_{\text{ion}}}{\sigma} = \frac{\lambda}{\lambda_{\text{ion}}}$$

where $N\sigma_{\text{ion}}$ is the number of ionizing collisions per unit length and $N\sigma$ is the total number of collisions per unit length. According the above equation, the probability of collisions is defined between zero and 1, and independent of p and T.

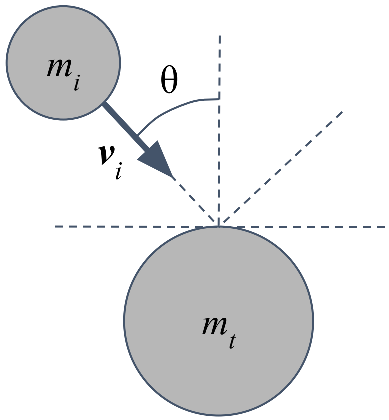
- The number of ionizing collisions per unit length $N\sigma_{\text{ion}}$ is also called as ionization efficiency η_{ion}:

$$\eta_{ion} = N\sigma_{ion}$$

E. Nasser, Fundamentals of Gaseous Ionization and Plasma Electronics, New York: Wiley, 1971.

IONIZATION
Elastic collisions

- Collisions can be divided into **elastic** (interchange of kinetic energy) and inelastic (potential energy changes too) types.



- Conservation of momentum (vertical axis) for binary collisions:

$$m_i v_i \cos\theta = m_i u_i + m_t v_t$$

- Conservation of the kinetic energy:

$$\frac{1}{2} m_i v_i^2 = \frac{1}{2} m_i (u_i^2 + v_i^2 \sin^2\theta) + \frac{1}{2} m_t v_t^2$$

- The fractional energy transferred from incident to the target particle is given by:

$$\frac{E_t}{E_i} = \frac{\frac{1}{2} m_t v_t^2}{\frac{1}{2} m_i v_i^2} = \frac{4 m_i m_t}{(m_i + m_t)^2} \cos^2\theta$$

- In a head-on collisions (θ = 0),

$$\frac{E_t}{E_i} = 1 \quad \text{if } m_i = m_t$$

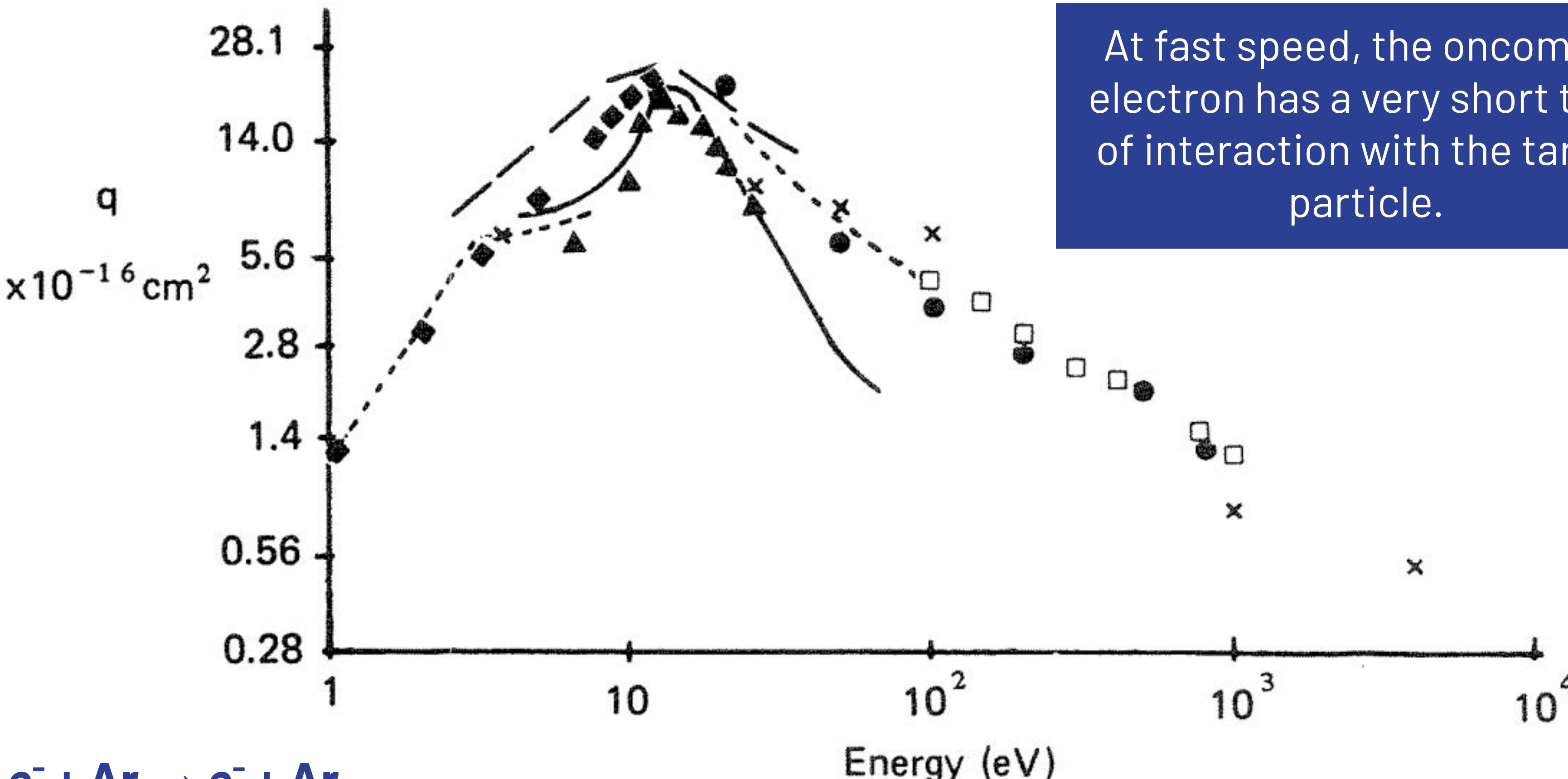
Collisions between gas particles: Ar + Ar

$$\frac{E_t}{E_i} \ll 1 \quad \text{if } m_i \ll m_t$$

Collisions between electrons and gas particles: e^- + Ar

IONIZATION
Elastic collisions

- Cross-section for elastic scattering of electrons in argon:

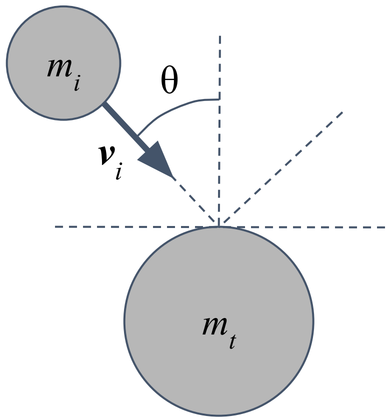


At fast speed, the oncoming electron has a very short time of interaction with the target particle.

$e^- + Ar \longrightarrow e^- + Ar$

IONIZATION
Inelastic collisions

- Both kinetic and internal energies are changed in **inelastic** collisions:



- Conservation of momentum (vertical axis) for binary collisions:

$$m_i v_i \cos\theta = m_i u_i + m_t v_t$$

- Conservation of energy:

$$\frac{1}{2} m_i v_i^2 = \frac{1}{2} m_i (u_i^2 + v_i^2 \sin^2\theta) + \frac{1}{2} m_t v_t^2 + \Delta U$$

- The fractional energy transferred from incident to the target particle is given by:

$$\frac{\Delta U}{E_i} = \frac{m_t}{m_i + m_t} \cos^2\theta$$

The maximum energy transfer may rise to more than 99.99% by inelastic collision!

- In a head-on collisions (θ = 0),

$$\frac{\Delta U}{E_i} = \frac{1}{2} \quad \text{if } m_i = m_t$$

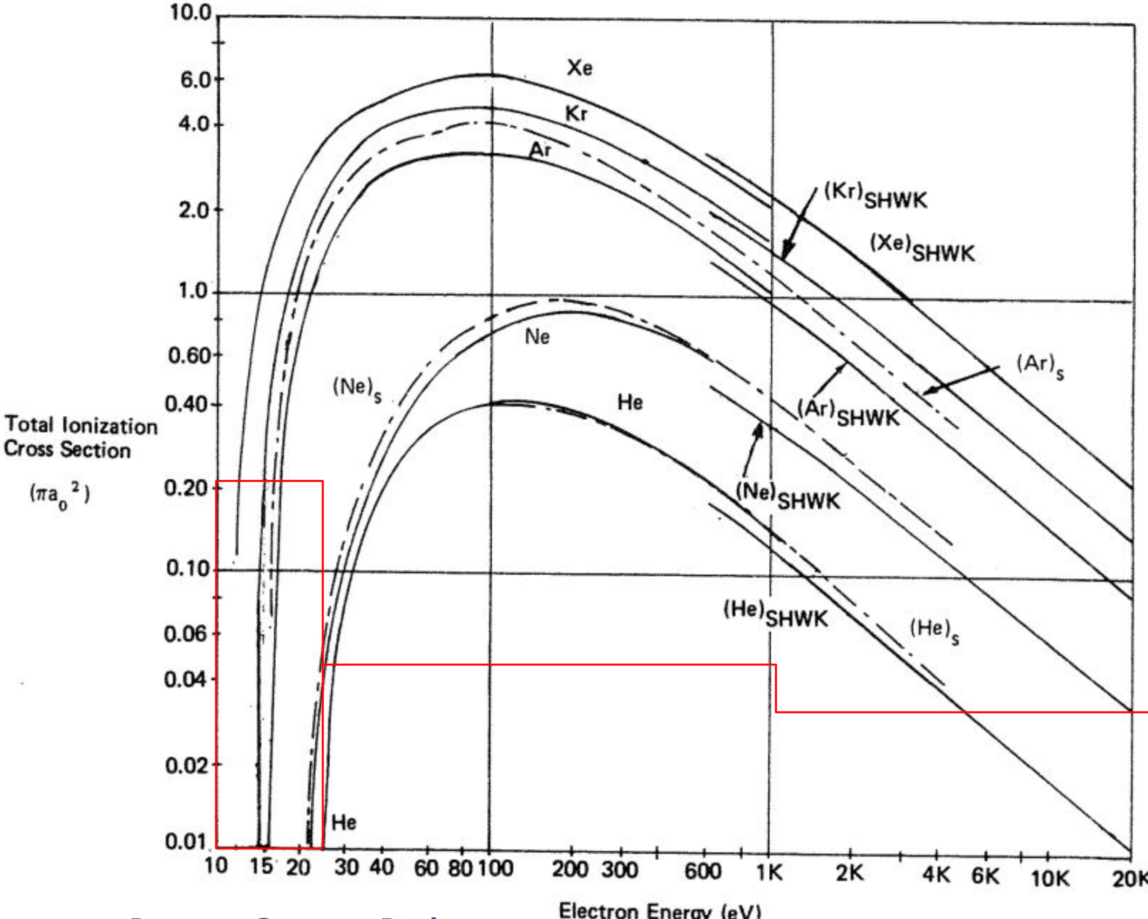
Collisions between gas particles: Ar + Ar

$$\frac{\Delta U}{E_i} \approx 1 \quad \text{if } m_i \ll m_t$$

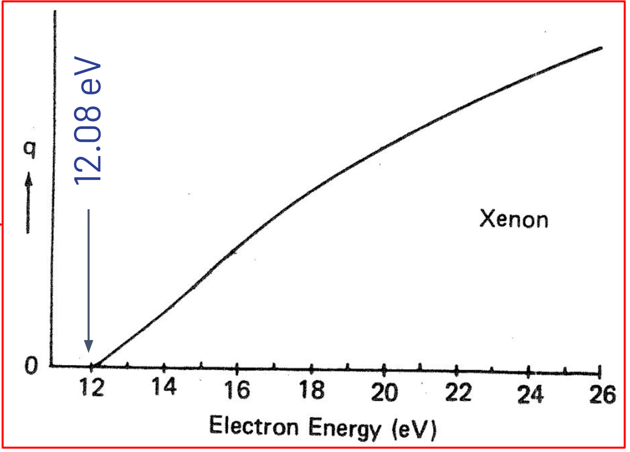
Collisions between electrons and gas particles: e^- + Ar

IONIZATION
Inelastic collisions

- The most important collision in gas discharges is by **electron impact ionization**:



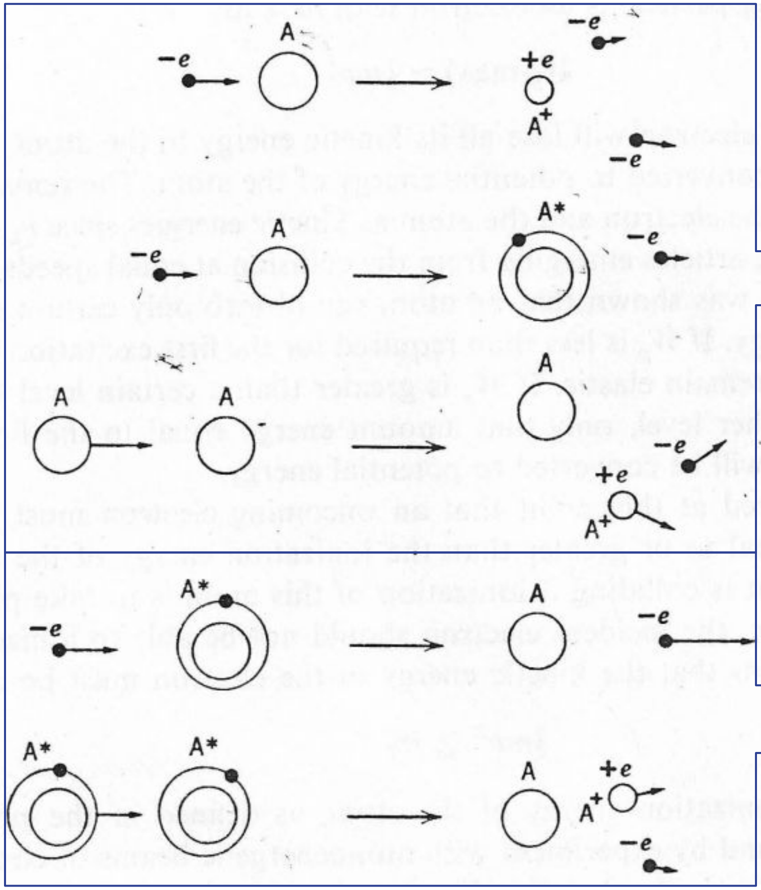
- The electron produced by electron impact can also produce ionization and then maintain the glow discharge.
- The minimum energy requirement for ionization is equal to the **ionization potential**:



$e^- + Ar \rightarrow 2e^- + Ar^+$

IONIZATION
Inelastic collisions

- The ionization is produced not only by electron impact, but with other possibilities such as atom-atom collisions:

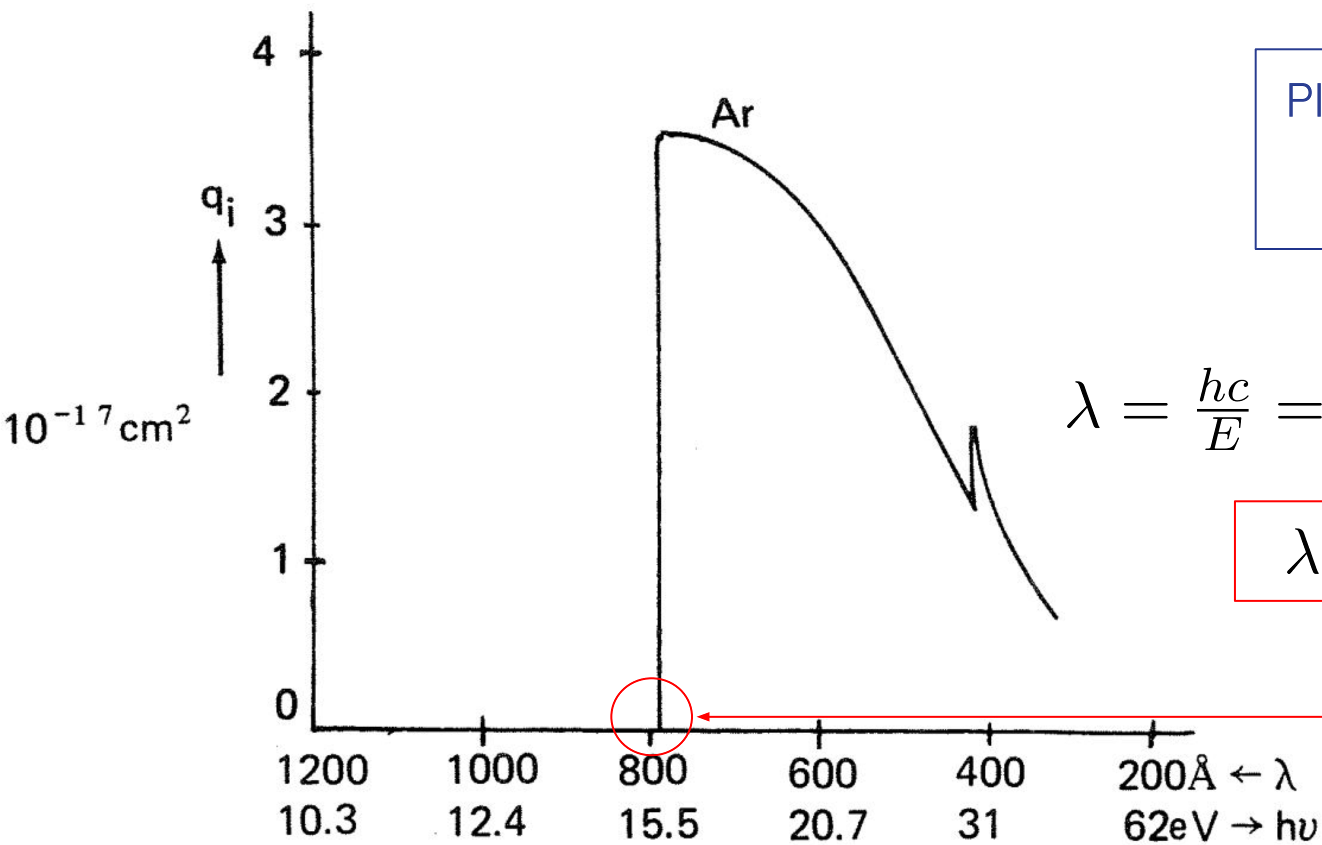


First-order collisions

Second-order collisions
(Step ionization)

IONIZATION
Inelastic collisions

- ...and thermal or **photo activation**:



Planck equation:

$$E = h\nu$$

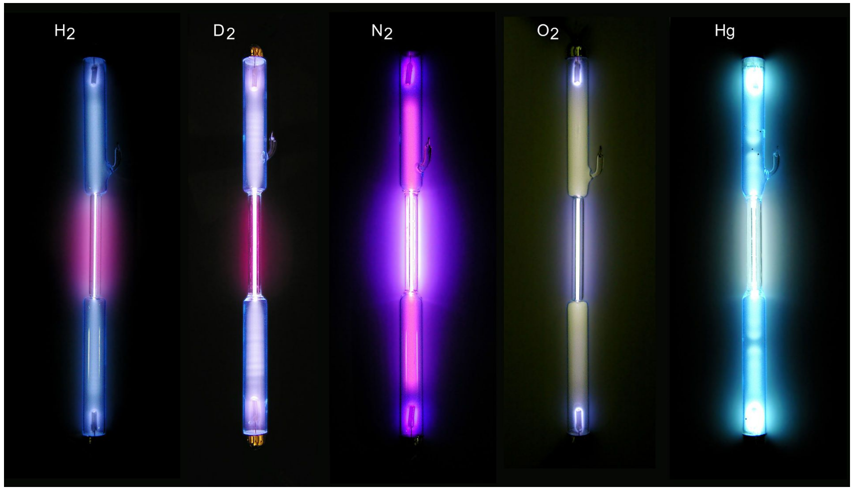
$$\lambda = \frac{hc}{E} = \frac{(6.62\times10^{-34})(3\times10^{8})}{15.8\times1.6\times10^{-19}}$$

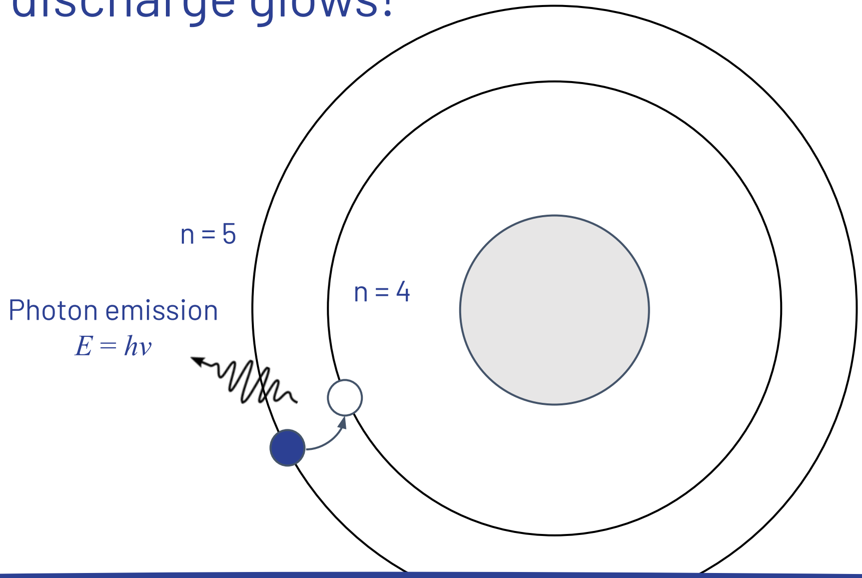
$$\lambda = 785.6\ \text{Å}$$

hv + Ar → e⁻ + Ar⁺

IONIZATION
Inelastic collisions

- The ingredients of a glow discharge are described by four types of inelastic processes: ionization, **excitation**, **relaxation**:
  - Excitation: $e^- + \text{Ar} \rightarrow e^- + \text{Ar}^*$ (metastable)
    - excitation potential for argon: 11.6 eV
  - Relaxation: $\text{Ar}^* \rightarrow h\nu + \text{Ar}$
    - This process explains why the discharge glows!





IONIZATION

Inelastic collisions: deionization processes

- …and recombination:
  - Radiative recombination: $e^- + Ar^+ \rightarrow Ar + h\nu$
  - 3-body collision:
    - $e^- + Ar^+ + e^- \rightarrow Ar + e^-$ [1]
    - $e^- + Ar^+ + Ar \rightarrow Ar + Ar$
  - Ion-ion collision: $X^- + X^+ \rightarrow X + X$
- There are many other important collision processes, such as dissociation for molecular gases, electron attachment for electronegative gas and neutral-ion collisions, where each reaction present its own cross-section. **The sum of the individual cross-section defines the total collision cross-section.**
- A regular gas mixing composed by two different particles, such as N_2 and Ar, reach tens of reactions easily! [1]

[1] A. Bogaerts, Spectrochimica Acta Part B 64 (2009) 126–140

IONIZATION

Inelastic *versus* elastic collisions

- Due to the discrete nature of the atoms, the gas particles can absorb only certain quantities of energy.

- For a head-on collision between an electron and one gas particle:

$$\Delta U \approx E_i \approx \frac{1}{2} m_e v_i^2$$

where m_e is the electron mass and v_i its initial speed before collision.

- If the initial kinetic energy of the oncoming electron is higher than the first excitation energy of the gas particle, the collision will inelastic; if not, it will be elastic:
  - The first ionization potential of the Hg is 10.4 eV, but the gas ionization begins at lower electron energies around 4.7 eV, which is the Hg excitation potential. It means that the ionization occurs by step ionization with two or more collisions in a row.

IONIZATION
Saha equation and degree of ionization

- The ionization of the gas atoms or molecules as a result of the thermal condition of the gas is known as thermal ionization. At high temperatures:
  - Ionization by collisions of the gas atoms with each other;
  - Photoionization resulting from the thermal emission of the hot gas;
  - Ionization by collision with high-energy hot electrons produced by previous processes.

- In thermodynamic equilibrium, the degree of ionization in terms of the gas pressure and temperature is given by:

$$\frac{\alpha^2}{1-\alpha^2} = \frac{2.4\times10^{-4}}{p} T^{2.5} \exp\left(-\frac{E_i}{\kappa T}\right)$$

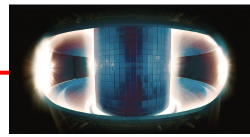
where p is given in torr, E_i is the ionization energy in eV, κ is the Boltzmann constant in eV/K (8.62×10^{-5} eV/K) and T the gas temperature in K.

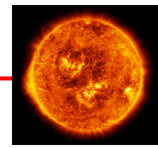
Meghnad Saha

https://en.wikipedia.org/wiki/Meghnad_Saha

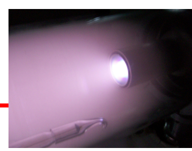
IONIZATION

Degree of ionization





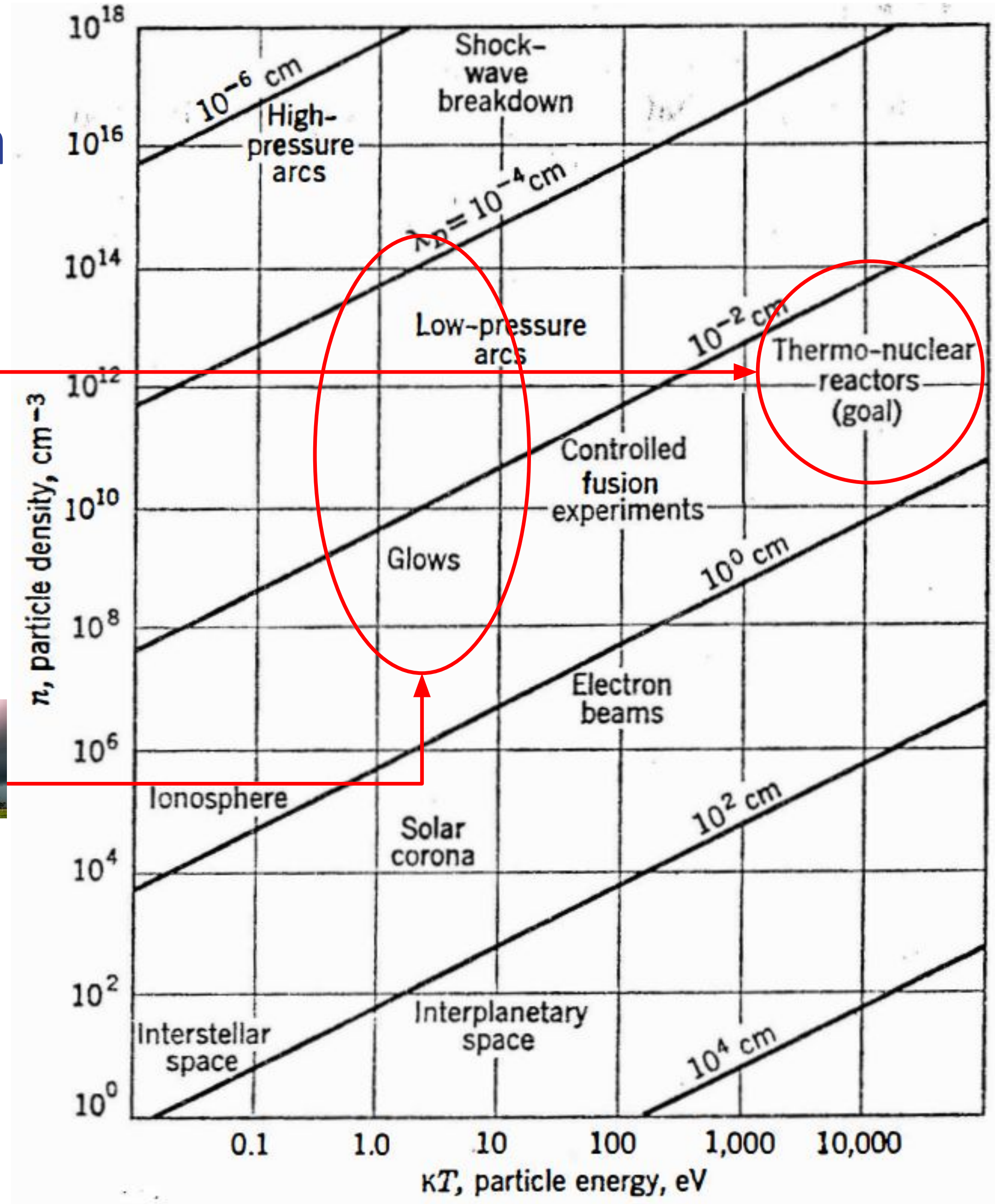
Hot plasmas: high ionization degree (nearly fully ionized)



http://www.inpe.br/webelat/homepage/menu/infor/relampagos.e.efeitos/solo.php

Cold plasmas: low ionization degree (<< 1%)

Ionization degree: $\alpha = \dfrac{n_i}{n_i + n}$



IONIZATION
Reading

- Chapter 2 - B. Chapman, Glow Discharge Processes: Sputtering and Plasma Etching (pages 21-46).
- Chapter 3 - E. Nasser, Fundamentals of Gaseous Ionization and Plasma Electronics (pages 54-97).

See you next topic!

Diego A. Duarte
diego.duarte@ufsc.br
https://lats.ufsc.br