Fundamentals of Plasma Physics
Collisions

Fall, 2023

对于等离子体，为什么关心碰撞过程

- 碰撞造成粒子的物理量的改变
  - 动量，影响粒子的输运
  - 能量，造成不同粒子之间能量的转移
  - 粒子数密度，新的粒子的产生和“旧”粒子损失（如电离，激发过程，复合过程）

碰撞是短程相互作用：感知对方的存在

- 经典力学中的碰撞(物理接触的必要性)
- 带电粒子之间的碰撞(两个粒子要接近，但仍然可用经典理论)
- 带电粒子与中性粒子的碰撞(更接近，量子效应明显)

- 以上碰撞过程相互作用尺度的变化，意味着描述方法从经典力学到量子力学的过渡，量子效应体现在截面上
- 何为“长程”相互作用？对于多粒子体系
- 本讲的目的：定性或定量的了解一些碰撞截面和入射粒子能量的关系

低温等离子体中各种粒子之间的碰撞

- 电子，正离子，负离子，各种中性粒子
- 本课程主要关注低温弱电离等离子体中的一种最重要的碰撞过程：电子和中性粒子的碰撞
- 在低温等离子体中，离子和中性粒子之间的碰撞也重要，中性粒子之间的碰撞会导致化学反应，但在此课程，两者都不讨论
- 电子和中性粒子碰撞的后果
  - The nature of target particles (atoms or molecules, electropositive or electronegative gases)
  - The electron energy (the cross section is a very strong function of the relative velocity, or the electron energy)

几个关于碰撞的基本物理概念

- 不同类型的碰撞：弹性碰撞，非弹性碰撞，和超弹性碰撞

- 碰撞截面
- 碰撞频率的概念
- 平均自由程的概念（两次碰撞之间粒子行走的距离？）

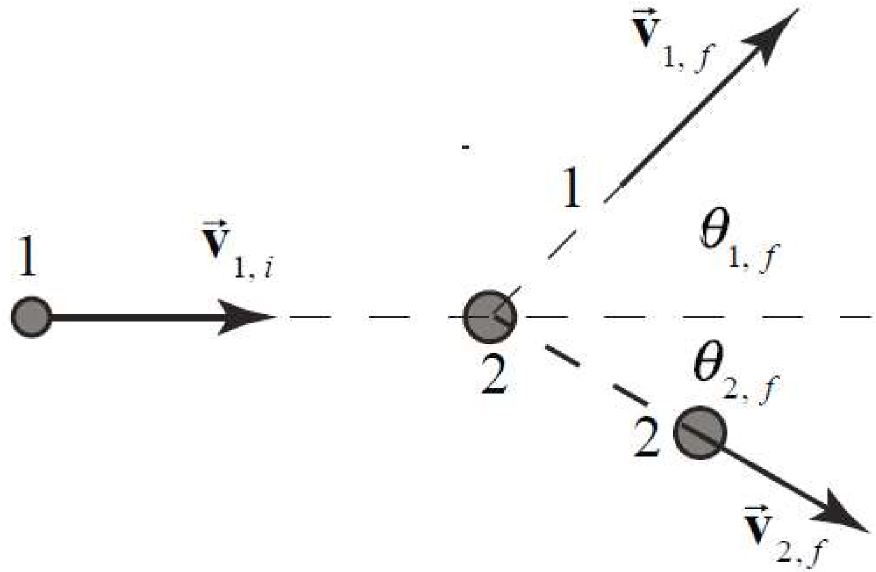
弹性碰撞的一些问题

- What fundamental laws should be applied to investigate collisions?
- Quantitatively, how do we describe the effects of collisions ?
- In the following, we will first focus on binary collisions (interaction between two particles， 弹性碰撞）

What we have learned before on collisions between two particles

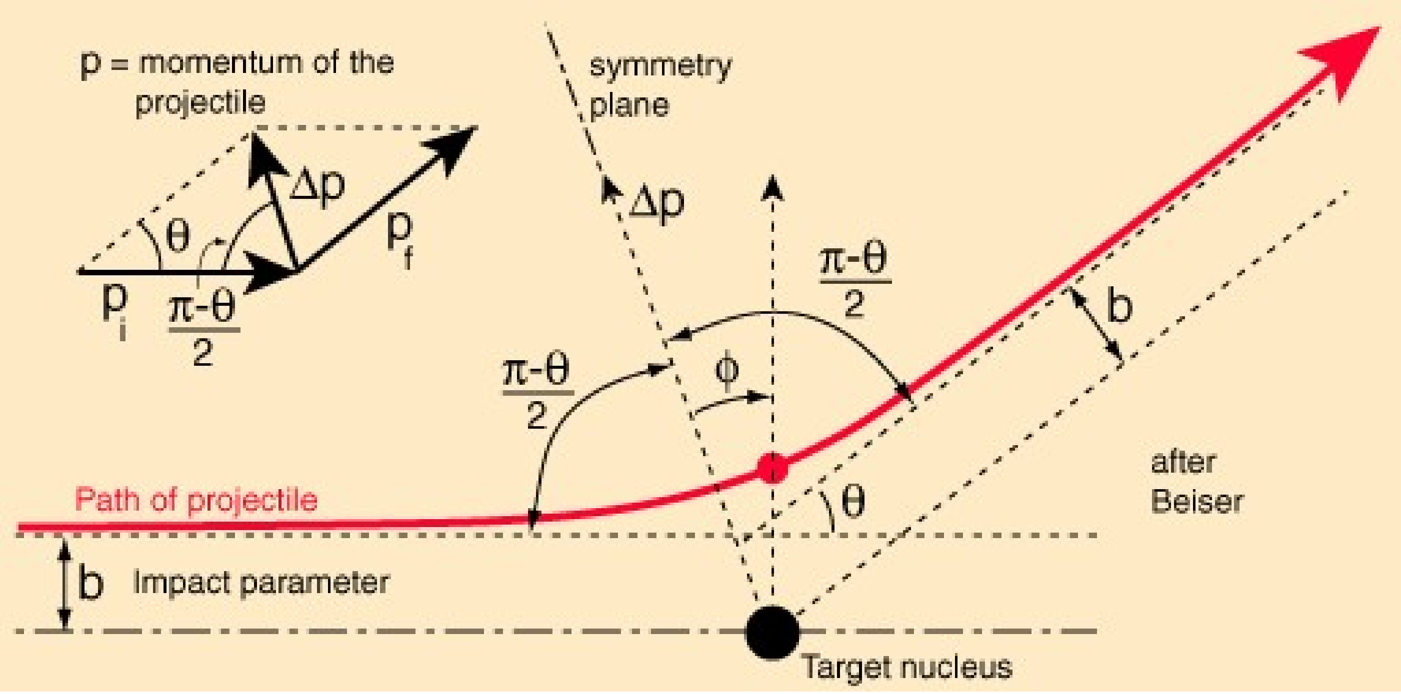
- Conservation of momentum
- Conservation of energy
- Relative velocity
- Impulse:

$$\vec{J} = \int_{t_i}^{t_f} \vec{F}(t)dt.$$

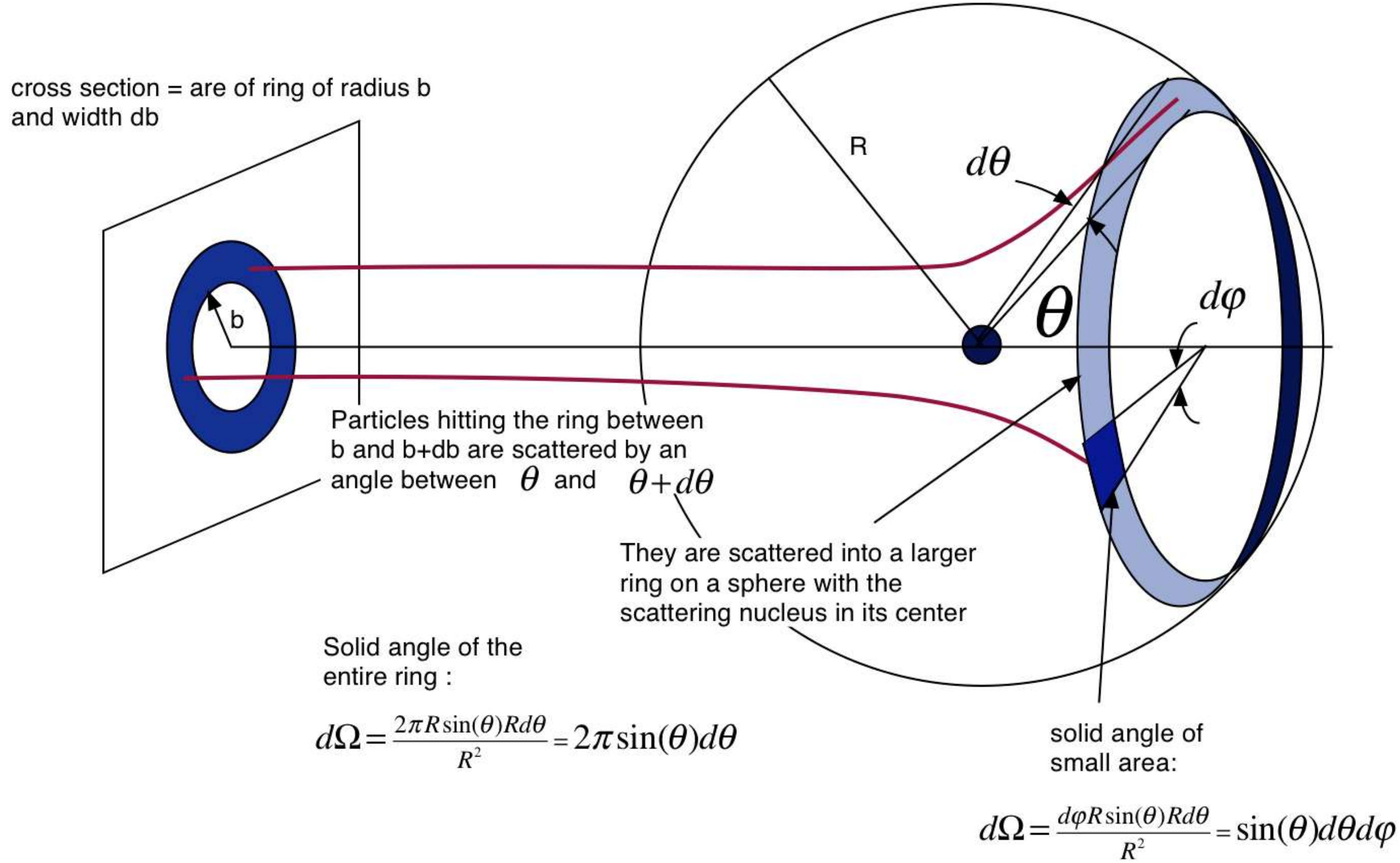


Basic parameters for a binary collision

- Impact parameter
- Scattering angle
- Incoming particle velocity (relative velocity, why?)
- Cross section (the most important parameter)
- Differential scattering cross section

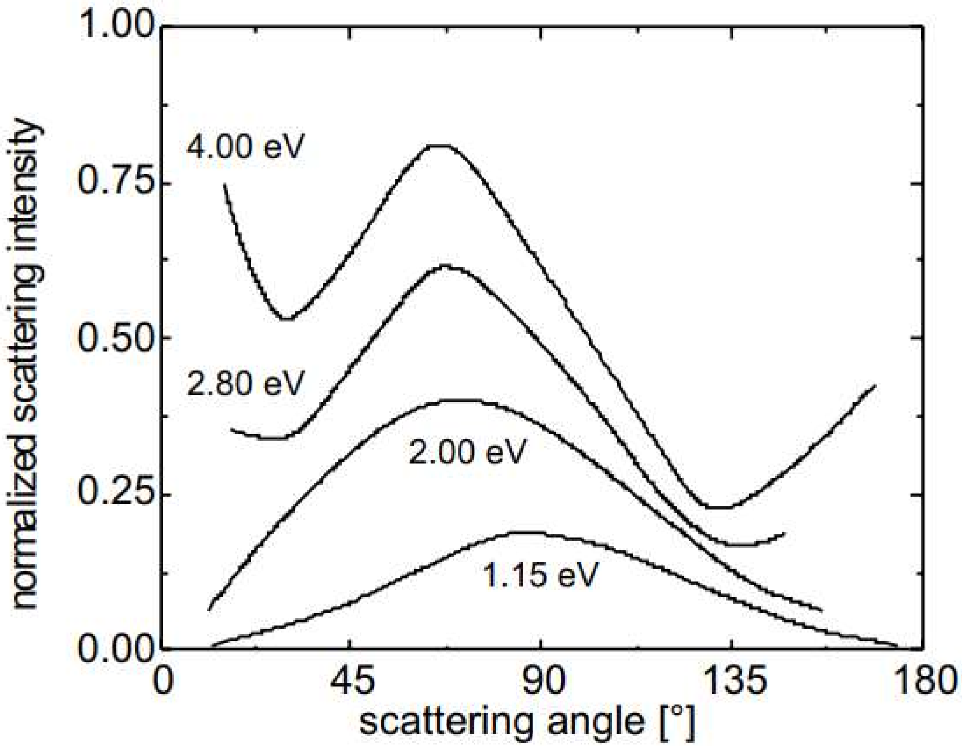


微分散射截面（Differential Scattering Cross Section）对谁微分，为啥要关注微分？



低能电子在氩中的散射强度随散射角的变化

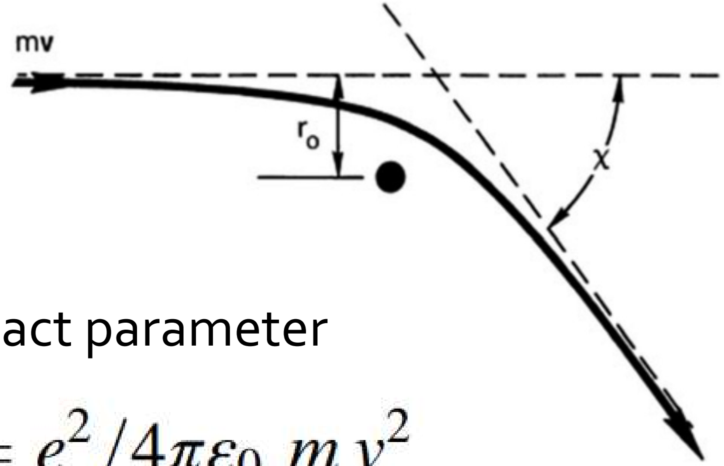
$$\frac{\mathrm{d}\sigma(v,\vartheta)}{\mathrm{d}\Omega} = \frac{b}{\sin\vartheta}\frac{\mathrm{d}b}{\mathrm{d}\vartheta}$$



Coulomb collision in fully ionized plasmas

we focus on 90 degree scattering only

$$\Delta(mv) = |FT| \approx \frac{e^2}{4\pi\varepsilon_0 r_0 v}$$



Impact parameter

$$\Delta(mv) \cong mv \cong e^2/4\pi\varepsilon_0 r_0 v, \quad r_0 = e^2/4\pi\varepsilon_0\, m\, v^2$$

$$\sigma = \pi r_0^2 = e^4/16\pi\varepsilon_0^2 m^2 v^4$$

- 在两体碰撞中，为什么关注90度或更大角度的偏转?

- 带电粒子之间发生库伦碰撞时，针对90度或更大角度的偏转，速度越小，impact parameter 越大，最大的”impact parameter”是多少?

- 德拜长度

- 最小的”impact parameter”是多少？尺度越来越小，量子力学效应

- cross section is used for the description of a binary collision
- In a discharge, there are many particles and many collisions happening at the same time
- The relative speed in each collision will be different. The scattering angle after each collision will be different.
- one has to look at the "statistical average" of the collisional effect. In this case, we introduce two new concepts:
  - Collision frequency
  - Mean free path
- 微观到宏观的过渡

Mean free path and collision frequency of electrons in a gas

- electron-neutral mean free path

$$\lambda_{\mathrm{e}} = \frac{1}{n_g \sigma}$$

- Collision frequency

$$\nu_e = n_g \sigma v$$

$$\nu_e = n_g < \sigma v >= n_g K$$

- Collision frequency

$$\lambda_e = v \bullet \tau$$

- V is the relative speed, τ is collision time, which is the inverse of collision frequency.

$$\tau = \frac{1}{\nu_e}$$

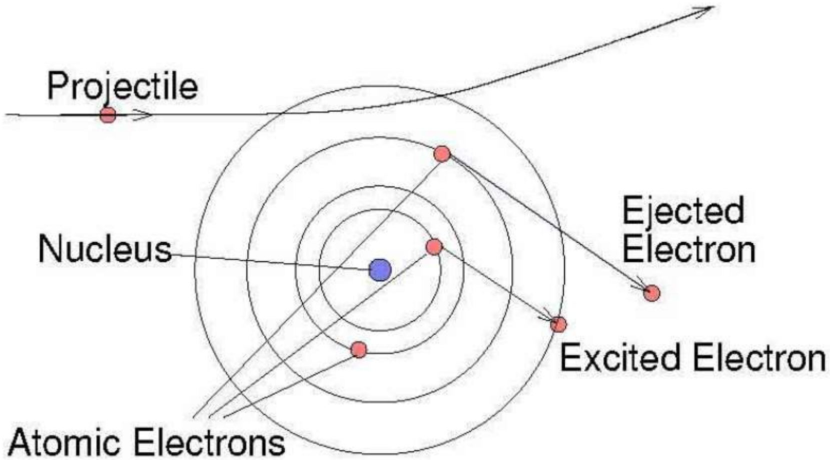
- <> represents "statistical average"

Collision frequency

- What is the physical meaning of collision frequency?
- It is Not the number of collisions per second

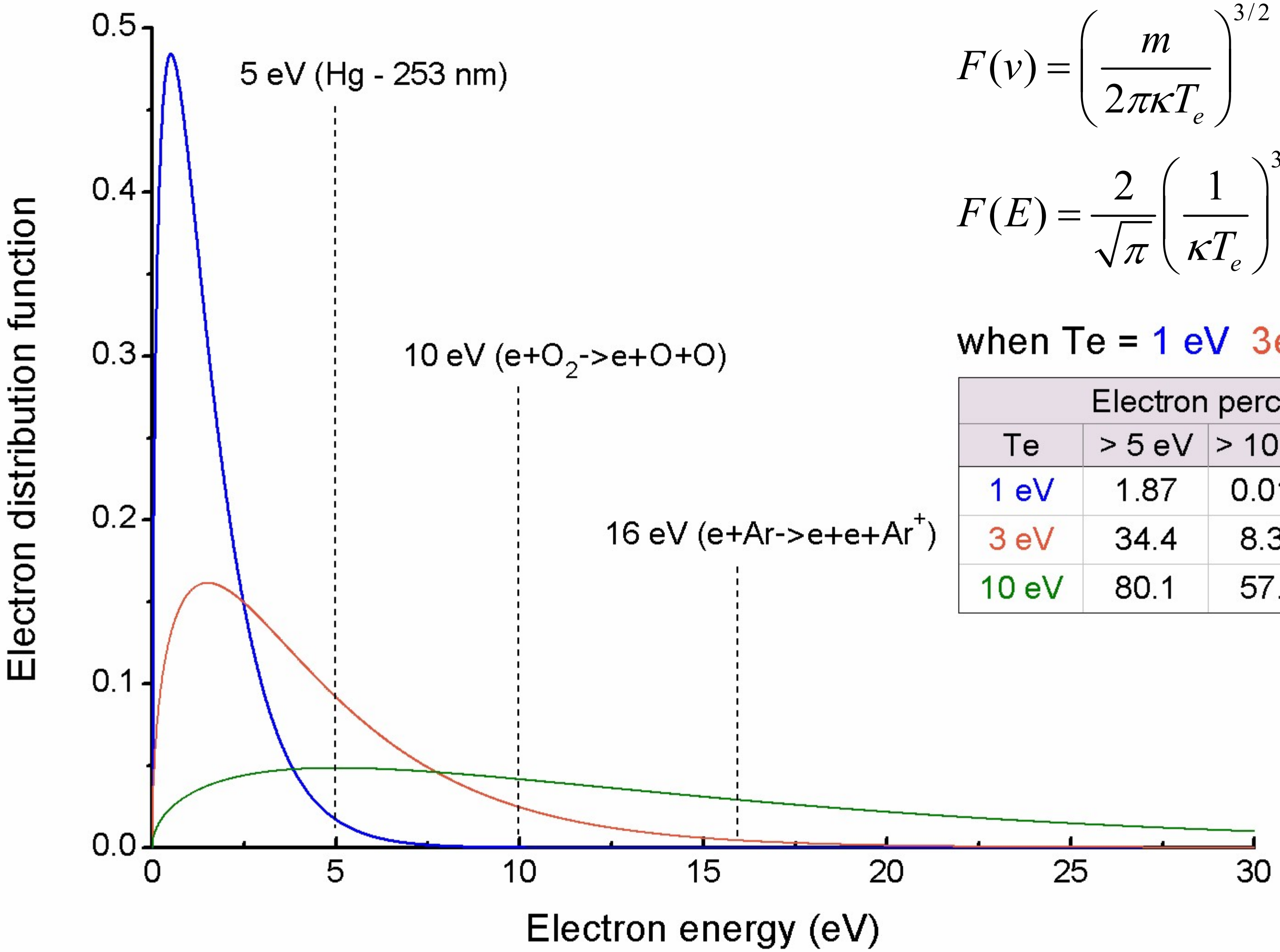
- It reflects the change in momentum of the flowing particles (the last term in momentum balance equation and the origin of resistivity)
- Energy transfer
- Some species is lost, a new species is generated (inelastic collisions)

三种非弹性碰撞截面和入射粒子能量的关系



- 活性粒子的产生机制
  - Ionization
  - Dissociation
  - Excitation
- 需要多高的能量才能电离一个原子?
- 用离子碰撞原子，可以发生电离吗?
- 需要多高的能量才能分解某一个分子?
- 电子和一个"静止"正离子碰撞时，碰撞截面和电子能量之间的关系?

在具有众多粒子的等离子体中，非弹性碰撞的统计效果与电子能量分布有关！



Maxwellian distribution

$$F(v) = \left(\frac{m}{2\pi\kappa T_e}\right)^{3/2} 4\pi v^2 e^{-\frac{mv^2}{2\kappa T_e}}$$

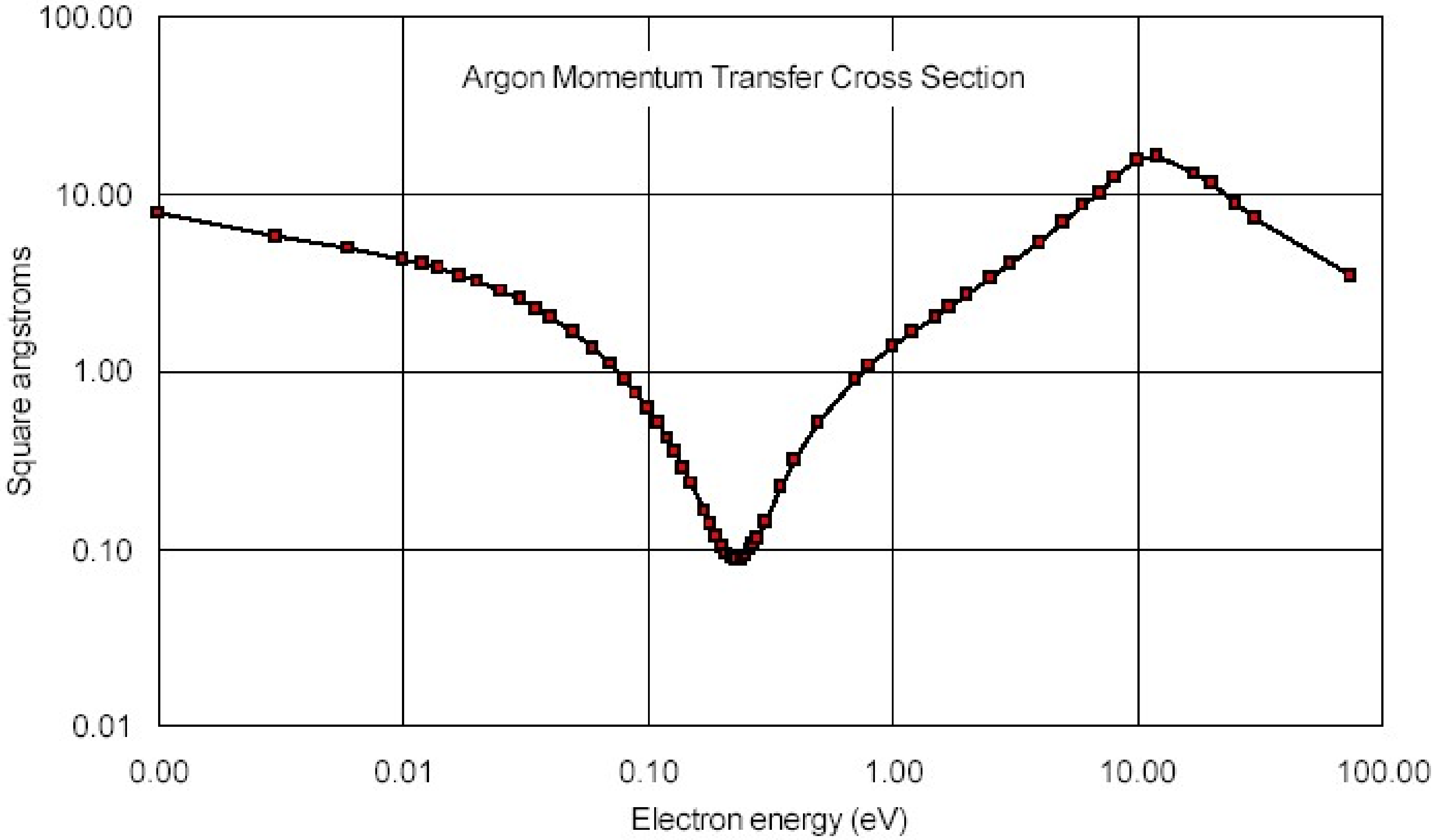
$$F(E) = \frac{2}{\sqrt{\pi}}\left(\frac{1}{\kappa T_e}\right)^{3/2} \sqrt{E} e^{-\frac{E}{\kappa T_e}}$$

when Te = 1 eV 3eV 10eV

Electron percent (%)			
Te	> 5 eV	> 10 eV	> 16 eV
1 eV	1.87	0.017	1E-4
3 eV	34.4	8.34	1.37
10 eV	80.1	57.3	36.2

cross section of some of the electron involved collisions

- Elastic collisions
- Inelastic collision:
  - Excitation
  - Ionization
  - Dissociation of a molecule
  - Vibrational excitation of a molecule

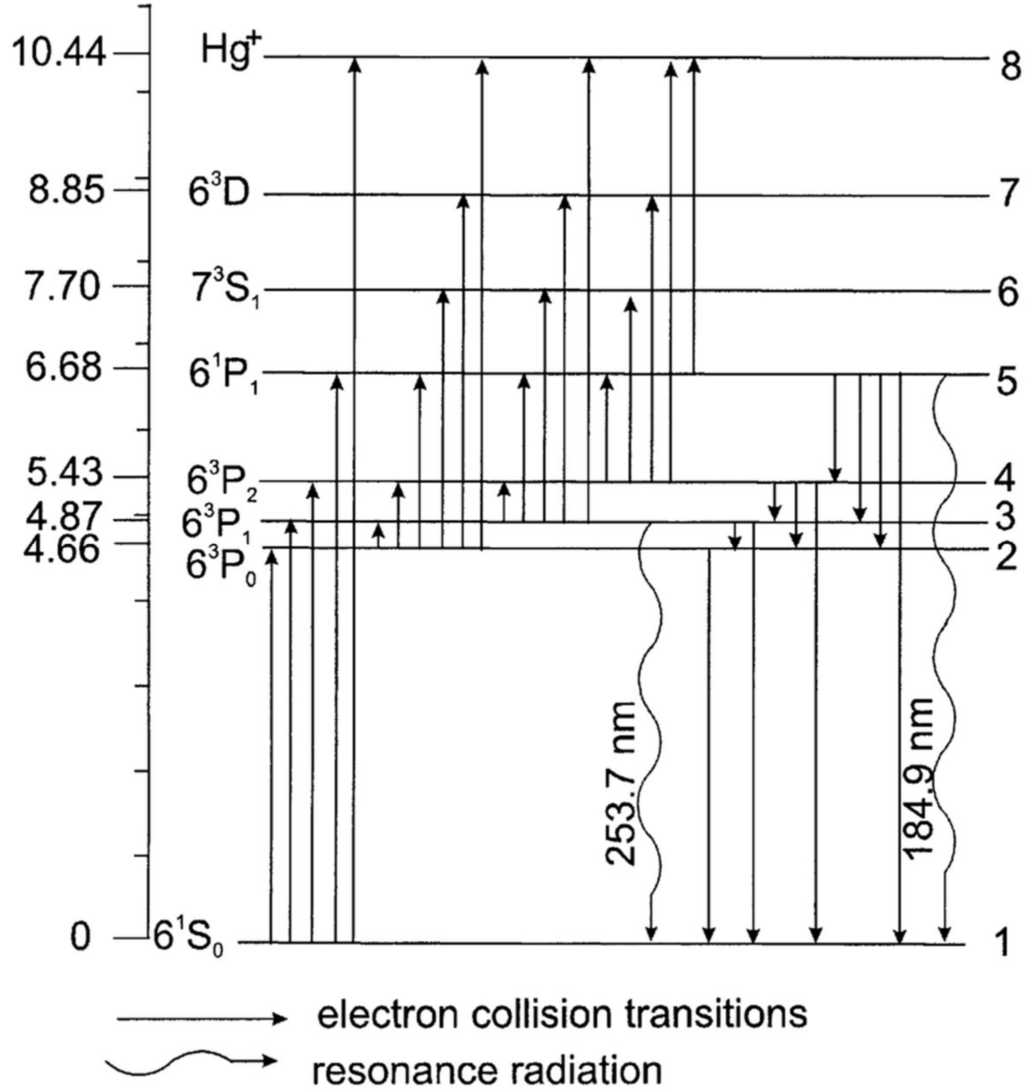

Argon Momentum Transfer Cross Section
100.00
10.00
1.00
0.10
0.01
Square angstroms
0.00
0.01
0.10
1.00
10.00
100.00
Electron energy (eV)

Three examples of inelastic collisions

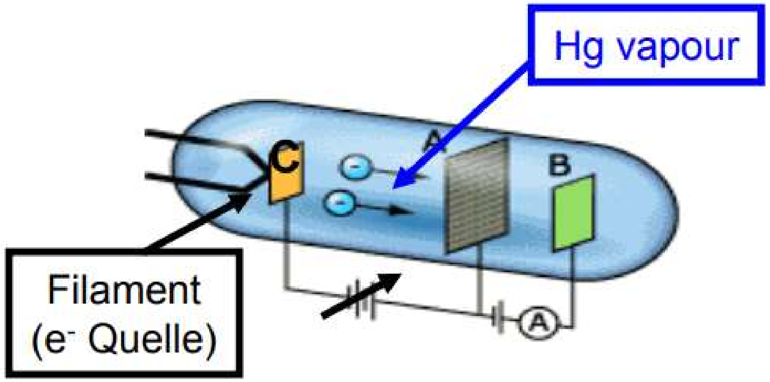
- Electron in mercury vapor
- Electrons in noble gases
  - Excitation
  - ionization

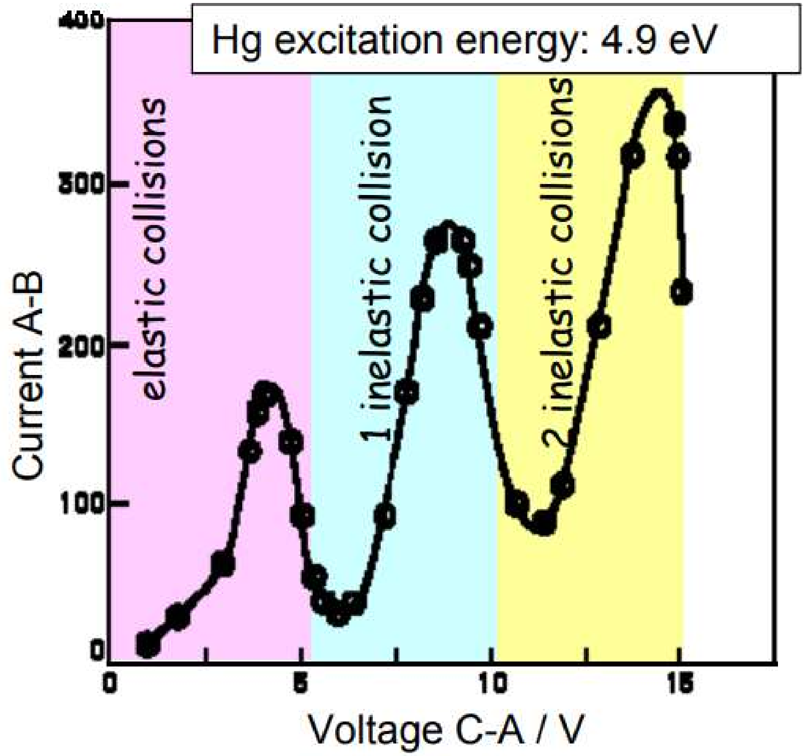
- Inelastic collisions between the electrons and mercury atoms

- The figure on the right side is a mercury (80) energy level diagram



Franck-Hertz experiment





The Nobel Prize in Physics 1925

"for their discovery of the laws governing the impact of an electron upon an atom"

James Franck

1/2 of the prize

Germany

Goettingen University
Goettingen, Germany

b.1882
d.1964

Gustav Ludwig Hertz

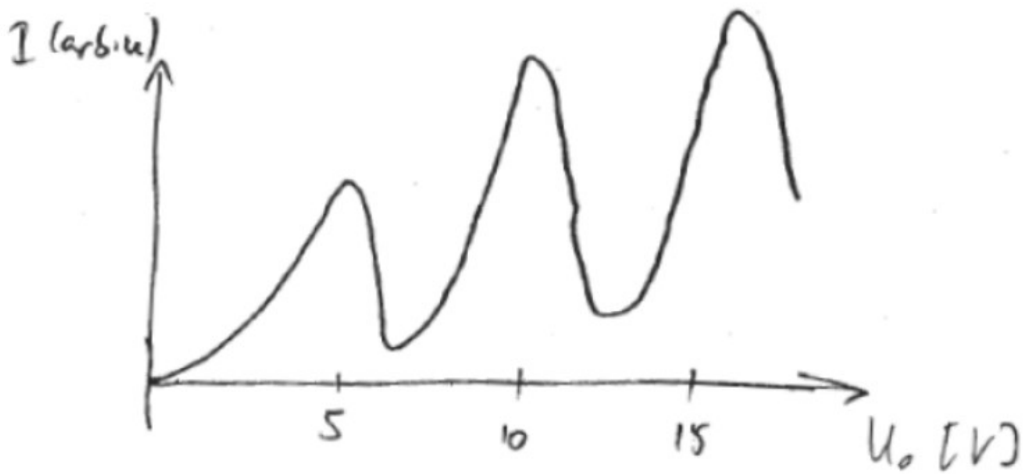
1/2 of the prize

Germany

Halle University
Halle, Germany

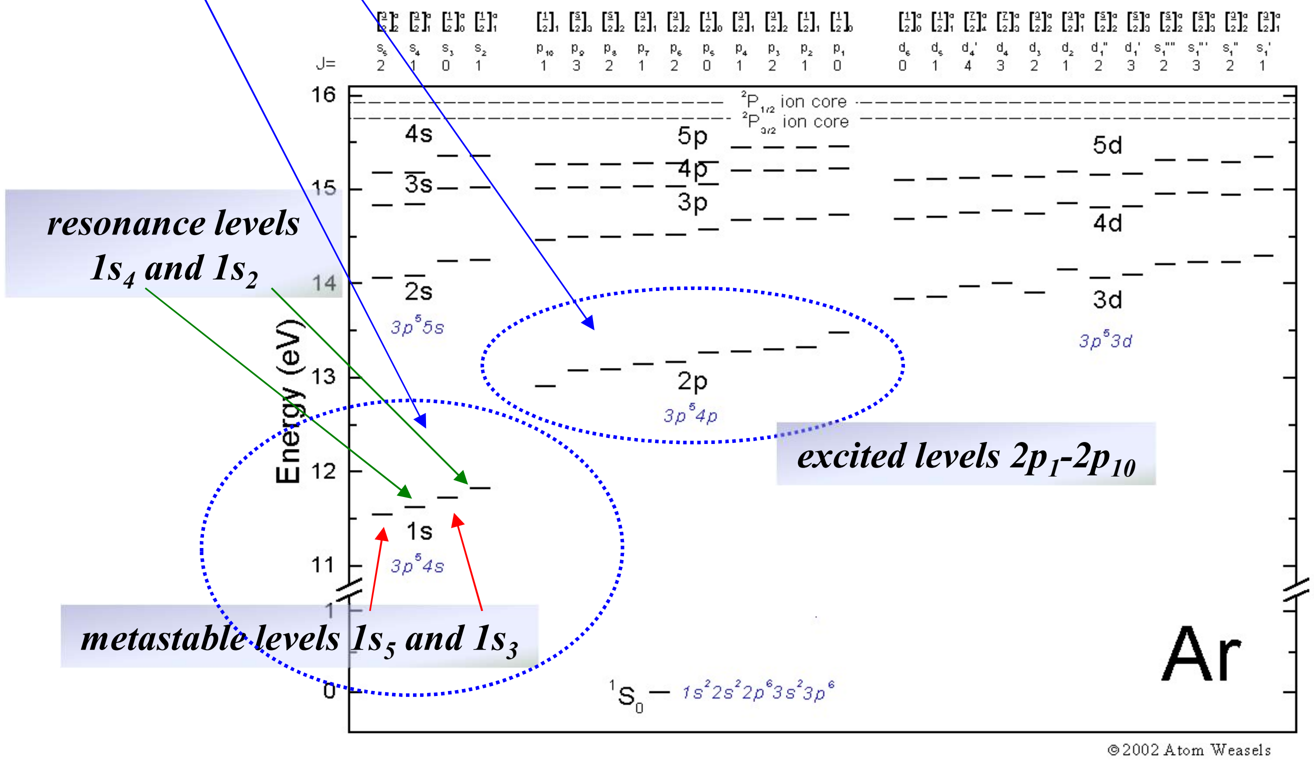
b.1887
d.1975

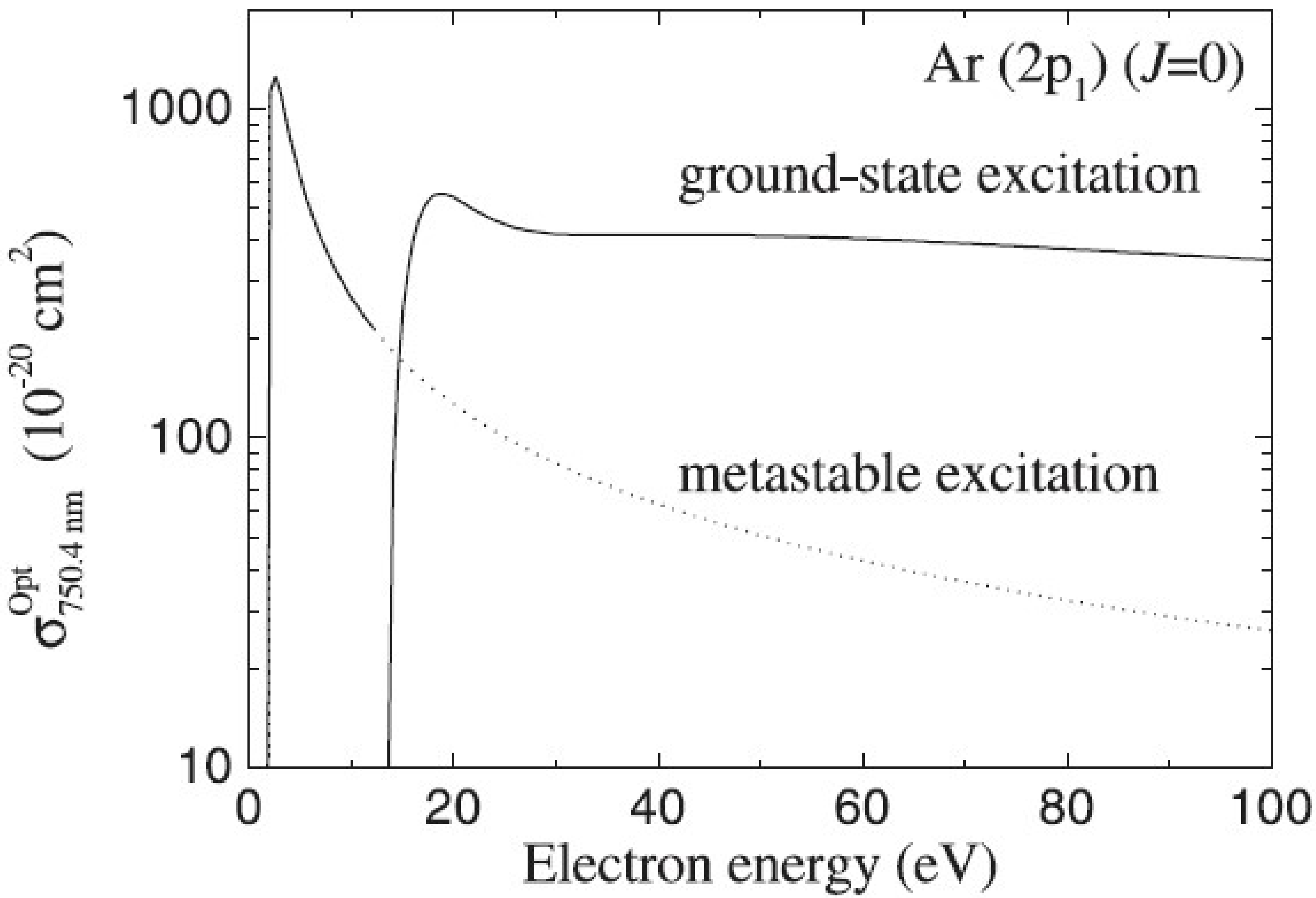
- 电子在加速向阳极飞的过程中穿过汞蒸气。其中一些通过了阳极栅网，到达检测器D，并被检测为电流。D和A之间有-0.5V电位差，可防止动能小于0.5 eV的低能电子到达检测器。因此，测量的电流不包括动能接近零的电子。
- 随着电压从零开始增加，尽管有汞蒸气，更多的电子还是能到达阳极，电流随电压增加。汞原子比电子重得多，弹性碰撞导致电子能量损失很少。在4.9V时，电流突然下降，因为很多电子和汞原子之间发生了非弹性碰撞，这些电子在一次碰撞中失去了所有动能，使汞原子进入激发态。因此，电子没有足够的能量来到达检测器D，导致电流急剧下降。在9.8V时也一样（一些电子和汞原子之间发生两次非弹性碰撞）。



An argon energy level diagram in Paschen notation

$$I = \Gamma\left(n_l\right) \cdot A \cdot n_u$$





Ar (2p1) (J=0)
ground-state excitation
metastable excitation
1000
100
10
0
20
40
60
80
100
Electron energy (eV)
σ Opt 750.4 nm (10-20 cm2)

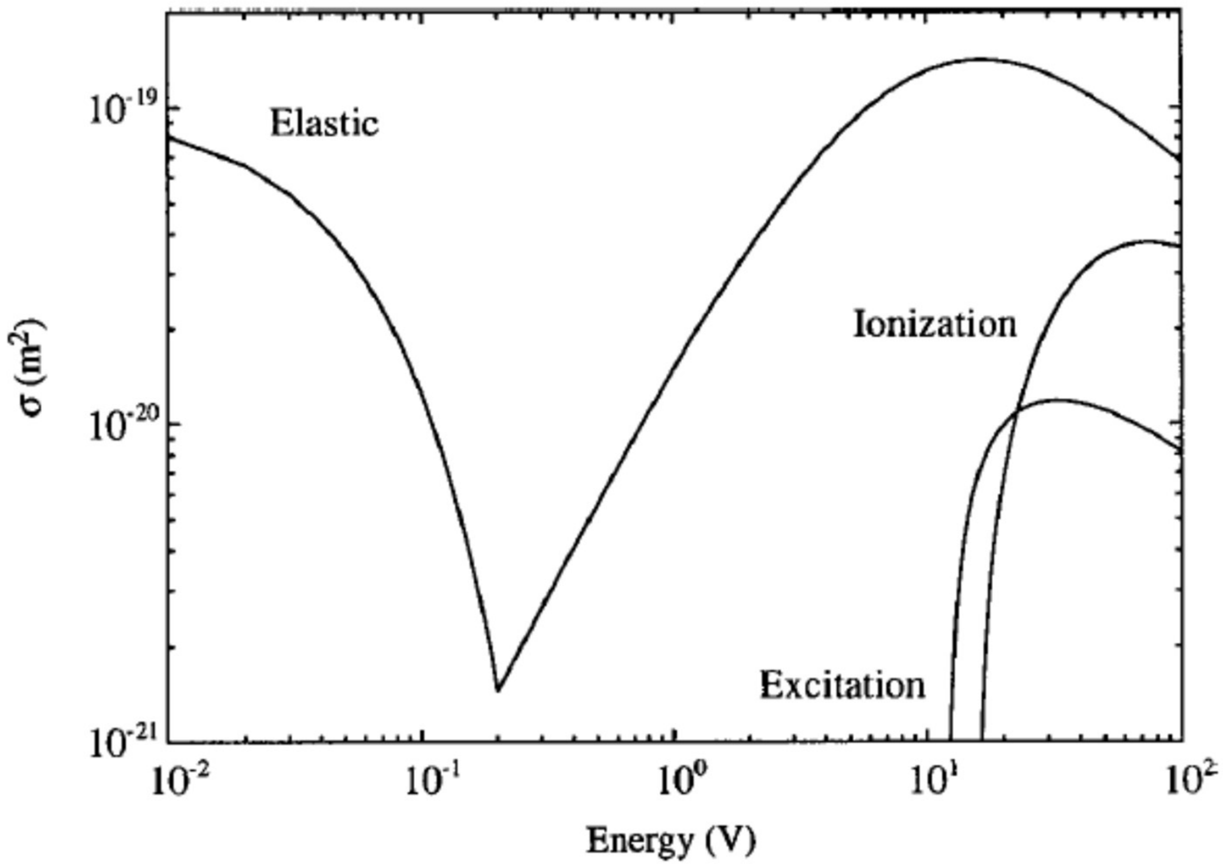
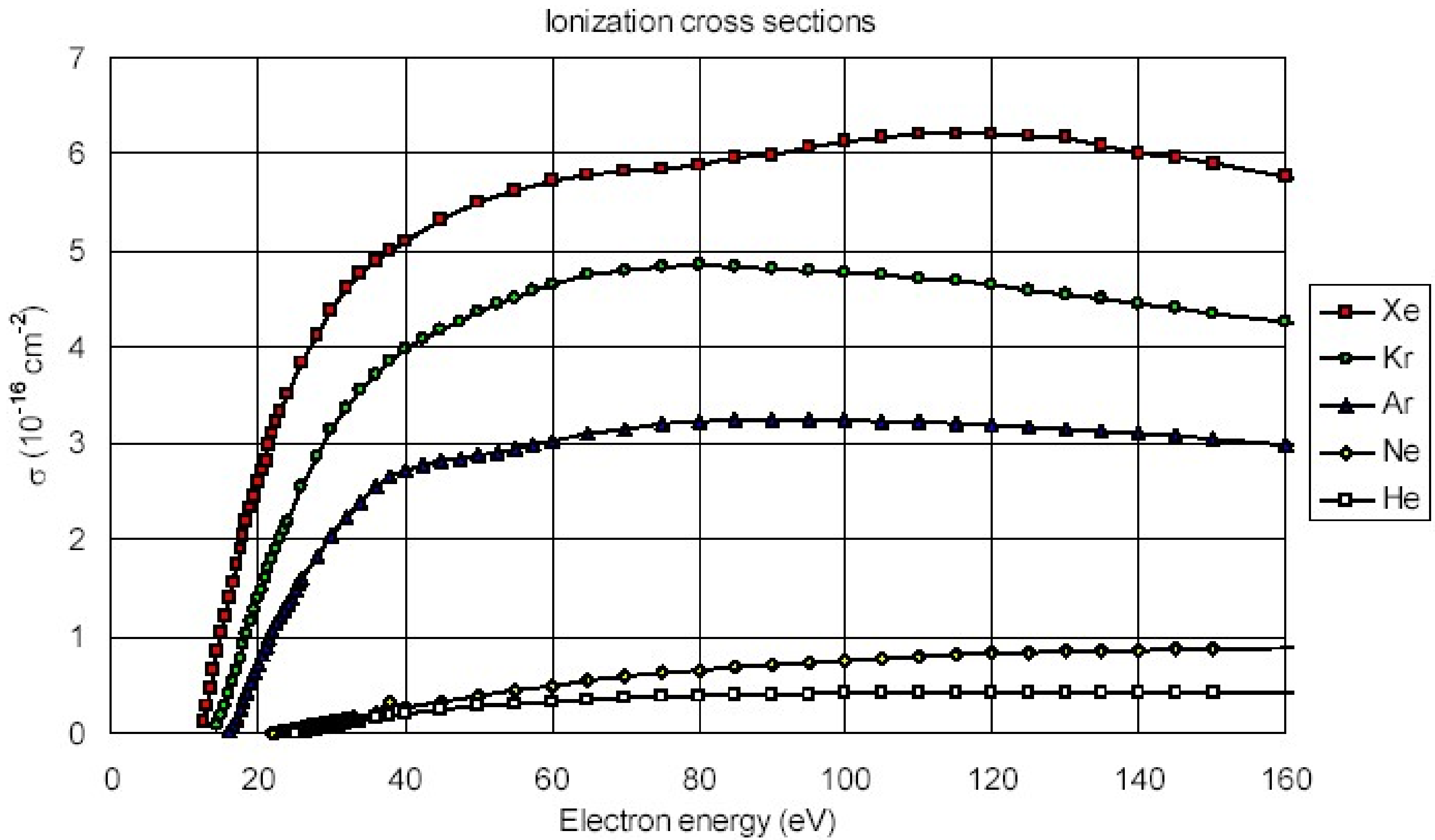


FIGURE 3.13. Ionization, excitation and elastic scattering cross sections for electrons in argon gas (compiled by Vahedi, 1993).

五种惰性原子的电离截面



- From these figures on electron impact cross sections, what do you observe?

- The peak values of cross sections

- The variation of the cross sections with electron energy

原子半径和电离截面的关系?

- He 31 原子序数2
- Ne 38 原子序数10
- Ar 71 原子序数18
- Kr 88 原子序数36
- Xe 108 原子序数54

Comparison between electron and ion impact ionization cross sections

- Threshold for electrons is 16 eV or so.
- What about ions?
- Why?
- How to estimate the threshold?

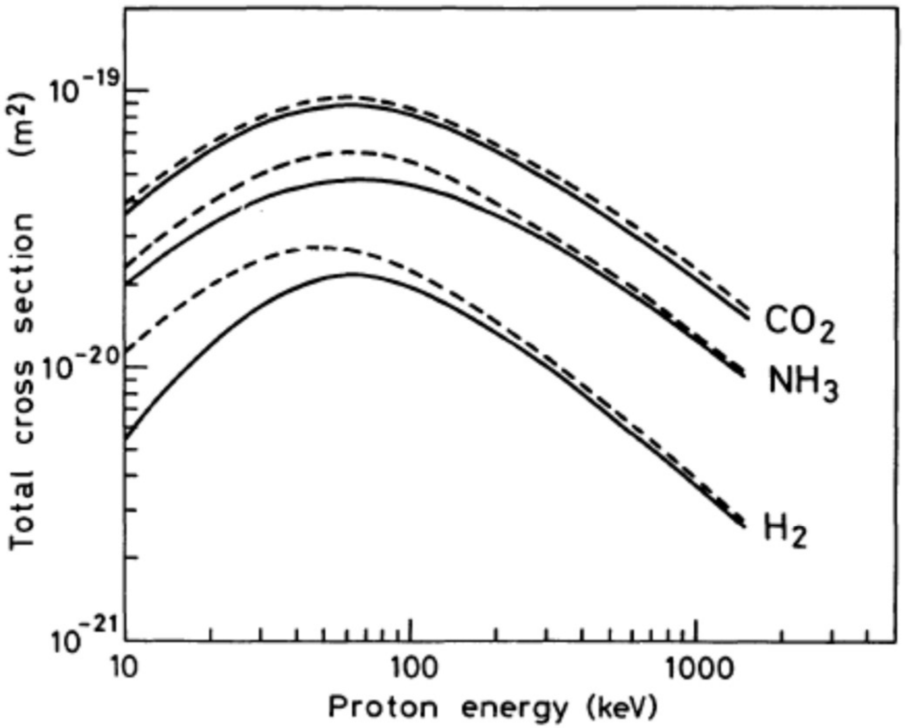


FIG. 1. Total single-ionization cross sections of H_2, NH_3, and CO_2 targets by proton projectiles. The solid lines are the recommended curves of Rudd *et al.* [1]. The dotted lines are calculated as a sum of the constituent cross sections taken also from Rudd *et al.* [1] as follows: $\sigma(H_2)=2\sigma(H)$, $\sigma(NH_3)=0.5\sigma(N_2)+1.5\sigma(H_2)$, and $\sigma(CO_2)=\sigma(CO)+0.5\sigma(O_2)$.

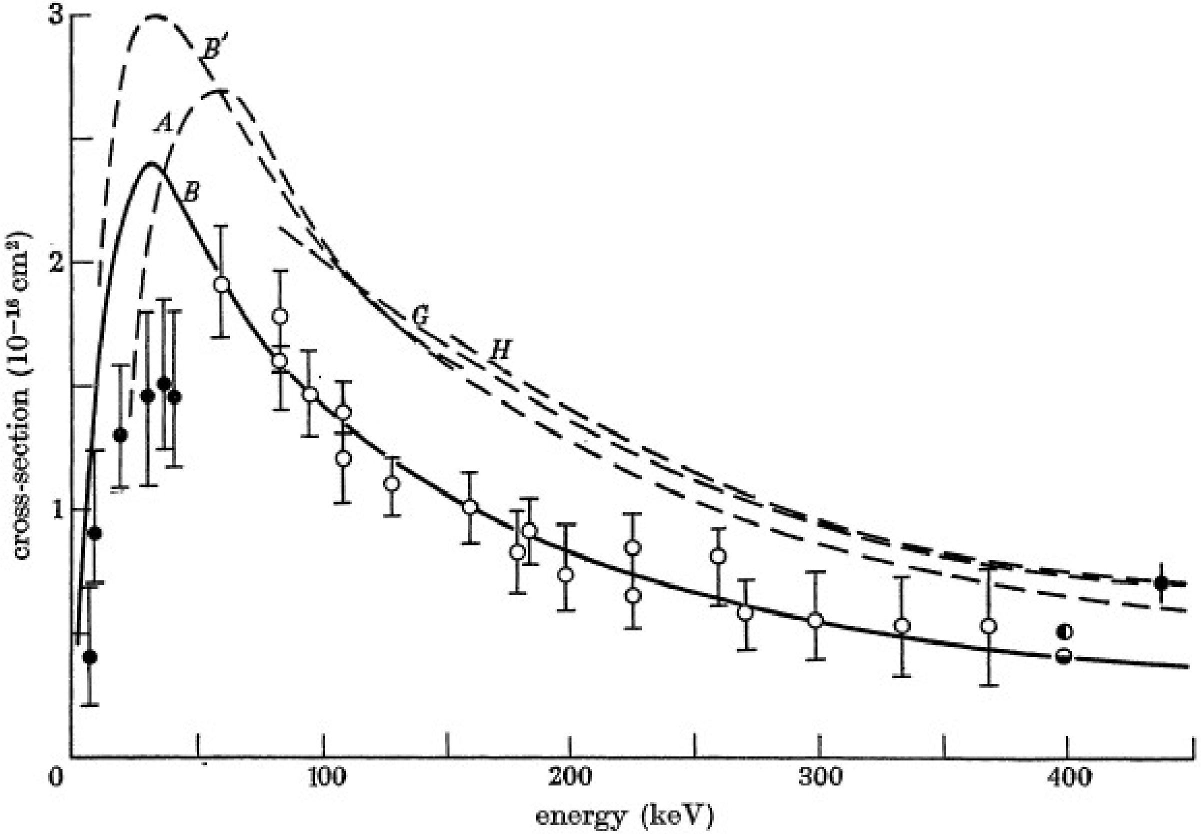


FIGURE 2. Ionization of atomic and molecular hydrogen by proton impact. Molecular hydrogen: B', Bates & Griffing (data obtained by use of scaling factor); G, Gilbody & Lee; A, Afrosimov *et al.*; H, Hooper *et al.* Atomic hydrogen: B, Bates & Griffing; ●, Fite *et al.*; ○, present data. Electron ionization for same relative velocity of impact: ◐, e + H, Fite *et al.*; ◒, e + H, Rothe *et al.*; ɸ, e + H_2, Tate & Smith.

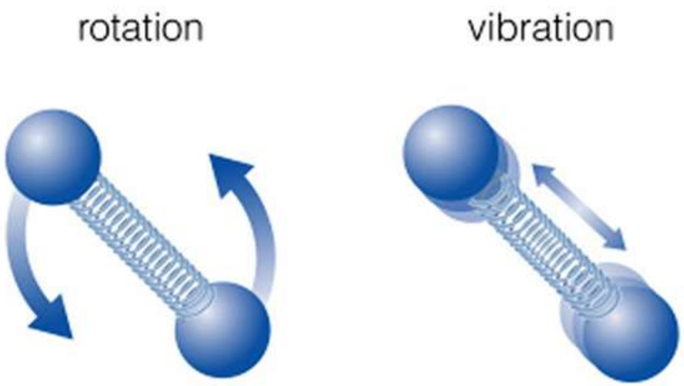
Electron collision with molecules

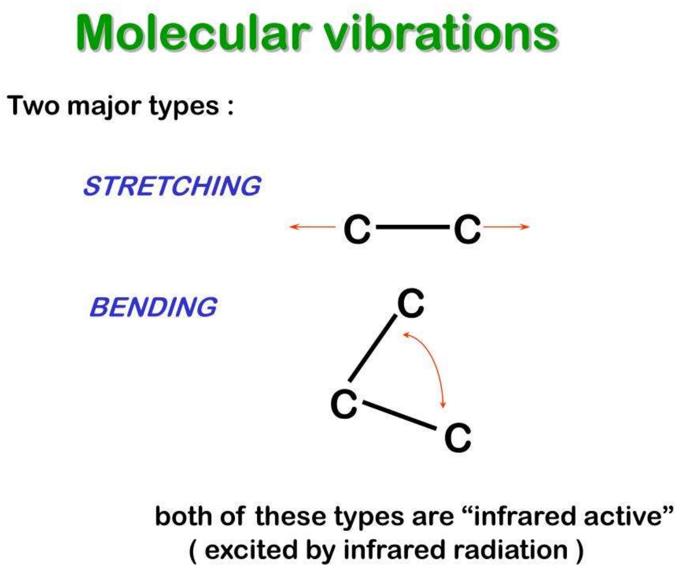
- We focus on inelastic collisions
- Rotational and vibrational excitation and their resonance nature
- Difference in emission spectra between discharges generated by atomic species and those by molecular species
- Electron impact ionization
- Electron impact dissociation

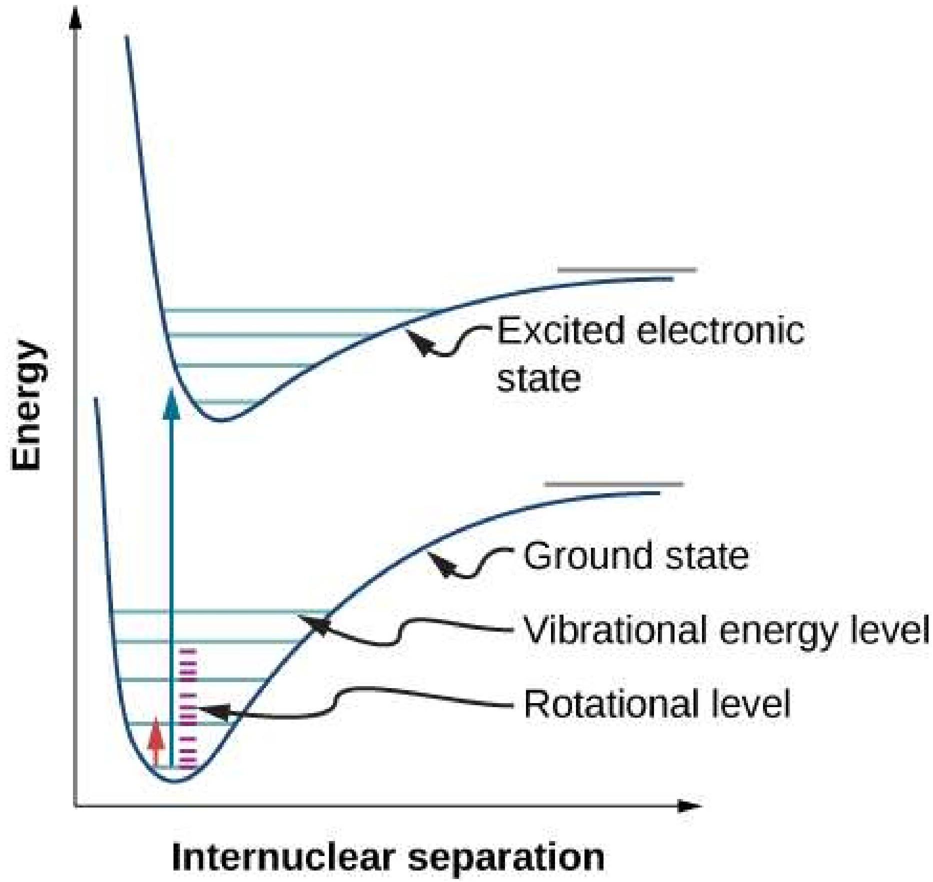
Electron collision with molecules

- Molecular gases are widely used in discharges (H_2, O_2, N_2, CH_4, CF_4, etc.)
- Molecules have additional degrees of freedom: vibrational and rotational motion
- The energy threshold for these excitations is much lower than that of electronic excitation. Inelastic collisions can occur with lower energy electrons
- Let us look at the nitrogen molecules as an example

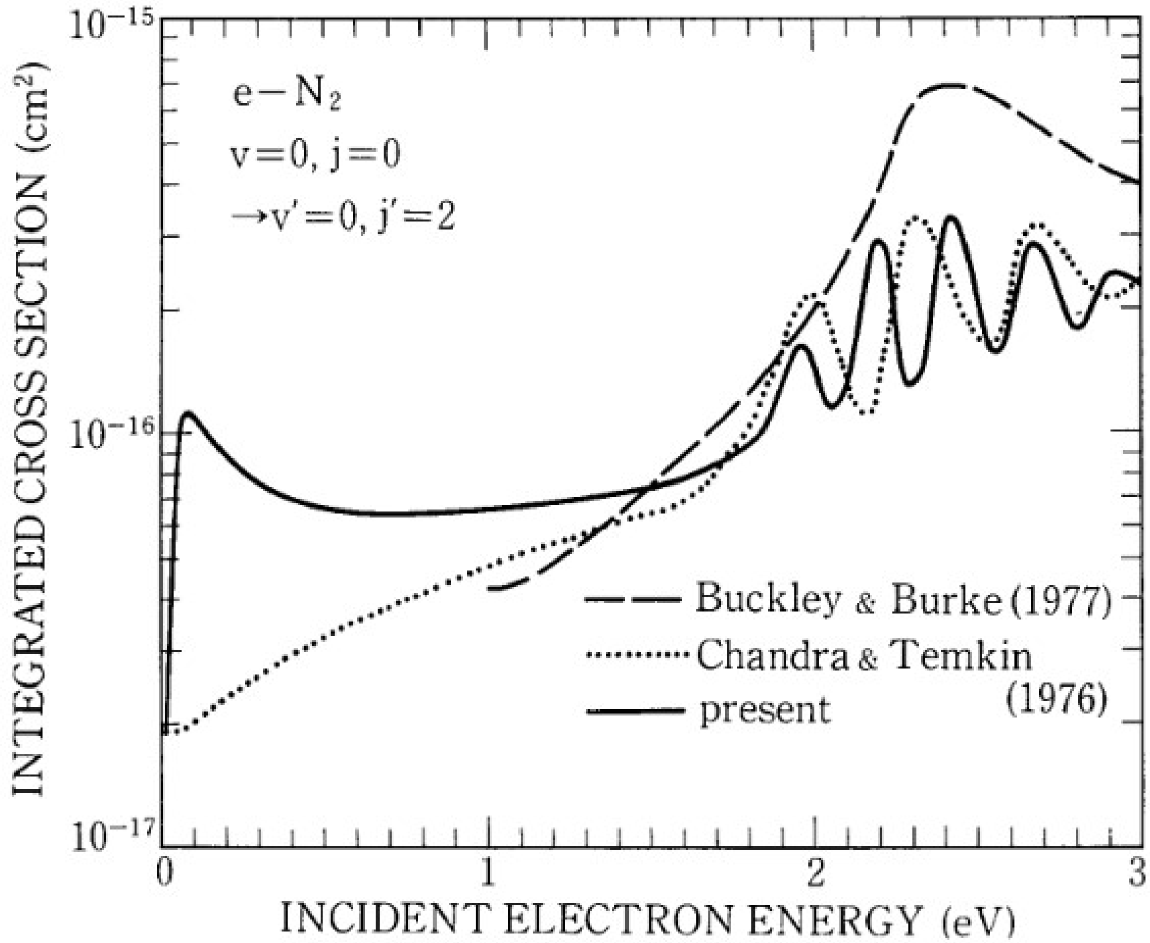
Molecules (such as N2) have additional degrees of freedom compared with atoms: vibration and rotation



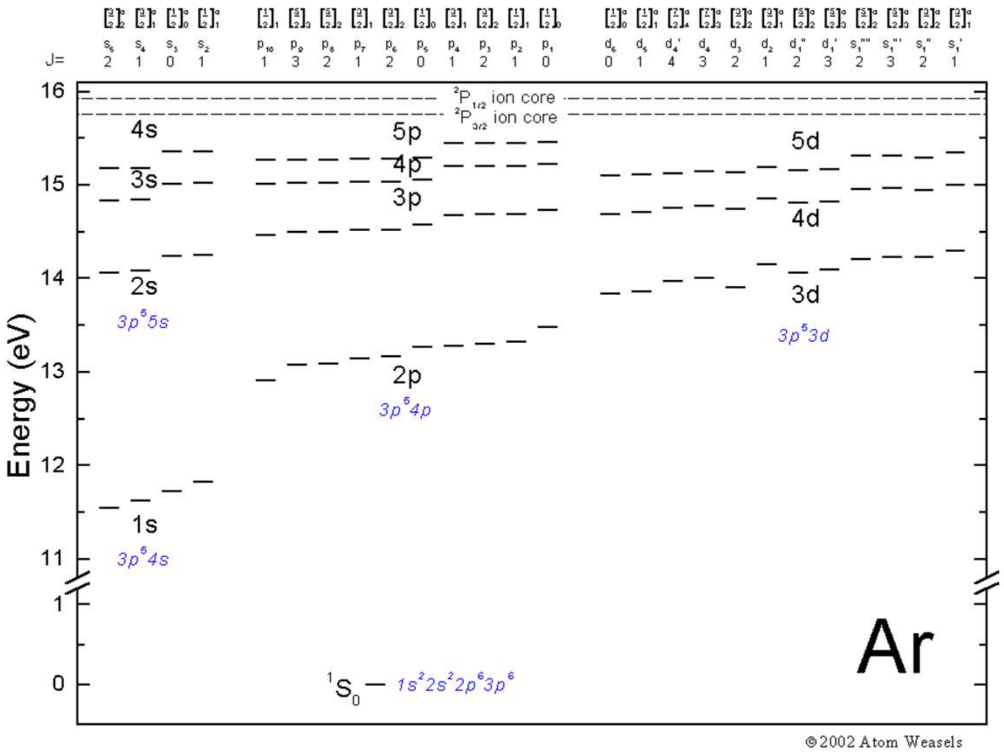


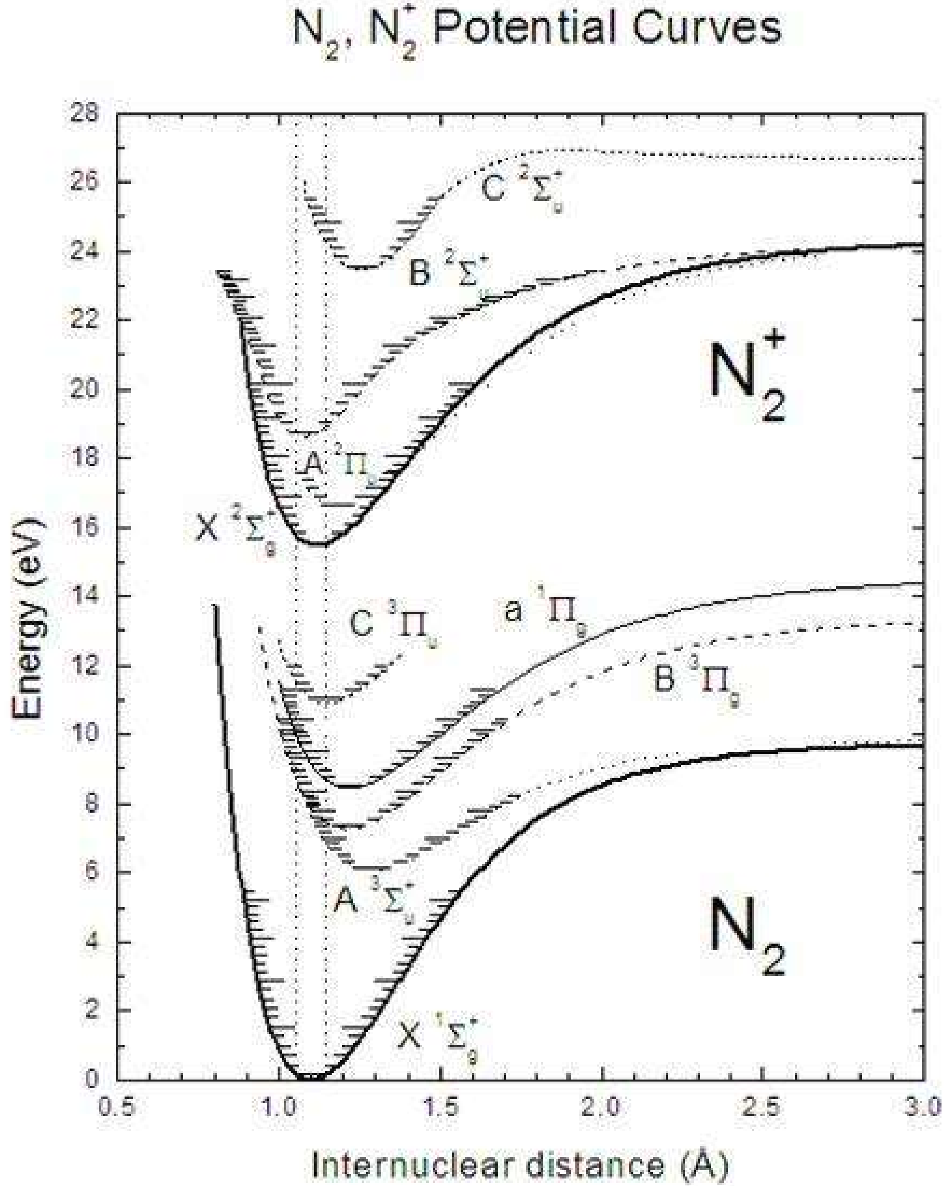


Kunizo Onda, Journal of Physical Society of Japan, Vol 54, 12 4544 (1985)

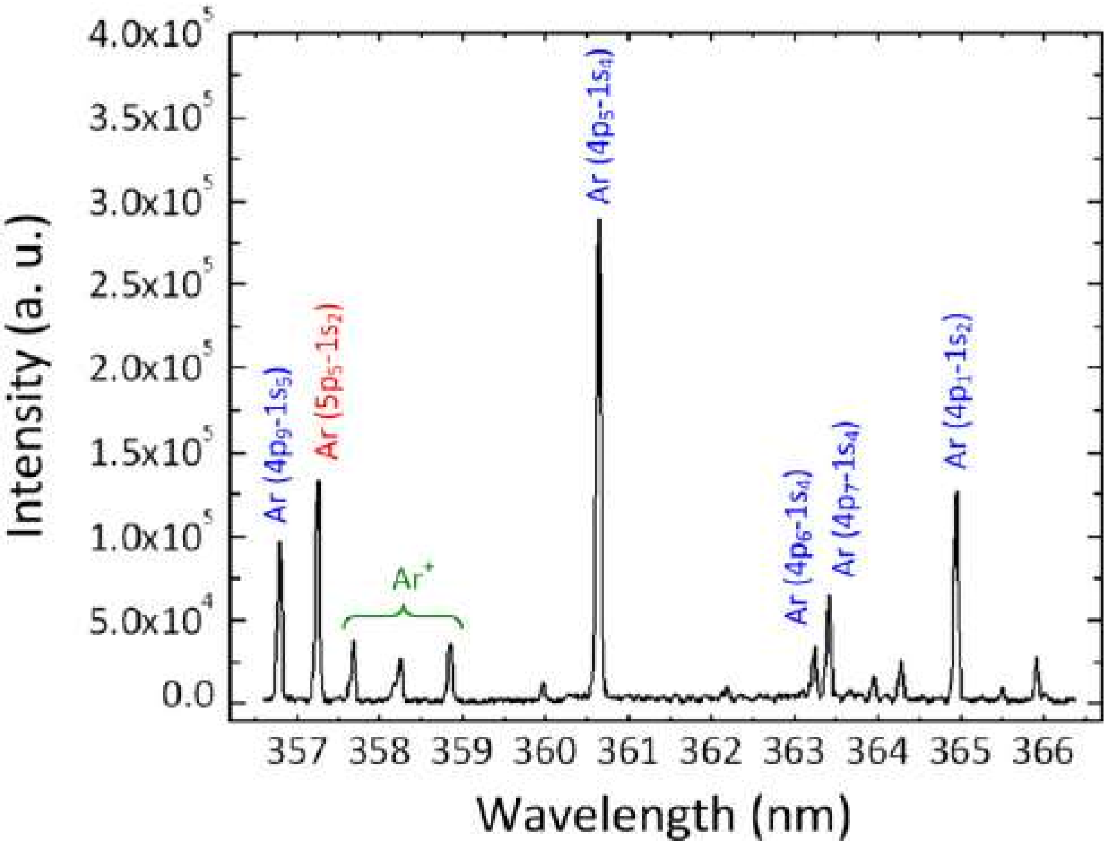


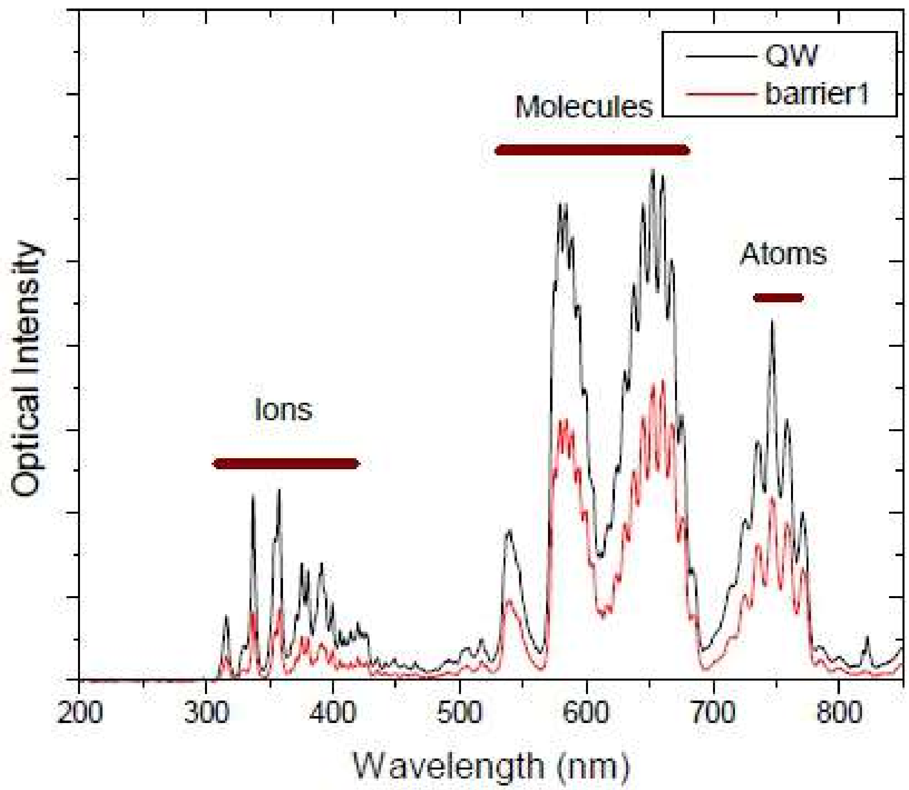
Potential energy diagram of N2 (right) compared with that of argon (below)



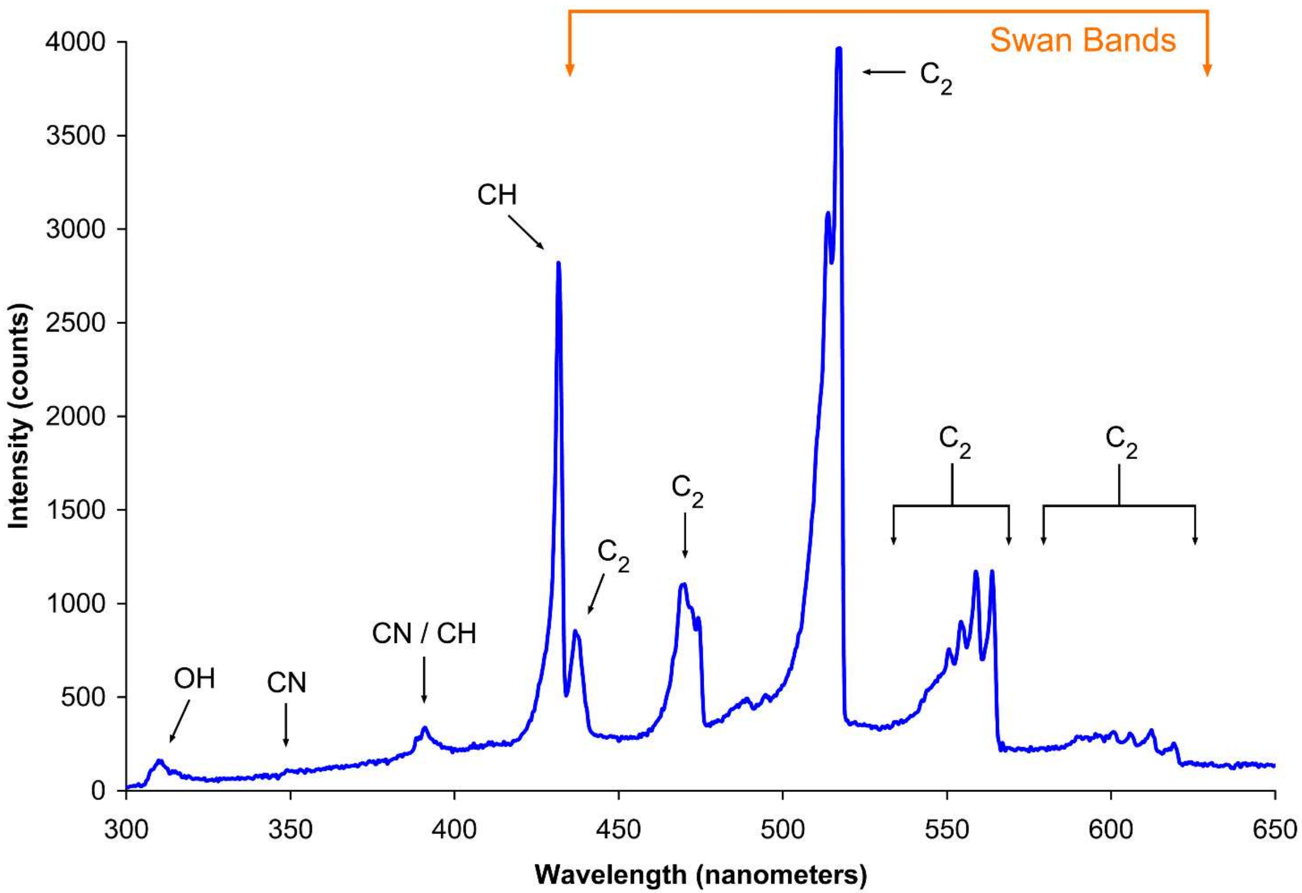


A large difference between the emission spectra between the discharges generated by these two gases

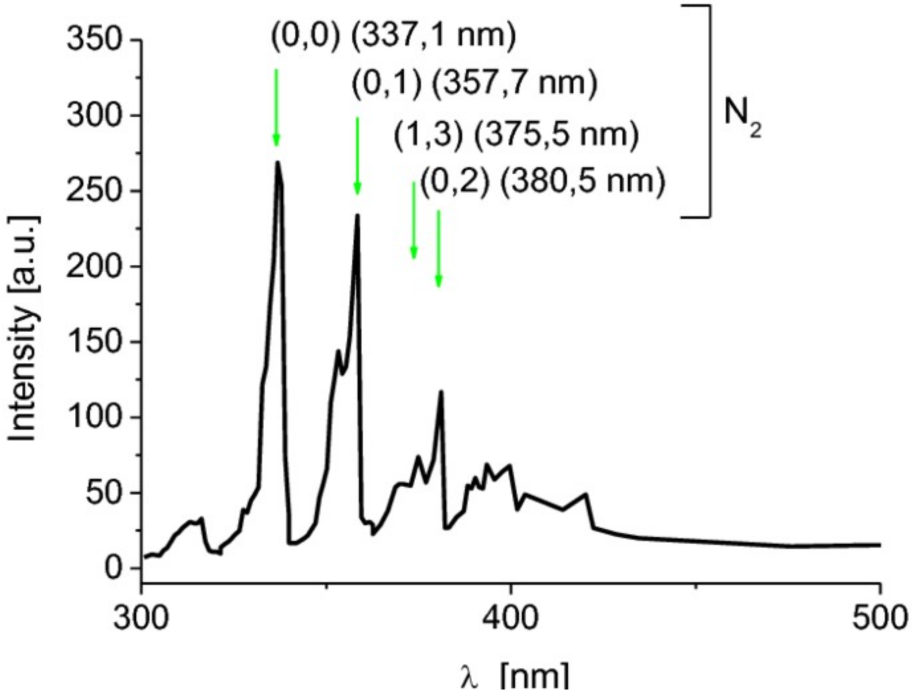


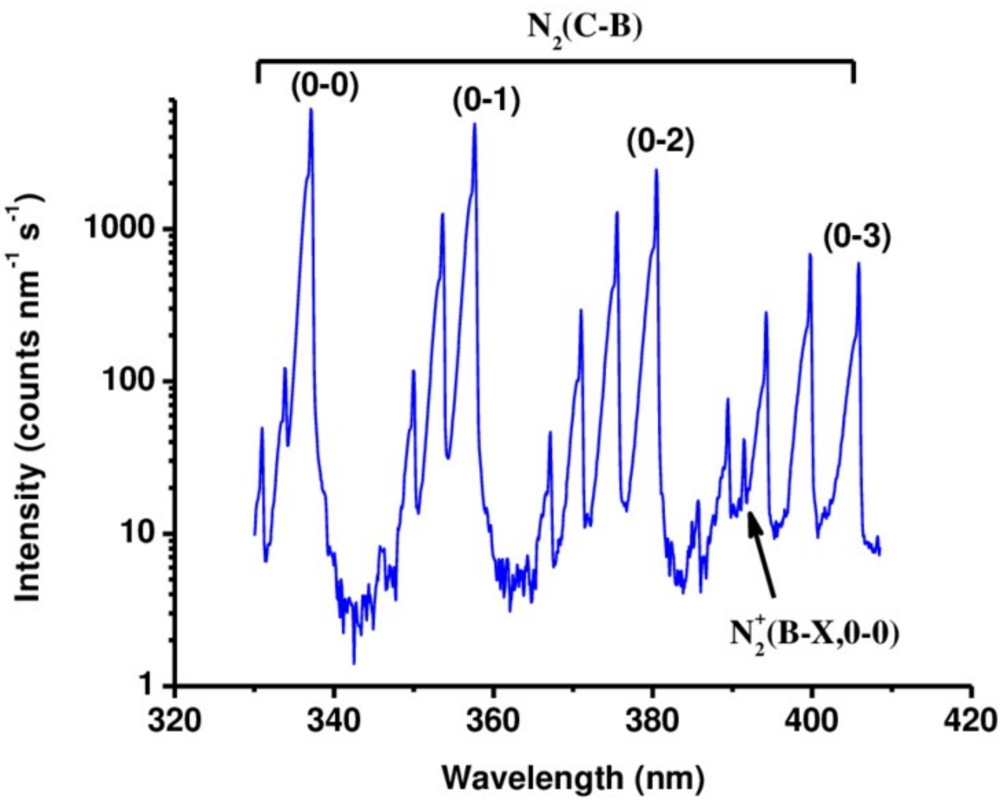


Spectrum of a hydrocarbon gas discharge



Spectrum collected by two spectrometers with different spectral resolution





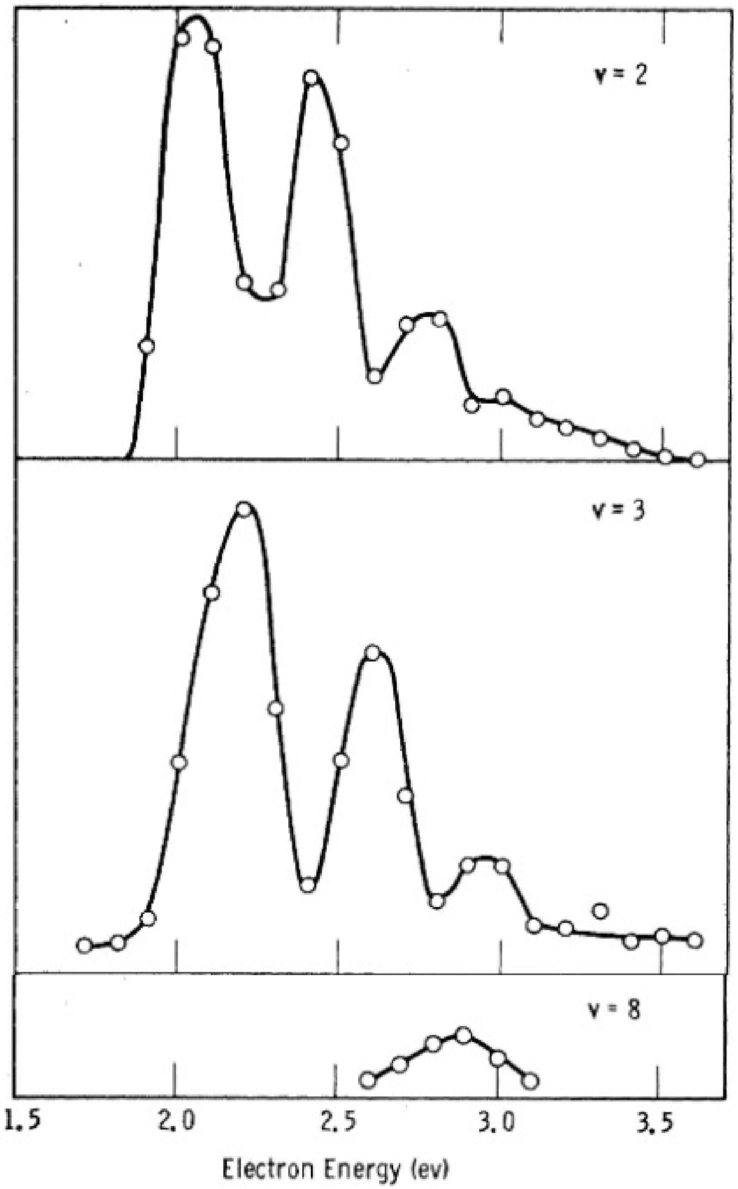
Why do we have peaks in the vibrational excitation cross section versus electron energy?

PHYSICAL REVIEW VOLUME 125, NUMBER 1 JANUARY 1, 1962

Vibrational Excitation of Nitrogen by Electron Impact*

G. J. SCHULZ
Westinghouse Research Laboratories, Pittsburgh, Pennsylvania
(Received August 24, 1961)

The vibrational excitation of nitrogen molecules by electrons in the energy range 1.5 to 4 ev is studied using a double electrostatic analyzer. The beam of essentially monoenergetic electrons (half-width about 0.06 ev) is produced by the first analyzer and is crossed by a molecular beam of N_2 in the collision chamber. The energy distribution of forward scattered electrons is analyzed in the second electrostatic analyzer. Peaks resulting from those electrons which have lost discrete amounts of energy in exciting vibrational levels up to $v=8$ are observed. The energy dependence of the cross section for vibrational excitation to $v=2, 3, 4, 5, 6, 7, 8$ is obtained and pronounced structure is observed. The experiment is consistent with the hypothesis that the vibrational excitation in N_2 around 2.3 ev proceeds via a temporary negative ion.



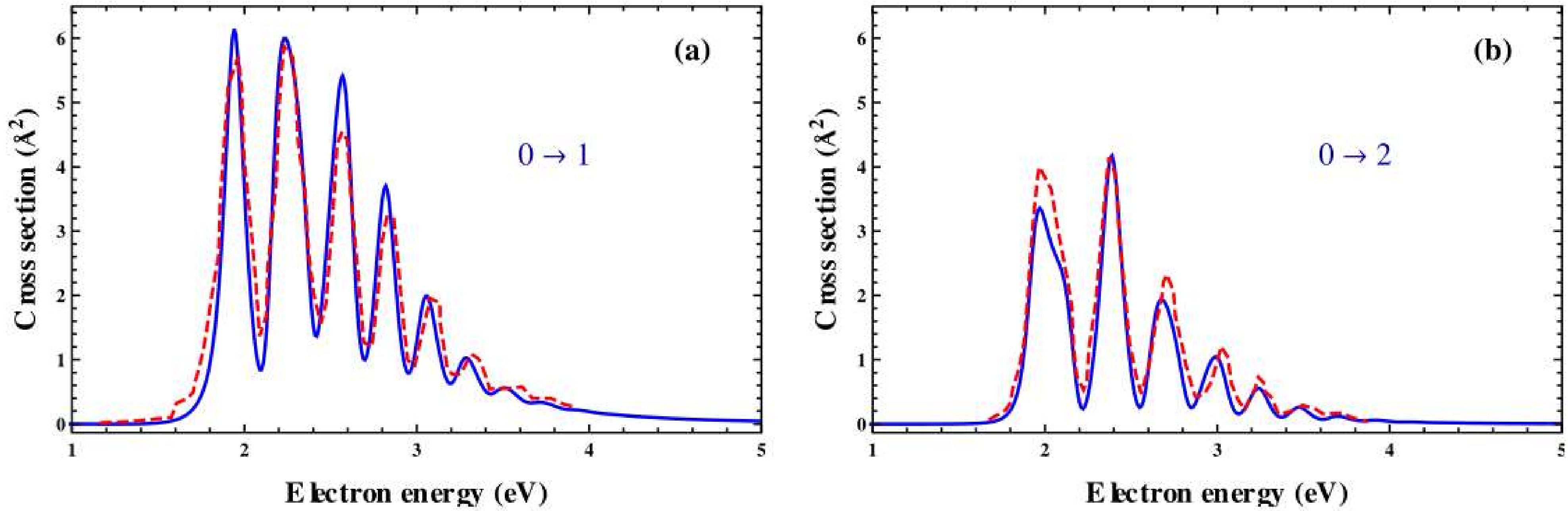
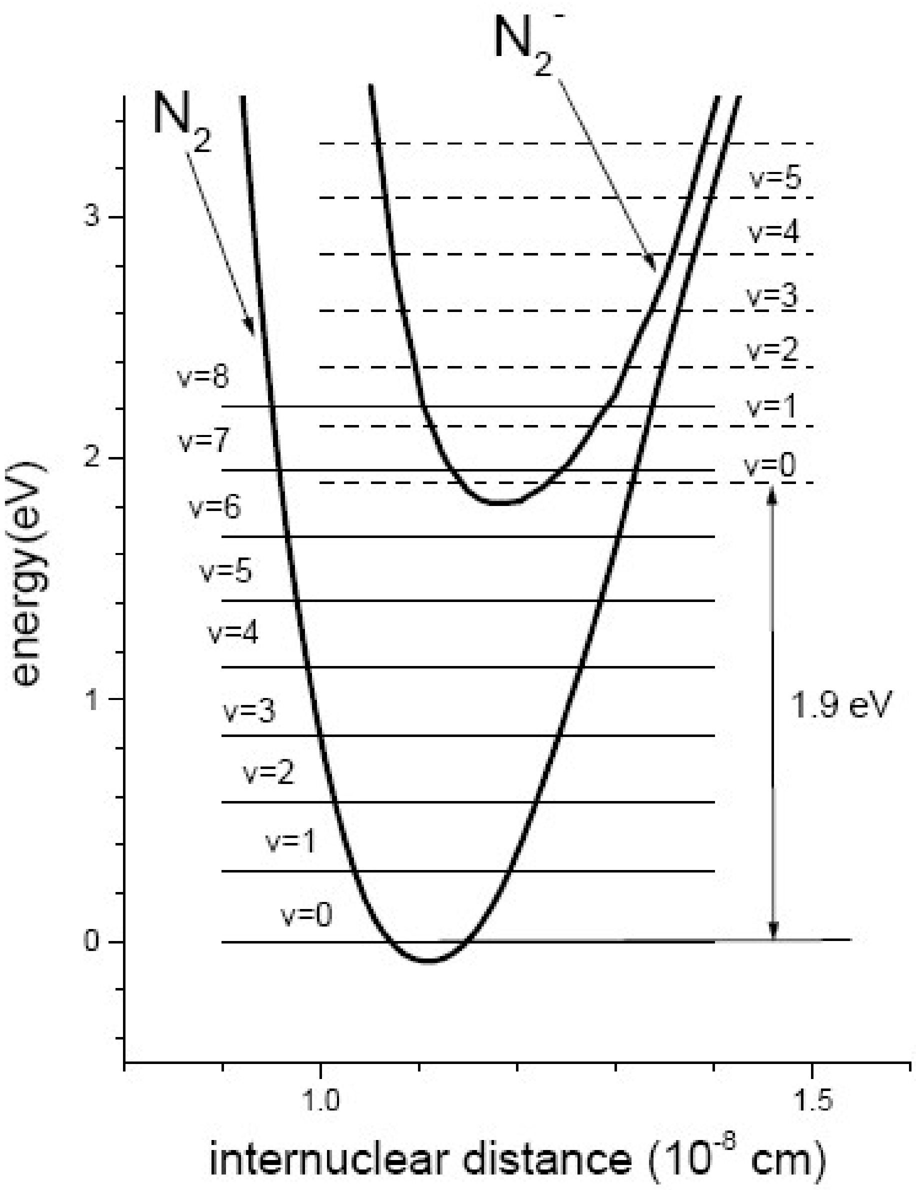


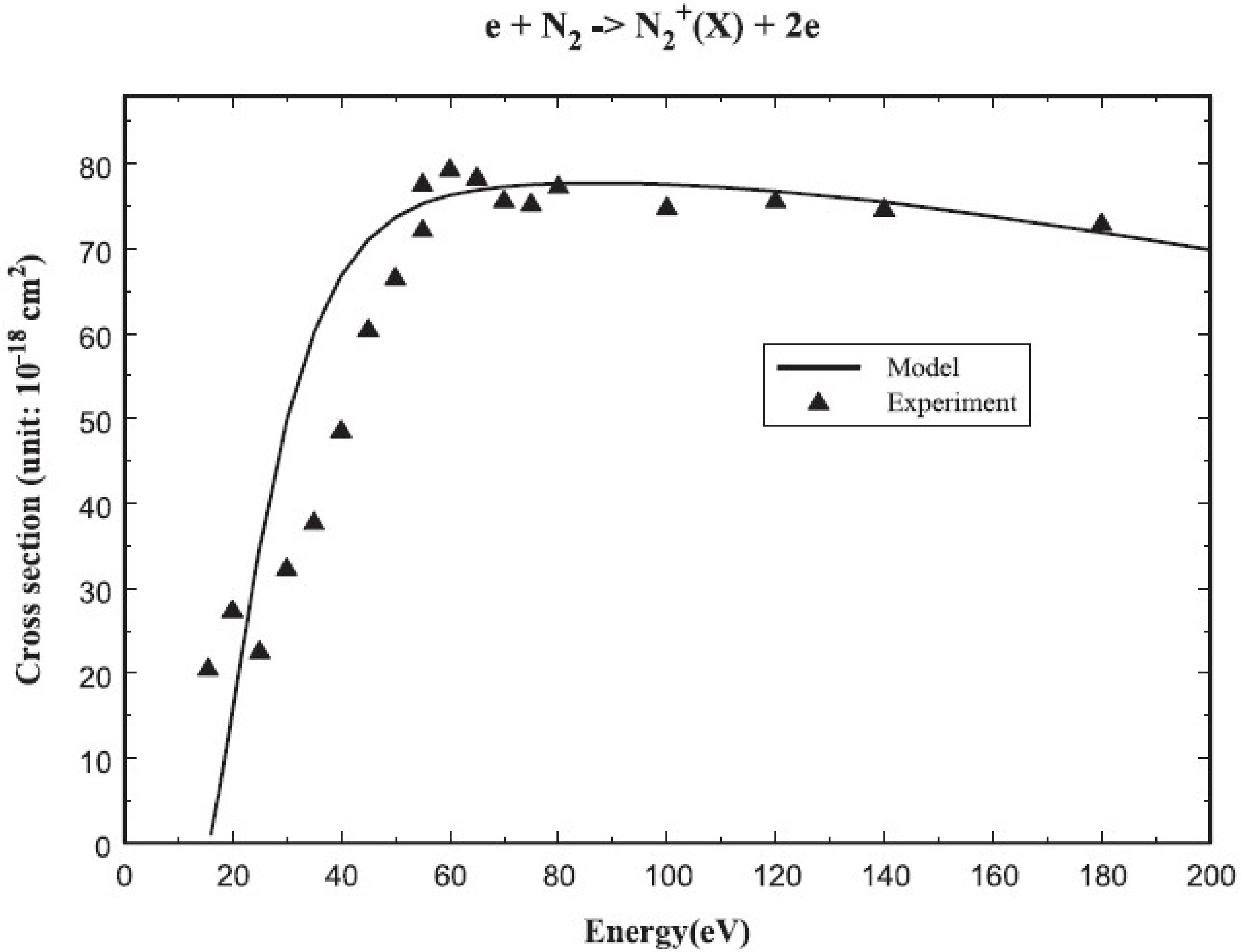
Figure 4. Electron–N_2 theoretical–experimental cross section comparison for the rotationless $v_i = 0 \rightarrow v_f = 1, 2$ transitions as the panels. Full lines: present calculations; dashed lines: unpublished experimental results of Wong as cited in [13].

V Laporta *et al* 2012 *Plasma Sources Sci. Technol.* **21** 055018

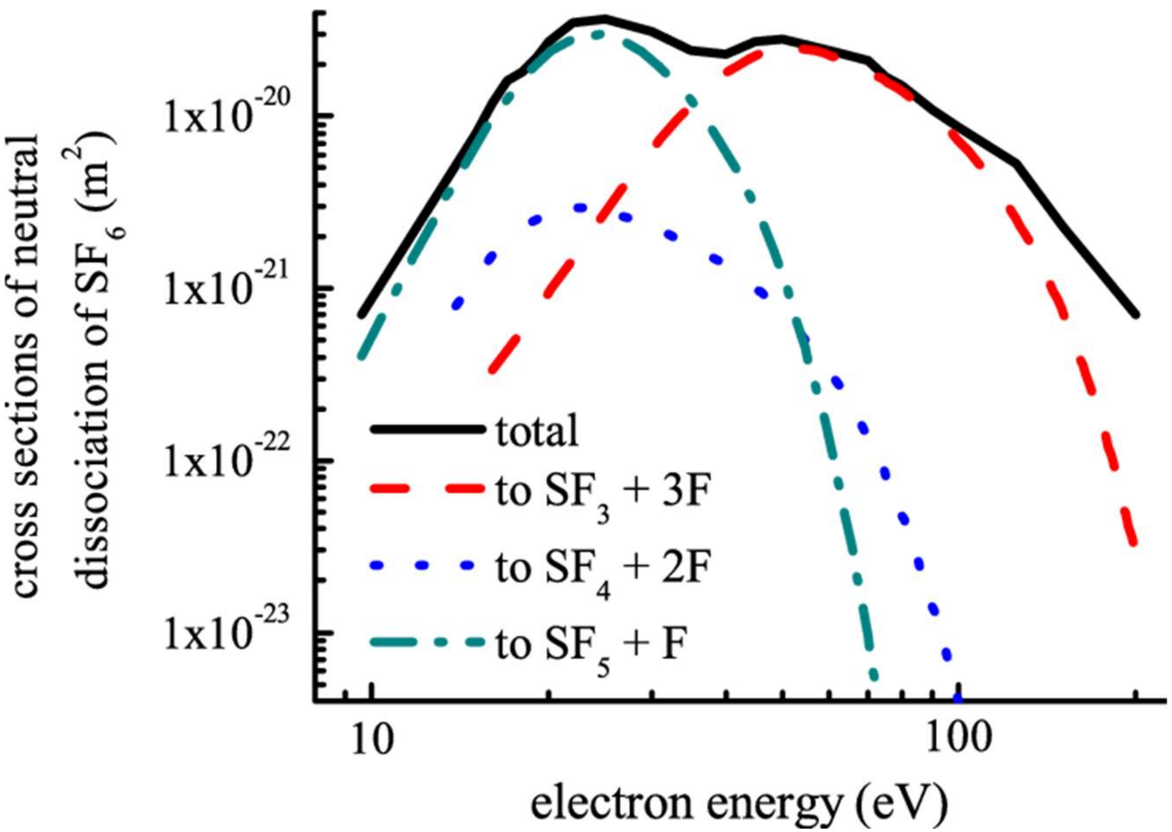
- Zoom in the potential energy diagram for vibrational levels
-



Electron impact of ionization of nitrogen molecule



Electron impact dissociation of SF6



The role of valence electrons on collisions

- The size of a hydrogen atom
- The distance between atoms in a molecules
- The lattice constant in a crystal
- The nature of interactions between an electron and a molecule: Coulomb interaction between the free electron and the valence electron. Energy acquired by the valence electron can be transferred to the heavy species by their interaction over a longer time.
- Interaction between heavy species are through their respective valence electrons

- For the incoming electrons, their “fate” during a collision process is energy dependent, it also depends on the target species
- Collisions between electrons themselves lead to thermal equilibrium distribution: Maxwellian! But electron collision with other heavy species may be the cause of a non-Maxwellian distribution

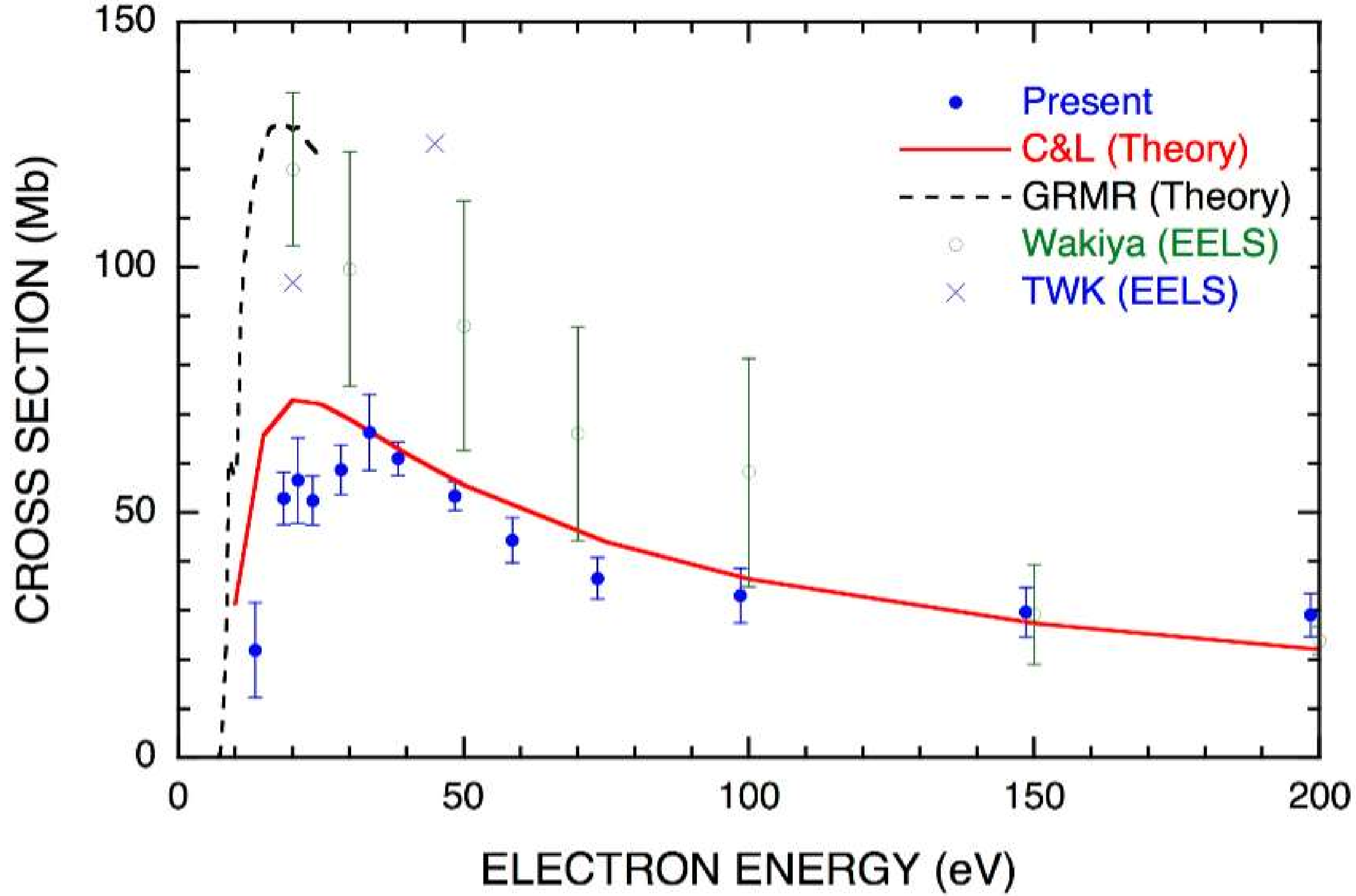
- What about collisional effect on positive ions?

- What about collisional effect on neutral species?

Current situation on cross sections

- Many cross section data are not available
- Many available cross section data do not agree with each other

- There is a large difference between collisional effects in a weakly ionized gases and a fully ionized plasma!



150
100
50
0
0
50
100
150
200
CROSS SECTION (Mb)
ELECTRON ENERGY (eV)
Present
C&L (Theory)
GRMR (Theory)
Wakiya (EELS)
TWK (EELS)

Major takeaways

- Many plasmas are generated due to collisional processes
- Collisions have a strong impact on energy transfer processes and particle transport process
- Collision is an interaction between two or three particles within a short range
- Collision frequency represents the rate of change in momentum of the incoming particle due to collisions
- Cross section represents the strength of the interaction
- The rate of these collision processes depends on the electron energy distribution function

Homework

- In two plasmas, one has a higher pressure than the other, which one has a more uniform electron density profile? Why?
- Will this recombination reaction happen in the middle of low pressure discharges? If not, explain why

$$e + Ar^{+} \rightarrow Ar$$

- If an electron collides with an argon atom, please discuss the kinetic energy of both the electron and the atom or ion, after an elastic or inelastic collision. If the initial kinetic energy of the electron is exactly 15.7596 eV, can ionization occur if it collides with an argon atom?

In this emission spectrum of a discharge containing argon, hydrogen and oxygen gases, do we have emissions from hydrogen and oxygen molecules, if so, where, why?