Ionization

The Townsend (symbol Td) is a physical unit of the reduced electric field (ratio E/N), where E is electric field and N is concentration of neutral particles.
It is named after John Sealy Townsend, who conducted early research into gas ionization.

Energy levels He

<u>Grotrian diagram </u>He

Ionization energy He

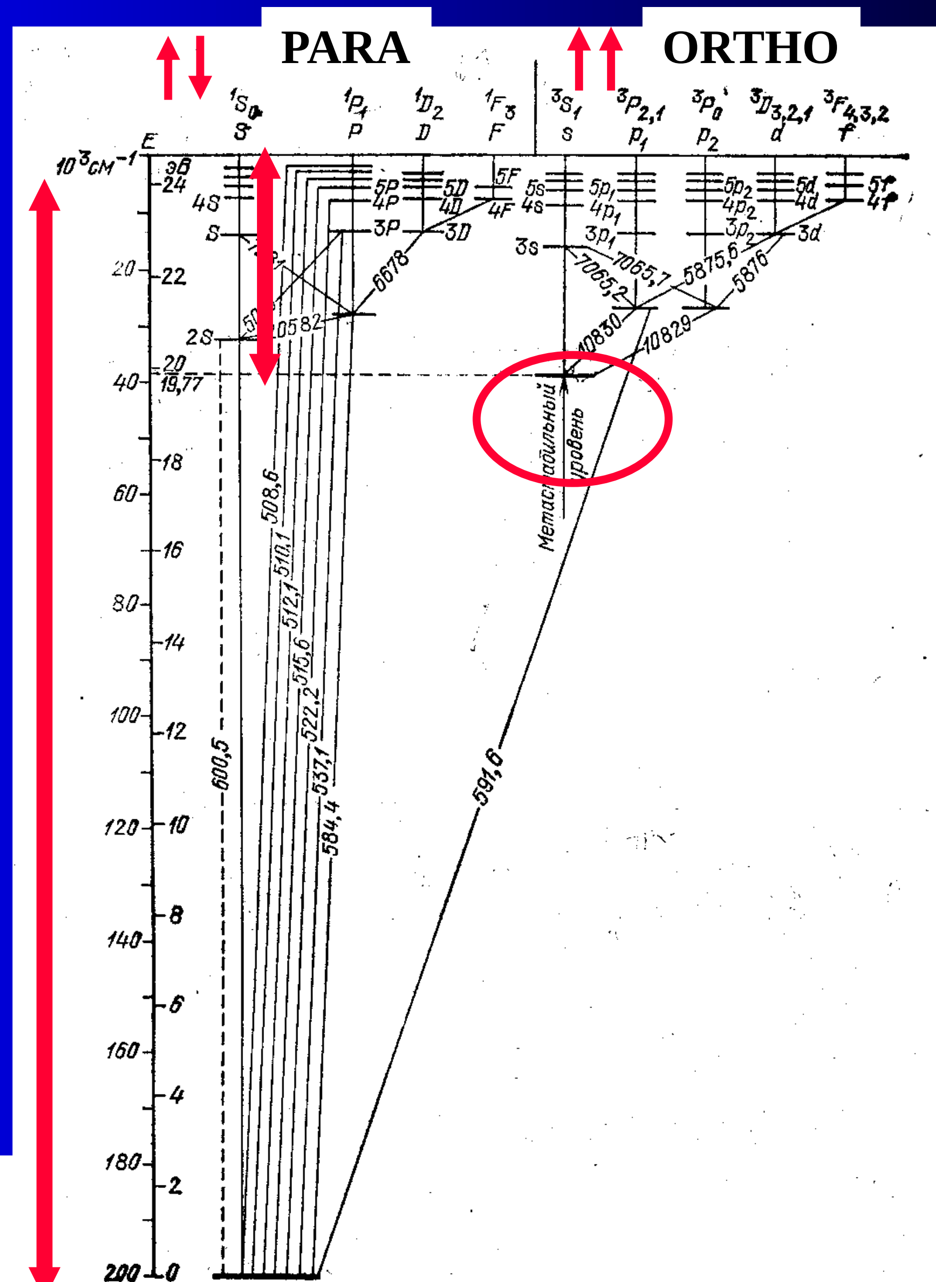


Рис. 3.8. Схема уровней атома He

24.46eV → ~198400 cm^{-1} → ~50nm

vacuum ultraviolet

Ionization cross section

Ionization by electron impact

Atoms

$$Ar + e^-(\varepsilon_0) \rightarrow Ar^+ + e_1^-(\varepsilon_1) + e_2^-(\varepsilon_2)$$

Molecules

$$N_2(\nu,j) + e^-(\varepsilon_0) \rightarrow N_2^+(\nu,j) + e_1^-(\varepsilon_1) + e_2^-(\varepsilon_2)$$

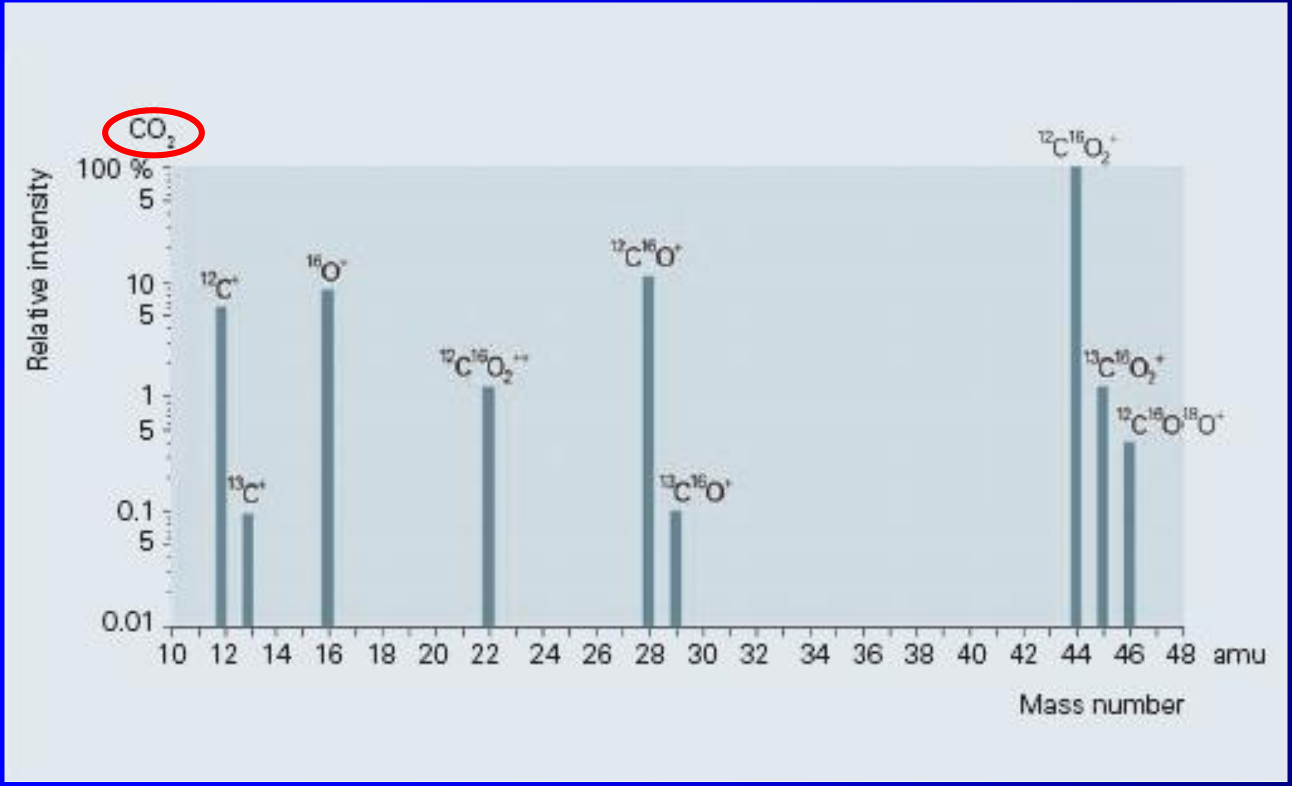
$$\rightarrow N^+(\varepsilon_{KIN}) + N(\varepsilon_{KIN}) + e_1^-(\varepsilon_3) + e_2^-(\varepsilon_4)$$

$NH_3 + e^-(\varepsilon_0) \rightarrow$ …..to many channels

Ionization by electron impact

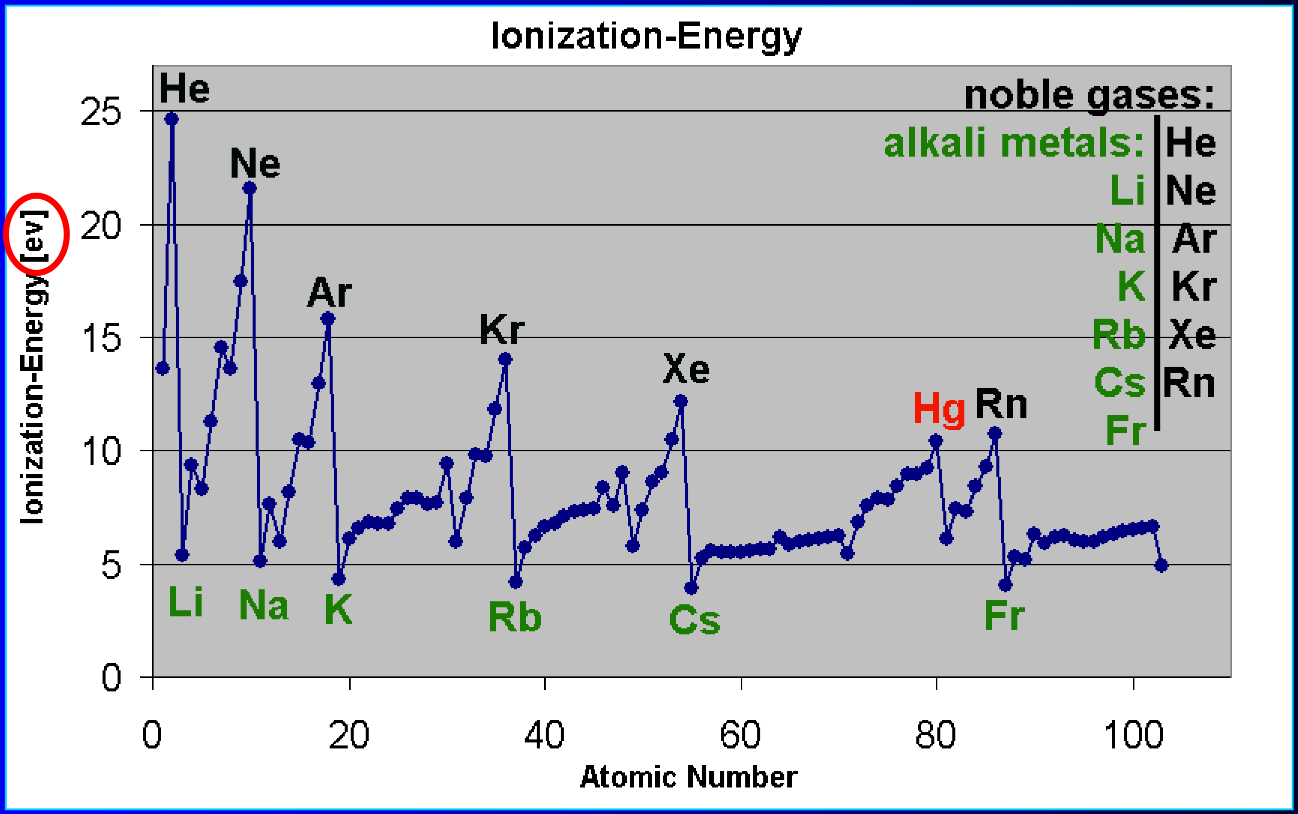
Interaction of electrons with atoms and molecules

Ionization by electron impact
Excitation by electron impact



N_2	28.0062
CO	27.9949
C_2H_4	28.0312

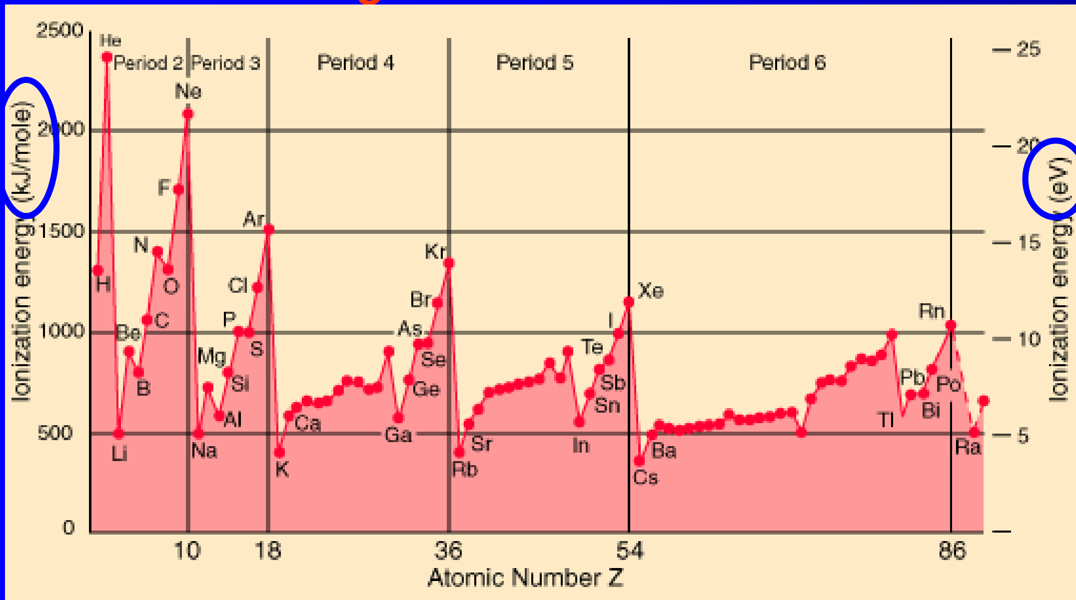
Ionization energies



$$Ar + e^-(\varepsilon_0) \rightarrow Ar^+ + e_1^-(\varepsilon_1) + e_2^-(\varepsilon_2)$$

$$N_2 + e^-(\varepsilon_0) \quad \rightarrow \text{ion} \ldots$$

Ionization energies

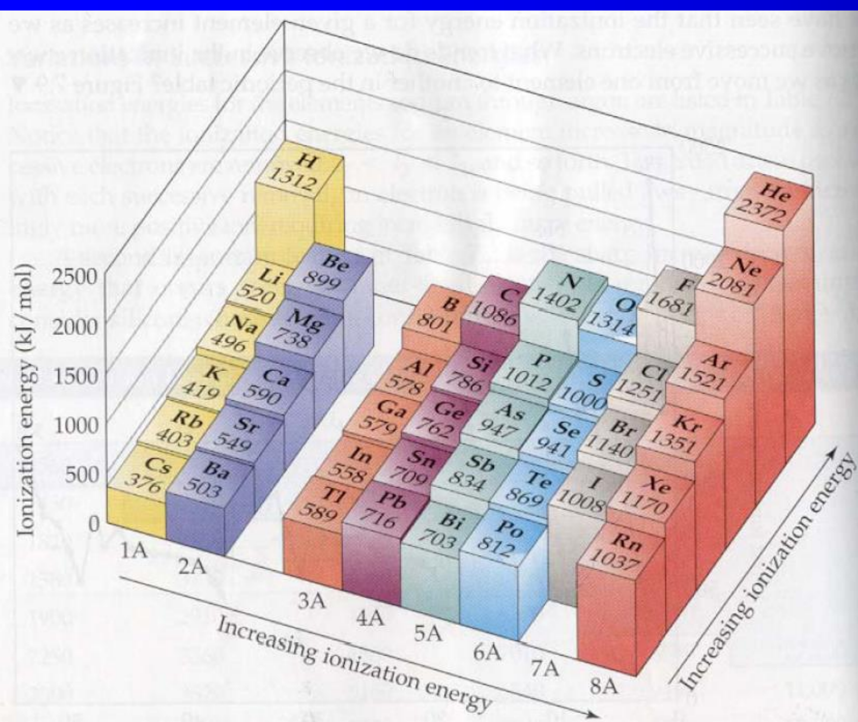


Ionization Energy

- **First ionization energy (IE_1)**

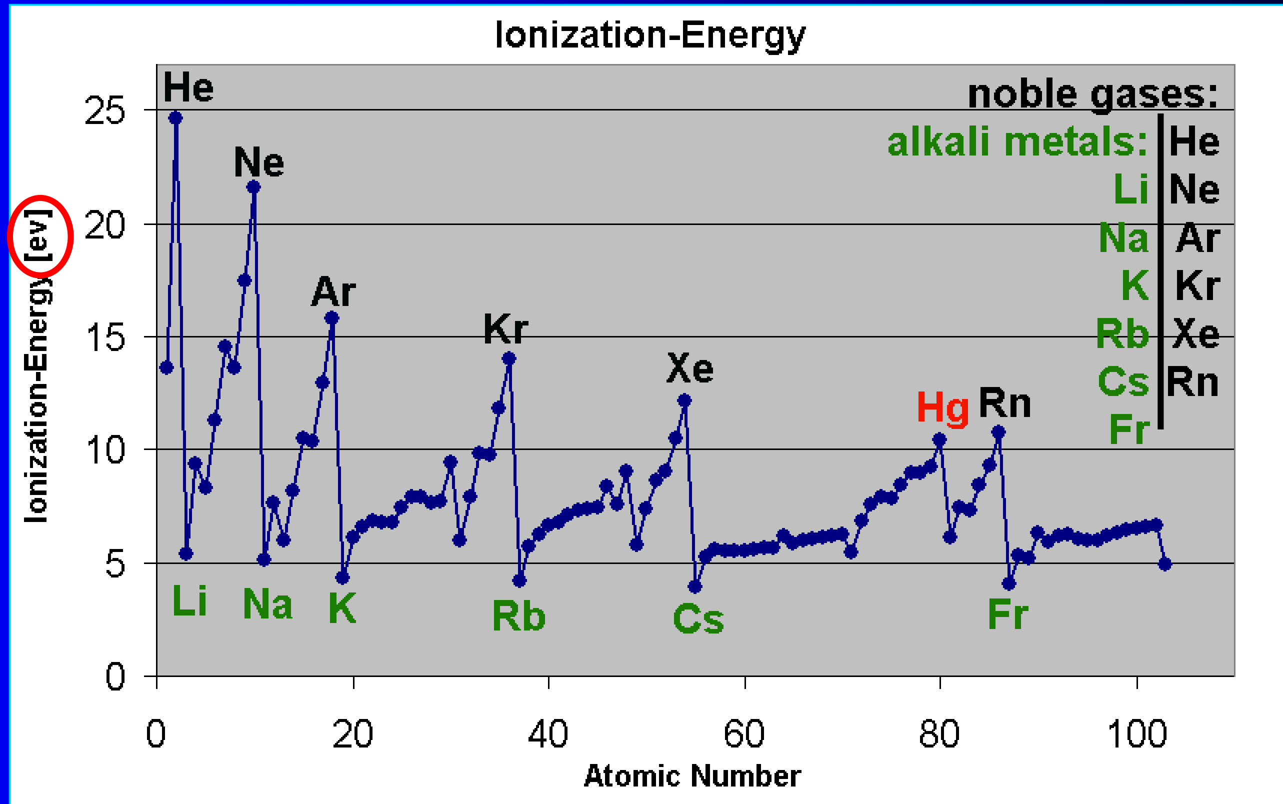
The minimum amount of energy required to remove the most loosely bound electron from an isolated gaseous atom to form a 1+ ion.

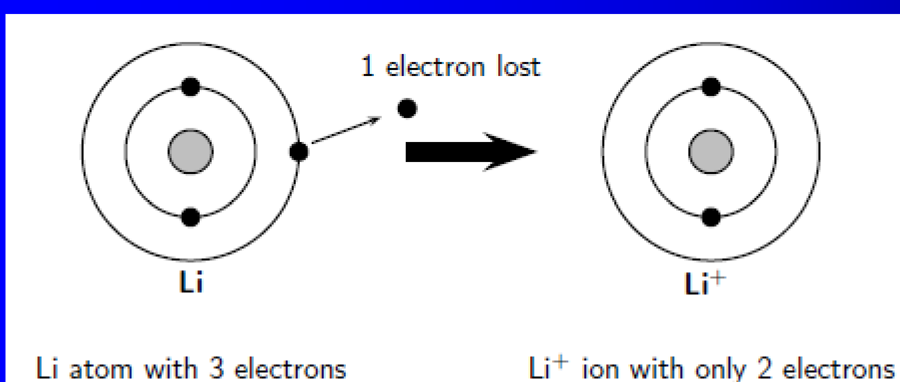
$$atom_{(g)} + energy \rightarrow ion^{+}_{(g)} + e^{-}$$

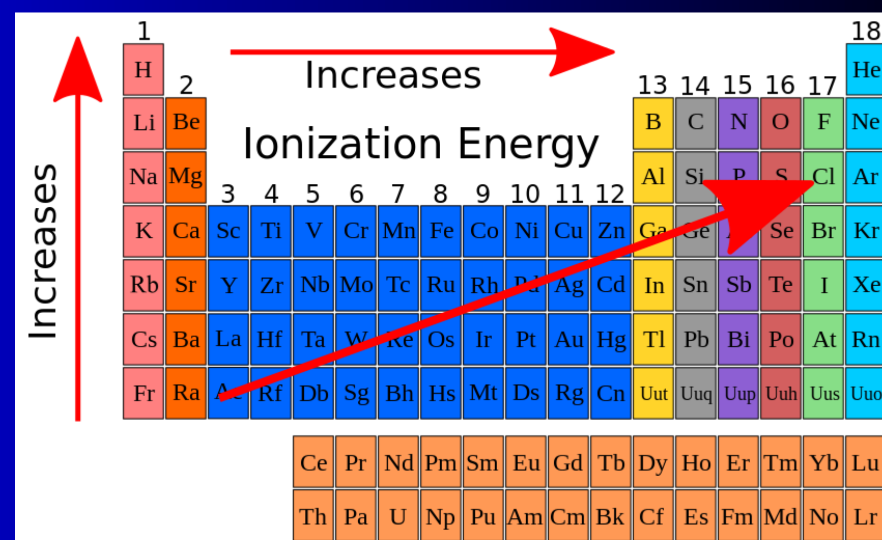


Element/Compound	Ionization Potential (Volts or eV)
He	24.6
Ar	15.8
H_2	15.4
N_2	15.6
O_2	12.1
CO_2	13.8
CO	14.1
C	11.3
Si	8.2
Fe	7.9
Ni	7.6
Na	5.1
K	4.3
Cs	3.9

Ionization energies







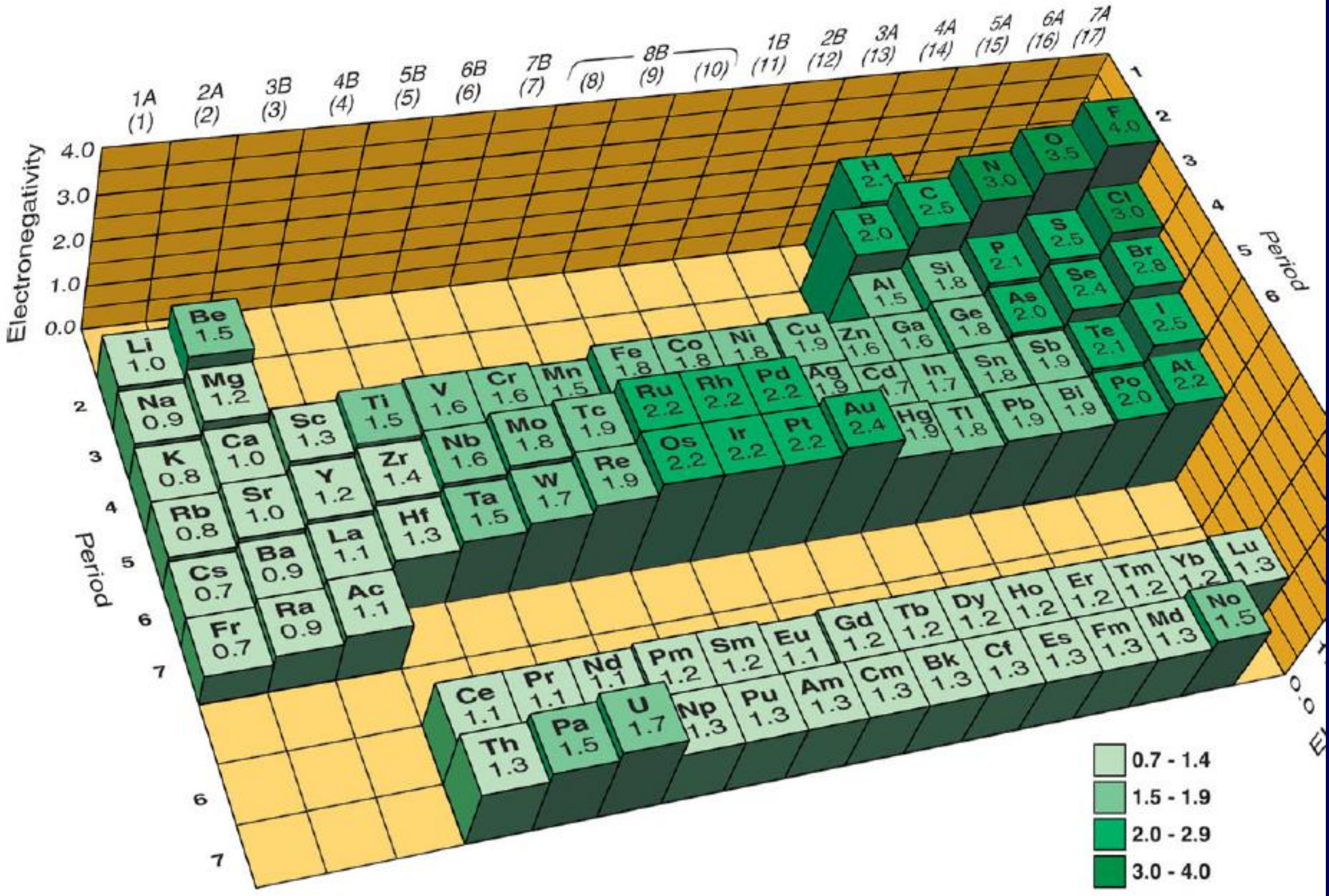
Electron affinity

$$A + e^{-}(\varepsilon_0) \rightarrow A^{-}$$

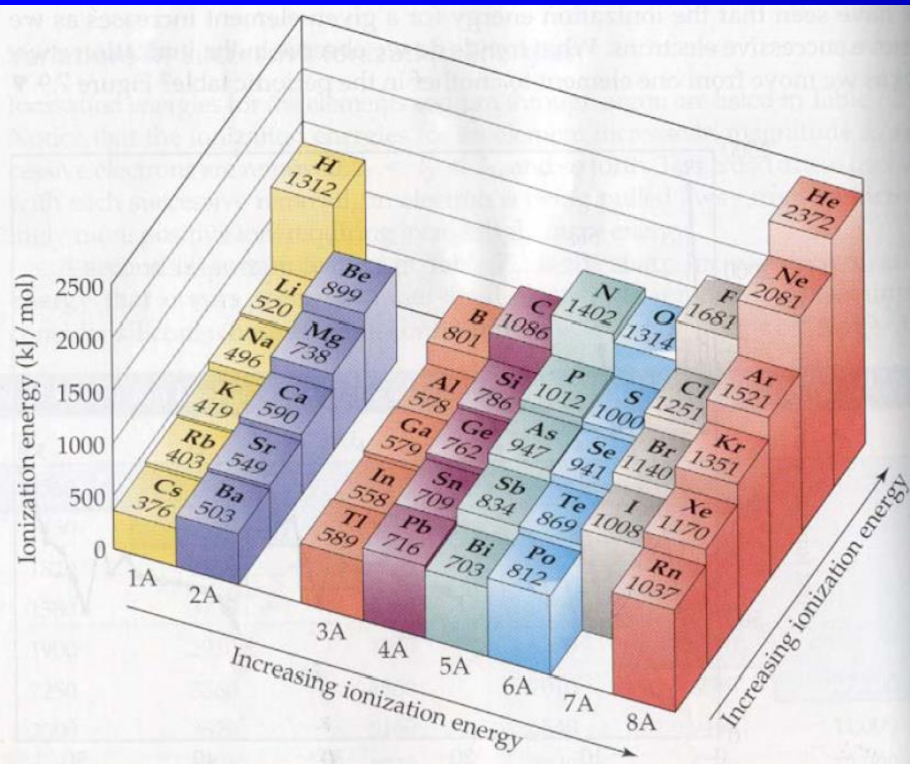
Electron Affinity

- Electron affinity is the amount of energy ***absorbed*** when an electron is added to an isolated gaseous atom to form an ion with a -1 charge.
- Electron affinity is a measure of an atom's ability to form negative ions.

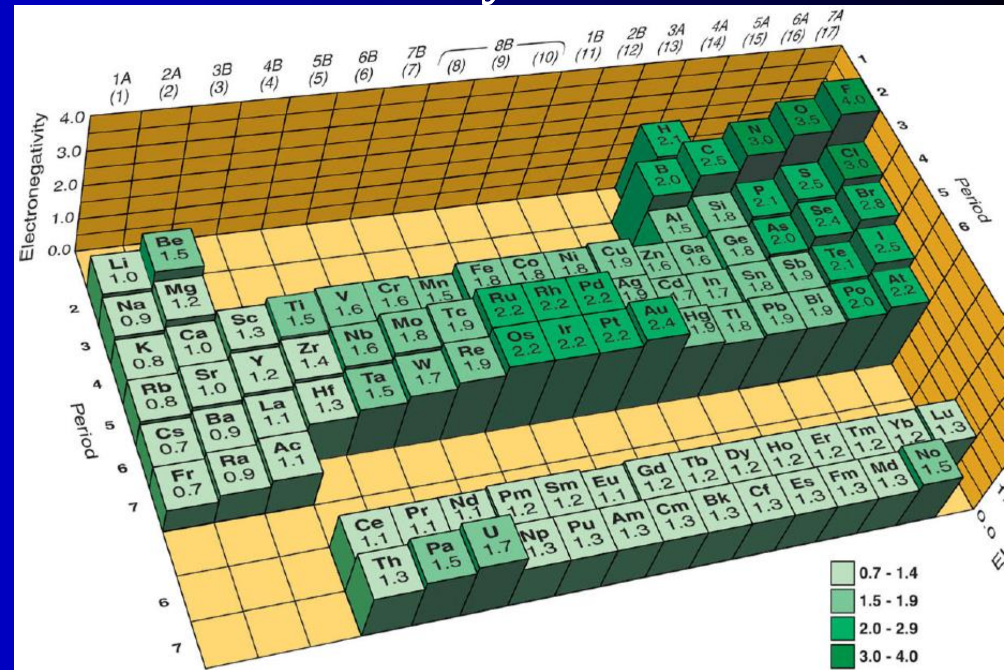
$$\text{atom(g)} + e^{-} + \text{EA} \rightarrow \text{ion}^{-}\text{(g)}$$



Ionization energies



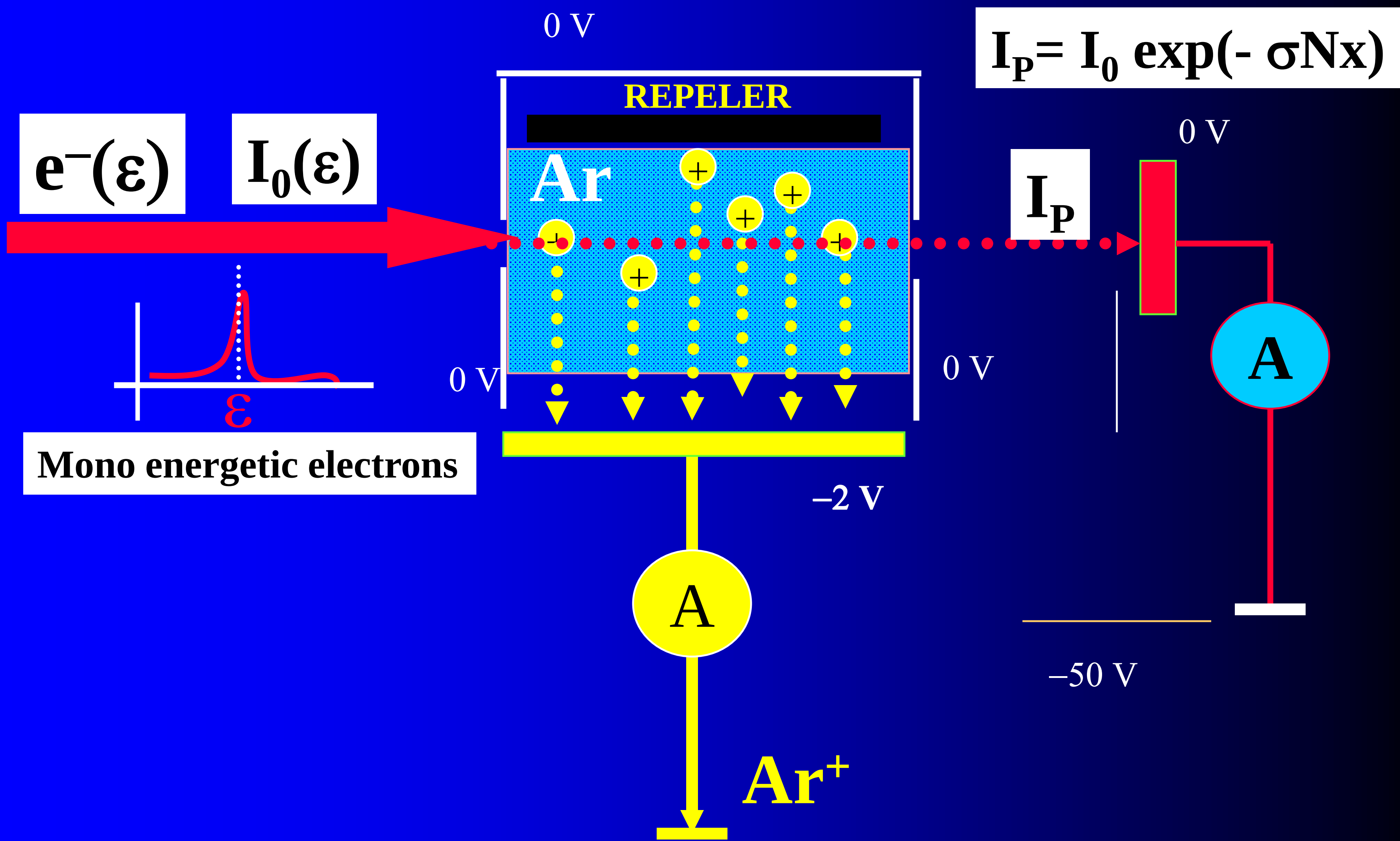
Electron affinity



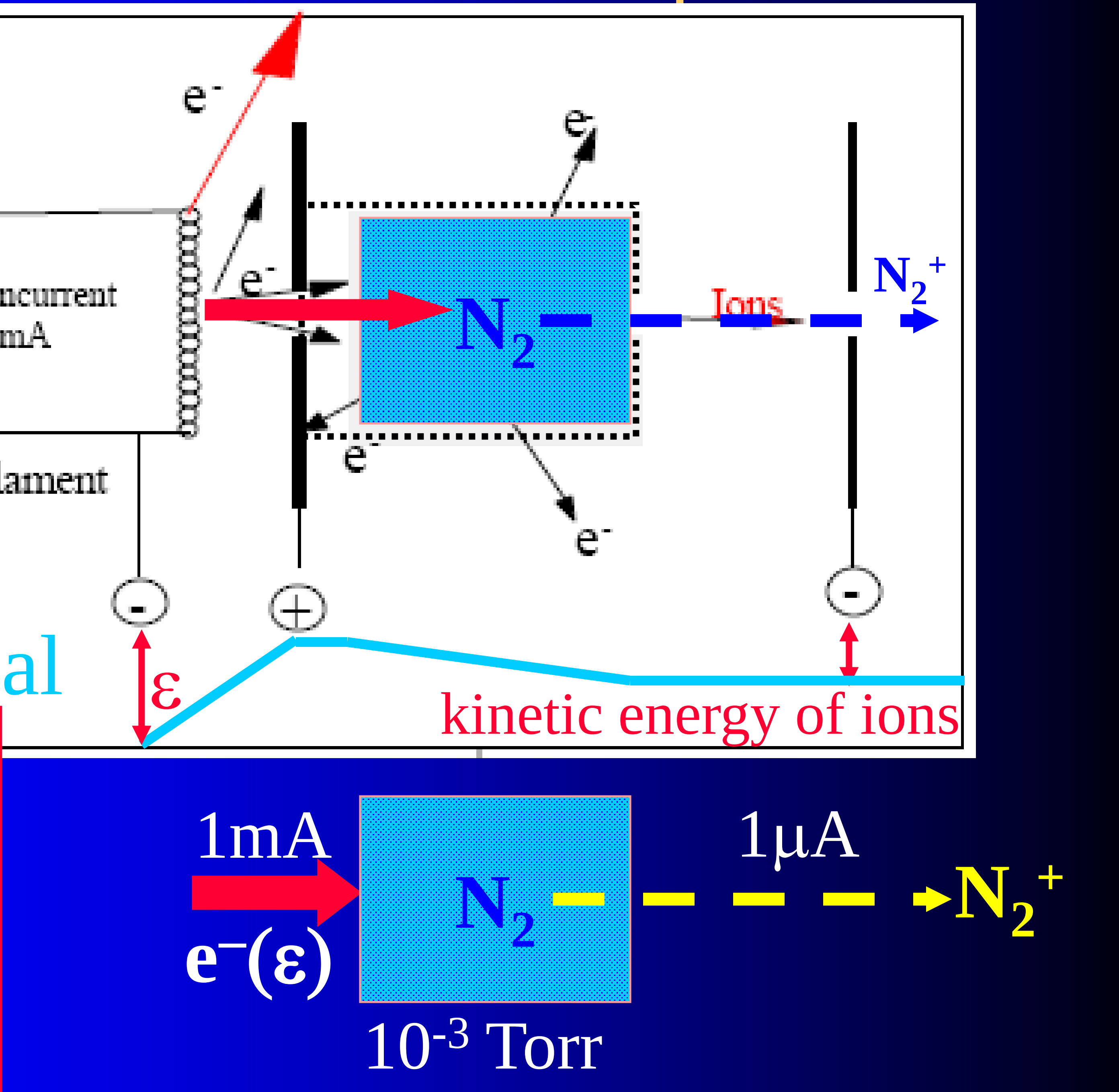
$$A + e^{-}(\varepsilon_0) \rightarrow A^{+} + 2e$$

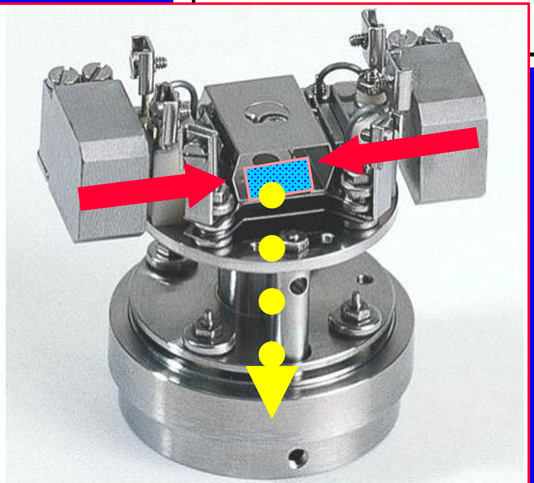
$$A + e^{-}(\varepsilon_0) \rightarrow A^{-}$$

Ionization cross section – idea of experiment



Electron impact ion source – ion source of mass spectrometer





Electron impact ionization

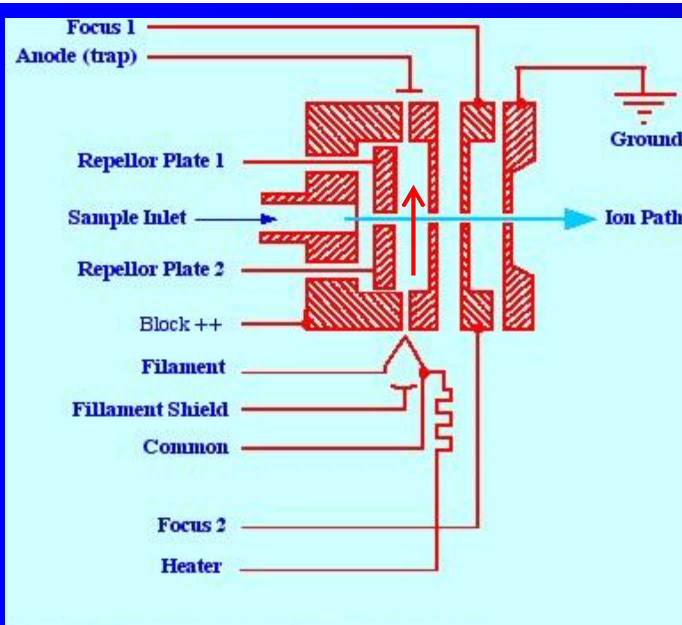
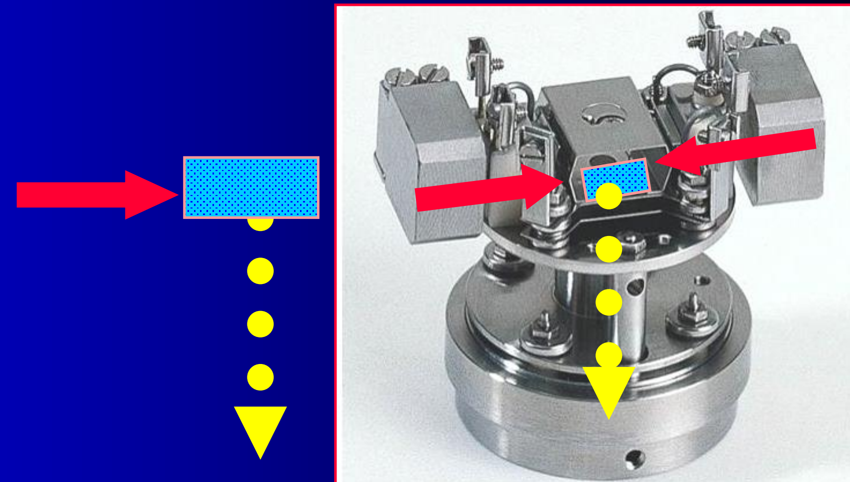
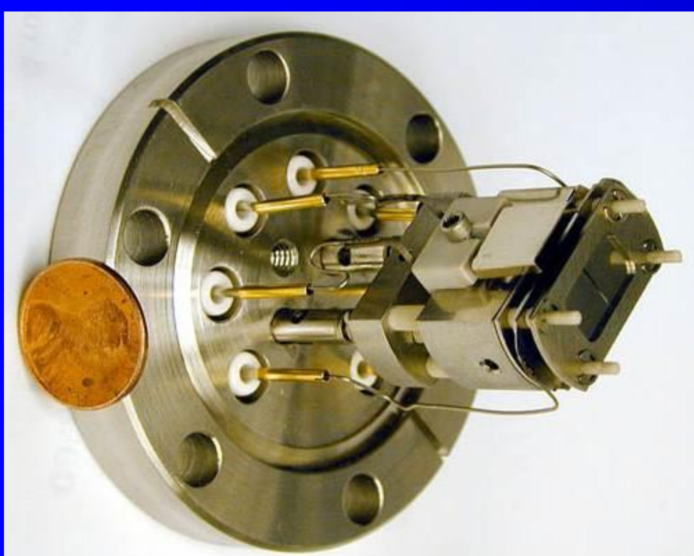


Figure 3. Cross Section of an Electron Impact Source





He +e$^-$

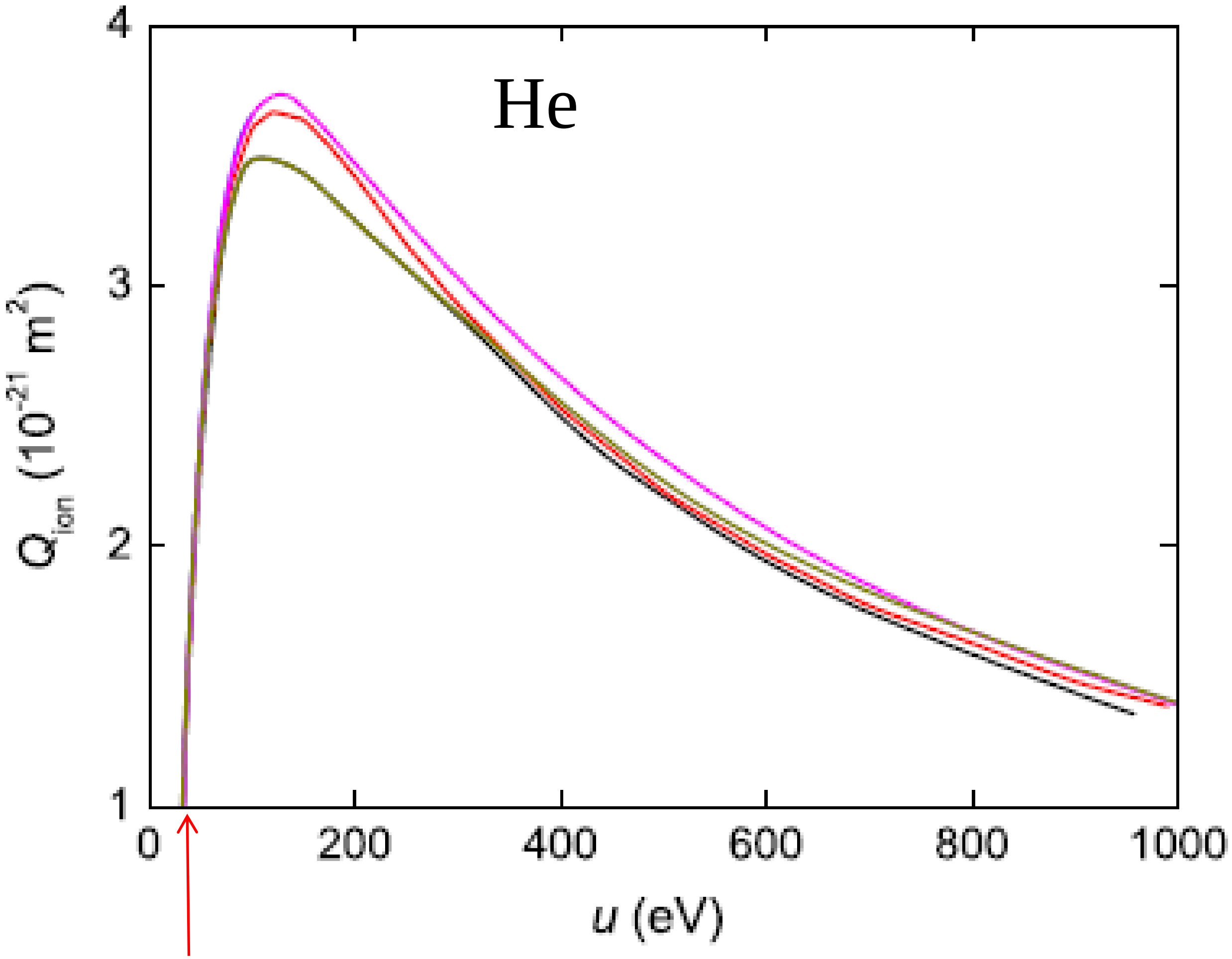
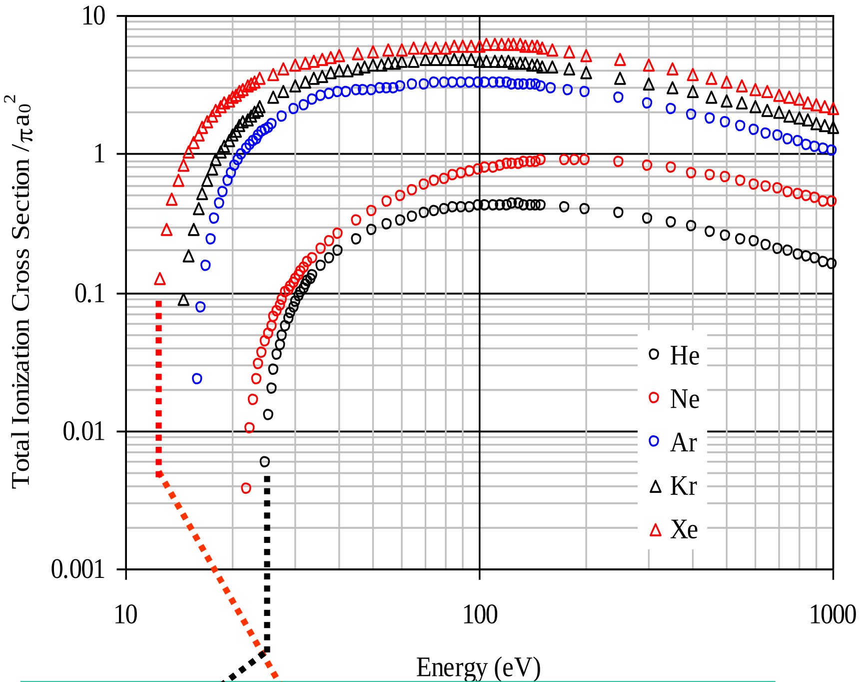
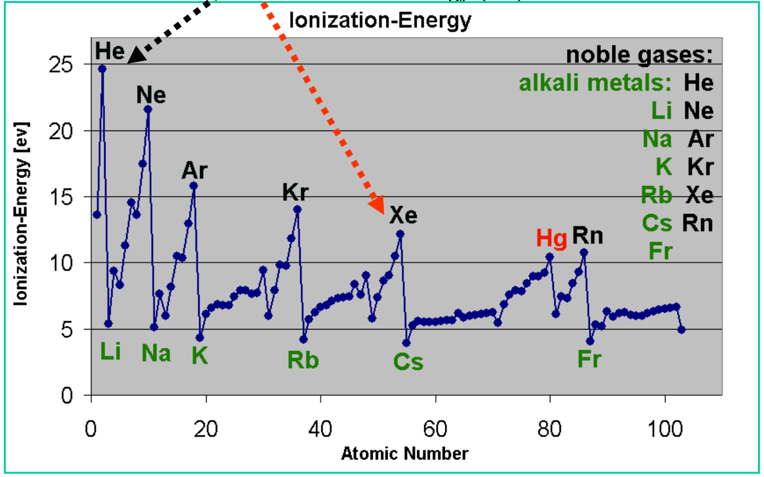


Figure 4. Ionization cross sections versus electron energy in helium, from the different databases: BIAGI-v8.9 (——), BIAGI-v7.1 (——), IST-LISBON (——), MORGAN (——), PHELPS (——).

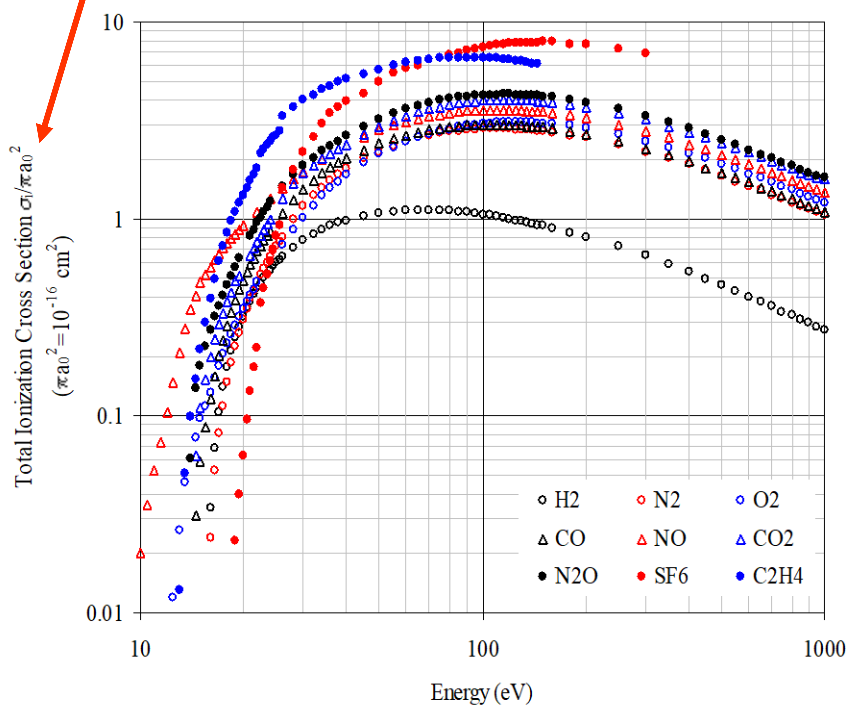
Standart definition cross section σ (in units …. ~ …cm^{-3})

Experimental results. Rare gases.





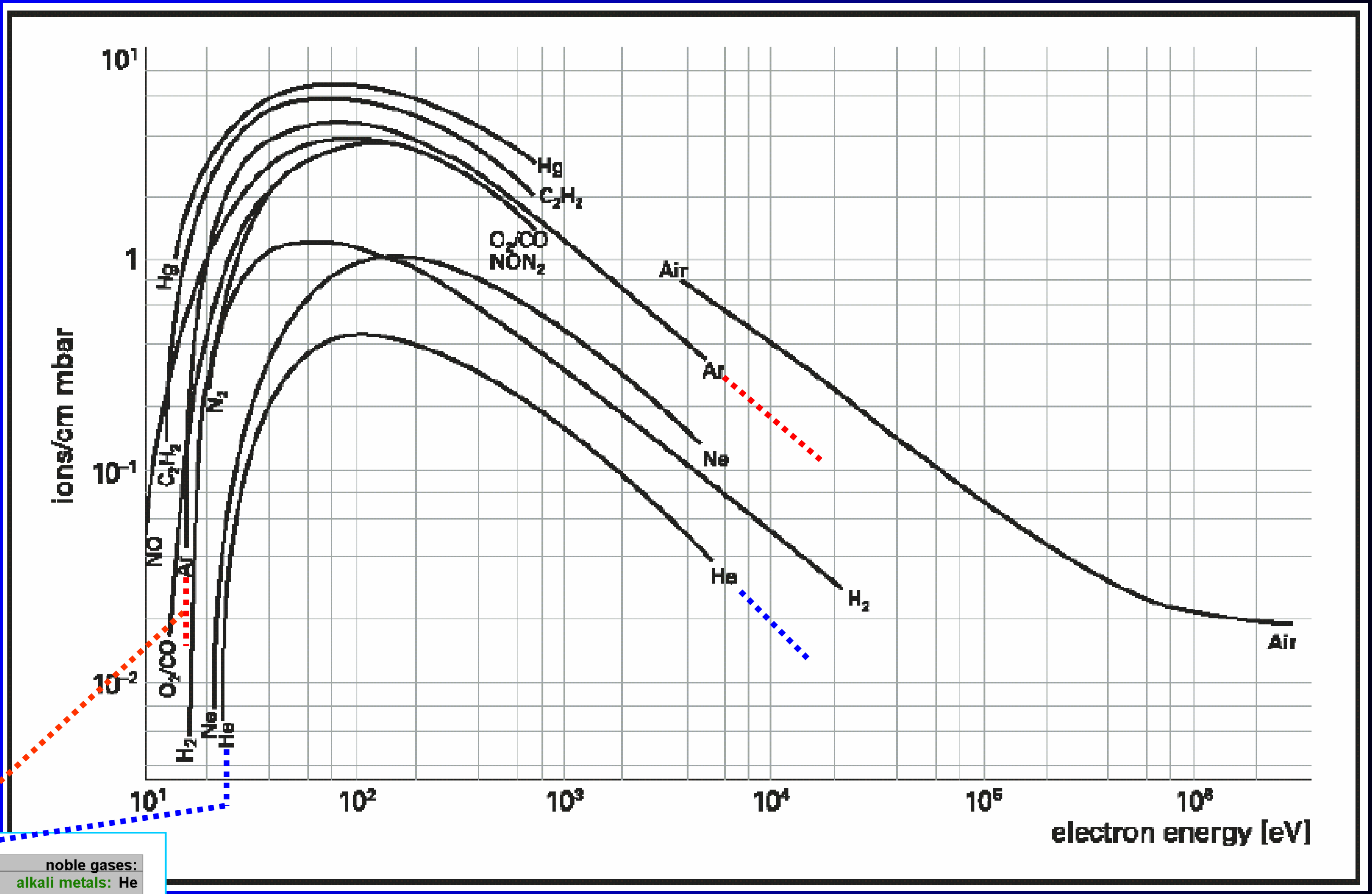
Experimental results. Diatomic molecules.

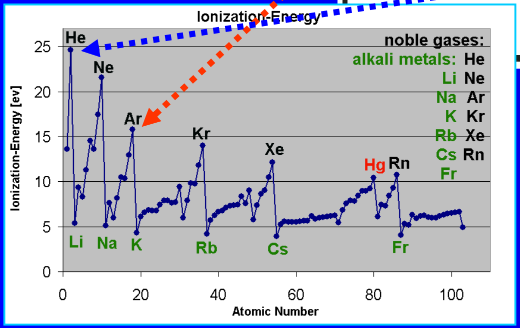


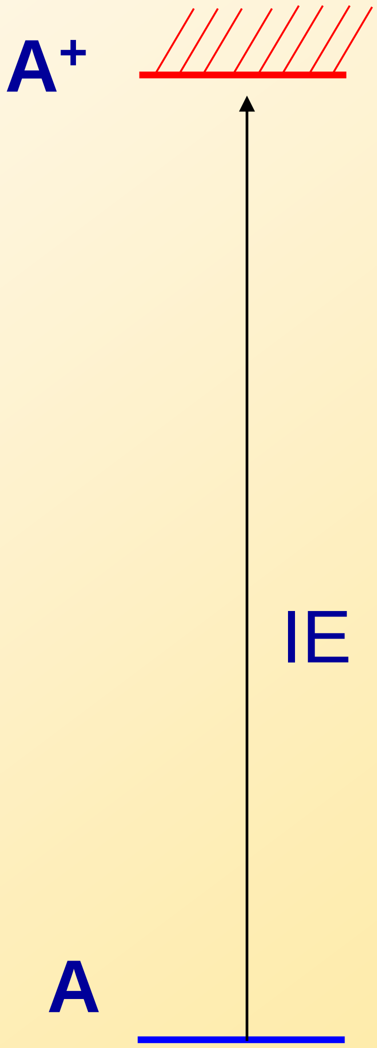
Steinar Stapnes

D. Rapp et al., Journal of Chemical Physics, 43, 5 (1965) 1464

Ionization by electron impact

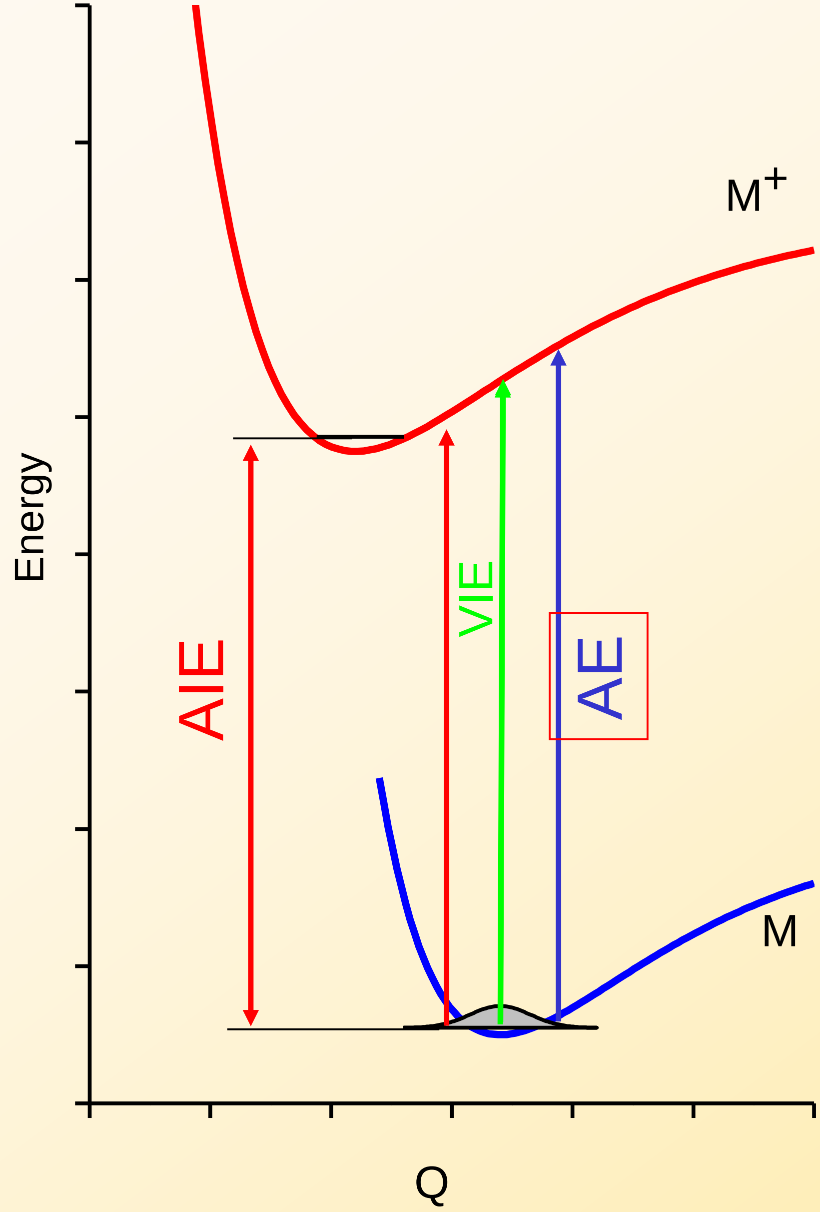






In case of atoms we have simple situation, the atom in the ground state and the ground state of the ion. The ionization energy is defined as a difference between this two states.

Adapted from lecture of prof. Š. Matejčik



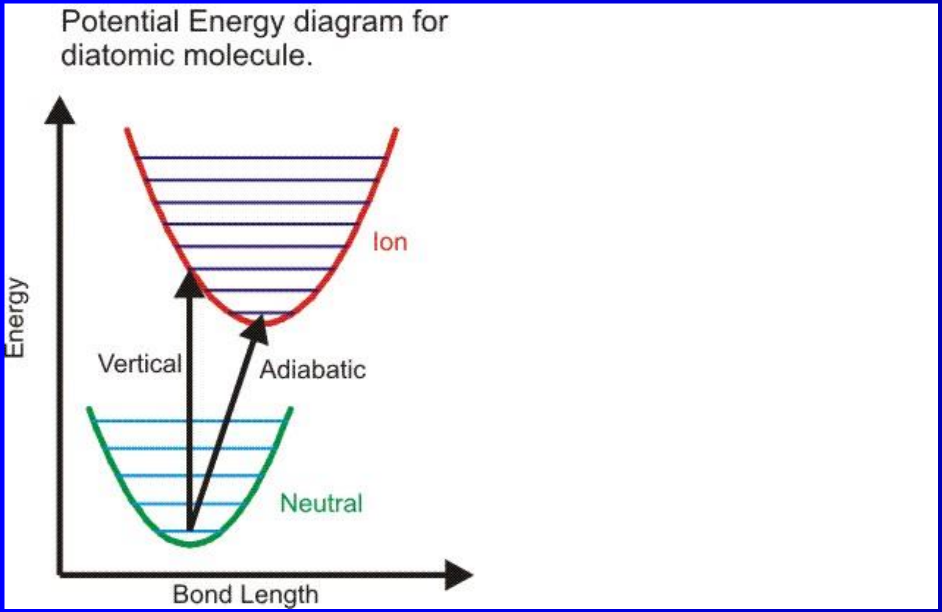
In the molecules is the situation more difficult. We have to work with potential curves or potential energy surfaces and thus the IE depends on the initial geometry of the molecules. For molecule usually two ionization energies are given, vertical IE and adiabatic IE.

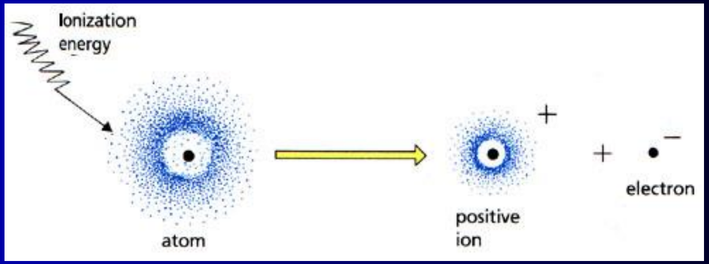
Vertical VIE is defined as the energy necessary to ionise the molecule in the equilibrium geometry

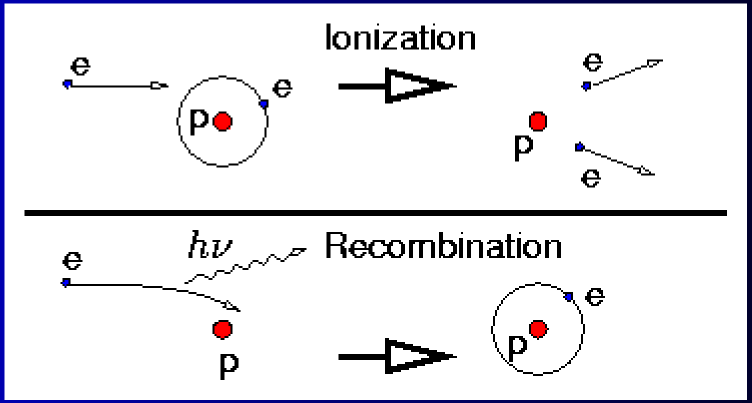
Adiabatic AIE is defined as the energy difference between the energies of the ion and molecule in its ground states

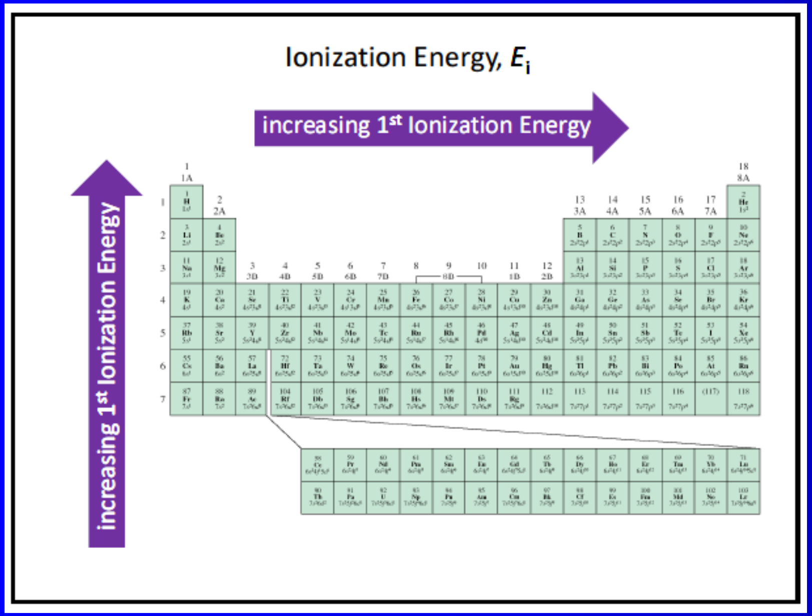
The experiments are sensitive on the lowest energy necessary to ionize molecule and this is called **appearance energy**. This corresponds to the ionization energy at low distances. As the geometry changes in the molecule and the molecular ion are only moderate, often is the AE very close to the AIE.

Adapted from lecture of prof. Š. Matejčik


Potential Energy diagram for
diatomic molecule.
Energy
Ion
Vertical
Adiabatic
Neutral
Bond Length

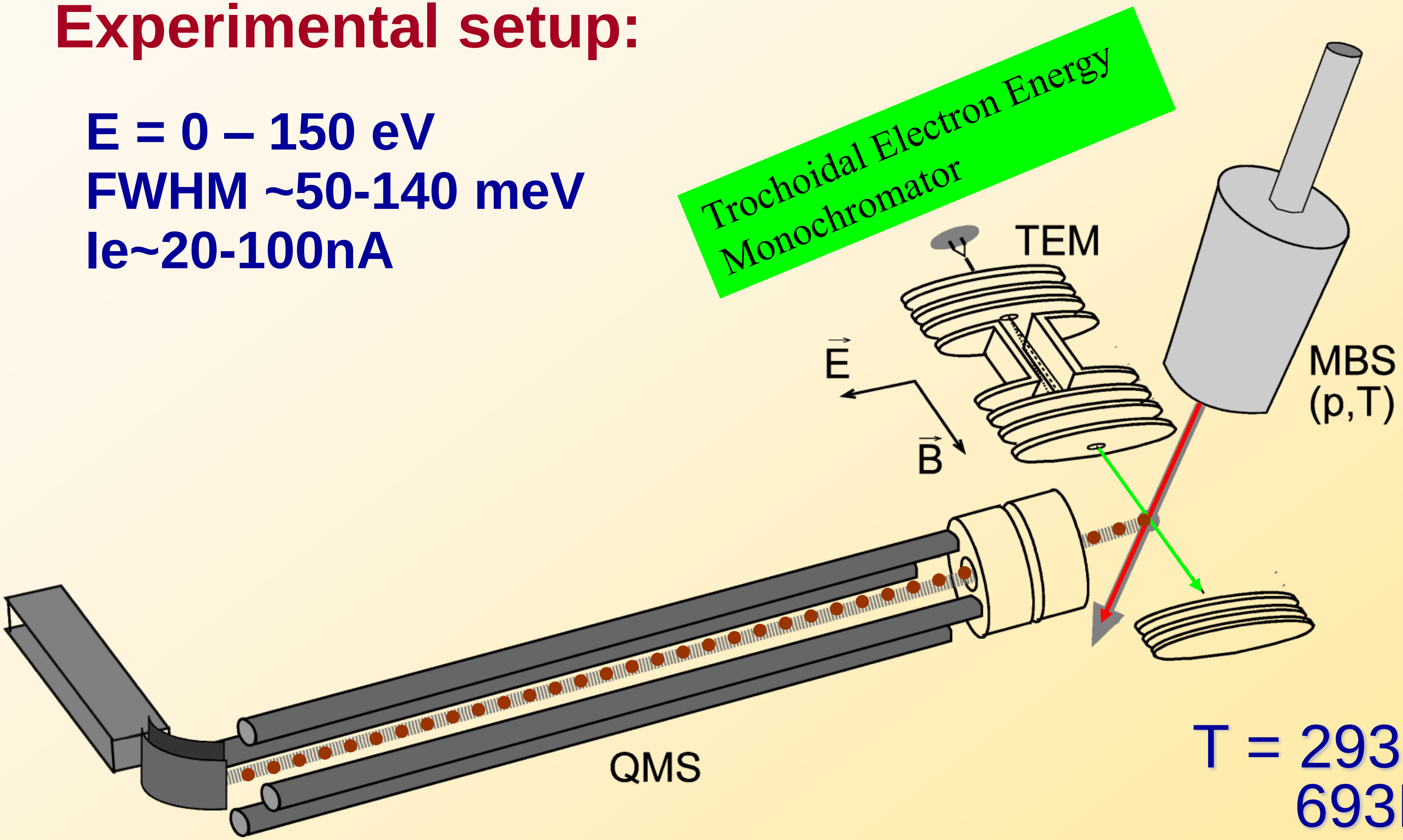

Ionization
energy
atom
positive
ion
+
+
electron


Ionization
e
p
e
e
p
e
hv
Recombination
e
p
p
e


Ionization Energy, E_i
increasing 1st Ionization Energy
increasing 1st Ionization Energy

Experimental setup:

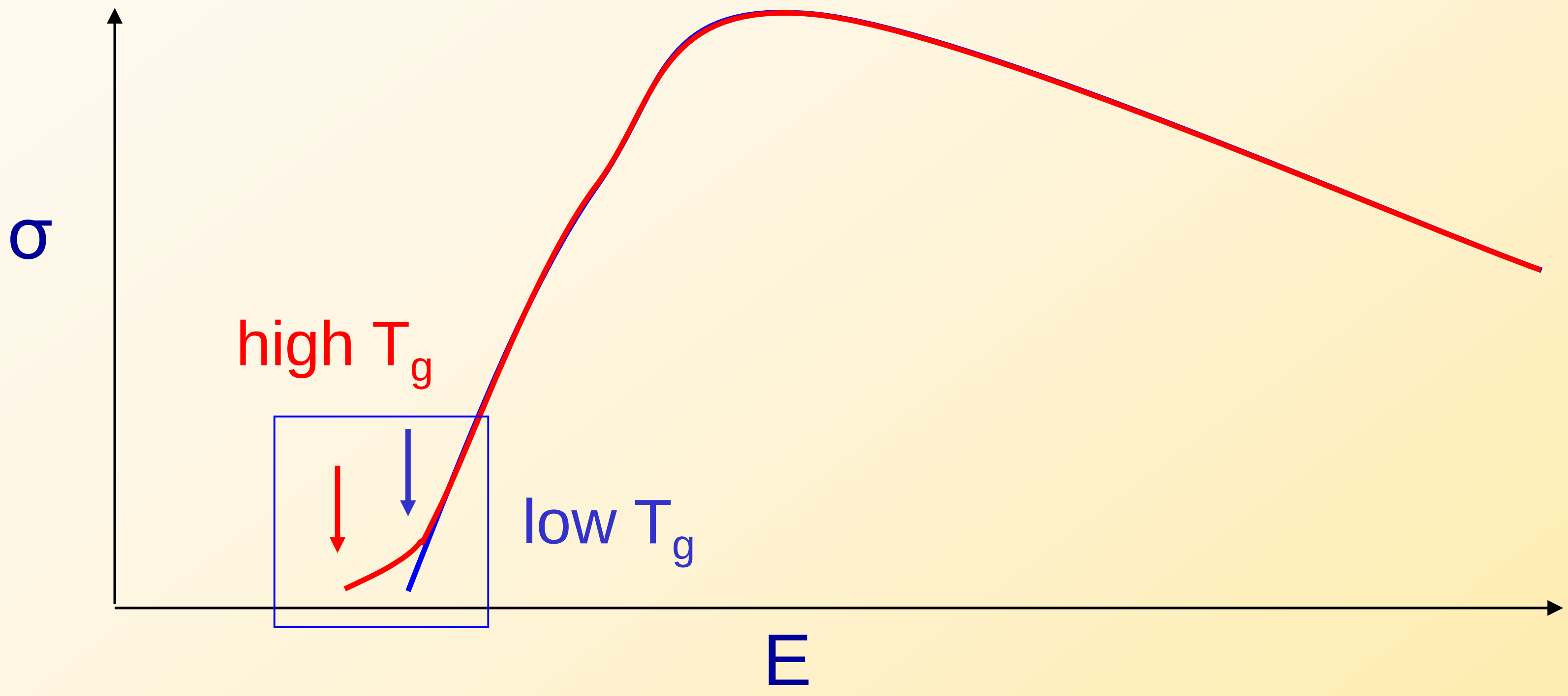
E = 0 – 150 eV
FWHM ~50-140 meV
Ie~20-100nA



T = 293K
693K

The apparatus consist of TEM, MBS and QMS. The TEM is well known, the FWHM was about 140 meV and the Ie ~100 nA
MBS- effusive type, the molecules in the beam have translational, vibrational and rotational temperature identical to the temperature of the MBS
The mass selected ions are registered as a function of the electron energy

Electron impact ionization



The EII is characterised from point of view of the kinetics by the cross section
The cross section has a monotonic character with maximum at about 100 eV
The EII is endothermic reaction with a threshold, called appearance energy of the ions
In present experimet we have focused on the estimation of the threshold behaviour of the CS, estimation of the AE
At elevated temperatures there are changes in the ion yield in the vicinity of the threshold

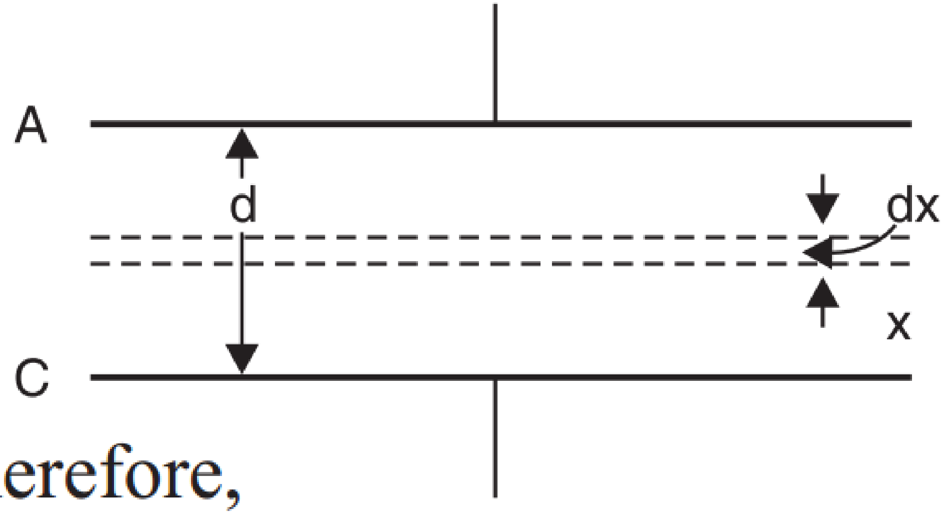
Adapted from lecture of prof. Š. Matejčik

Another definition α in units cm^{-1}

Mathematical Analysis

When these n electron move through a distance *dx*, they produce another *dn* electrons due to collision. Therefore:

$$dn = \alpha\, n\, dx$$



$$\frac{dn}{n} = \alpha\, dx$$

$$\ln n = \alpha x + A$$

Now at $x = 0$, $n = n_0$. Therefore,

$$\ln n_0 = A$$

$$\ln n = \alpha x + \ln n_0$$

$$\ln \frac{n}{n_0} = \alpha x$$

$$n = n_0 e^{\alpha x}$$

Another definition α in units cm^{-1}

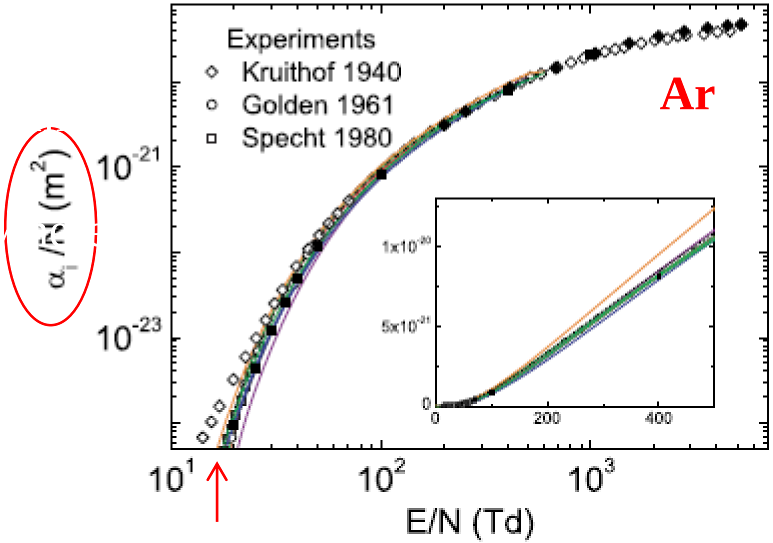


Figure 8. Measured and calculated reduced ionization coefficients. The solid lines are results from two-term Boltzmann calculations and the solid symbols (■) are from the Monte Carlo calculations using MAGBOLTZ (Biagi 2011). The colour code is BIAGI-v8.9 (——); BSR (——); HAYASHI (——); IST-LISBON (——); MORGAN (——); PHELPS (——); PUECH (——). The measurements are referenced in the text.

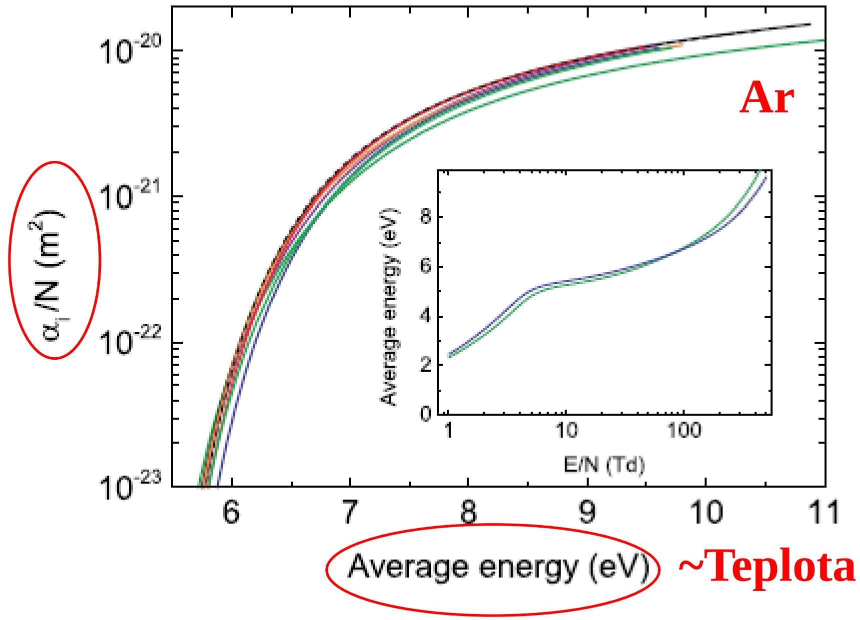
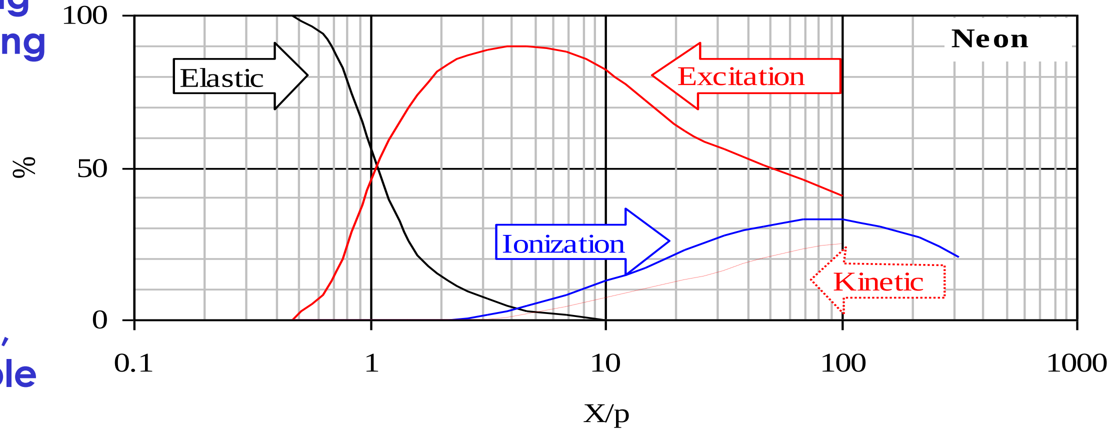


Figure 9. Reduced ionization coefficient versus average electron energy, calculated using a two-term Boltzmann solver. The inset shows the average energy versus E/N, and the colour code is BIAGI-v8.9 (——); BIAGI-v7.1 (- - - -); BSR (——); HAYASHI (——); IST-LISBON (——); MORGAN (——); PHELPS (——); PUECH (——).

From CERN-CLAF, O.Ullaland

Approximate computed curves showing the percentage of electron energy going to various actions at a given

X/p (V/cm/mmHg)



Elastic: loss to elastic impact

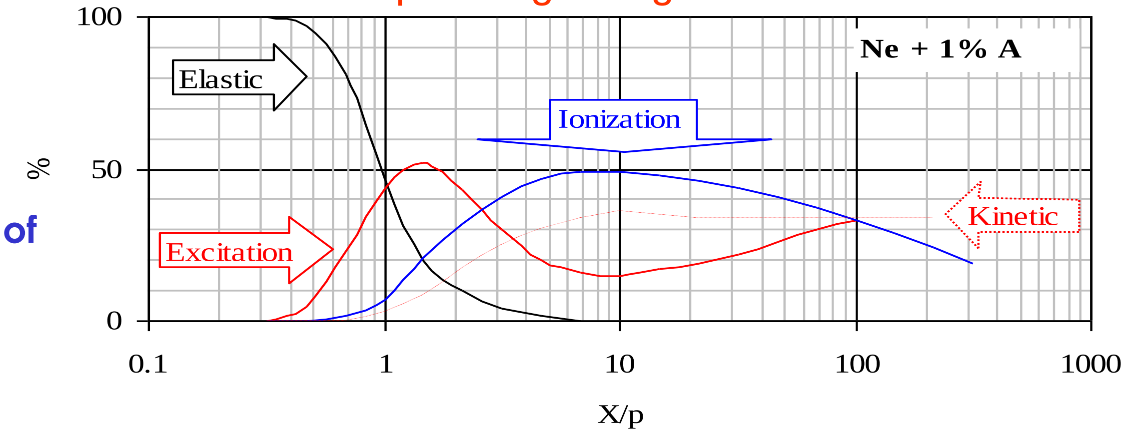
Excitation: excitation of electron levels, leading to light emission and metastable states

Ionization: ionization by direct impact

Kinetic: average kinetic energy divided by their "temperature"

Vibration: energy going to excitation of vibrational levels

Add a sprinkling of argon



L. B. Loeb, Basic Processes of Gaseous Electronics

Ion source

2.3. Electron impact ionization

The electron impact ionization is the most fundamental ionization process for the operation of ion sources.

<u>Why?</u>

- The cross section for the impact ionization is by orders of magnitudes higher than the cross section for the photo ionization.
- The cross section depends on the mass of the colliding particle. Since the energy transfer of a heavy particle is lower, a proton needs for an identical ionization probability an ionization energy three orders of magnitudes higher than an electron

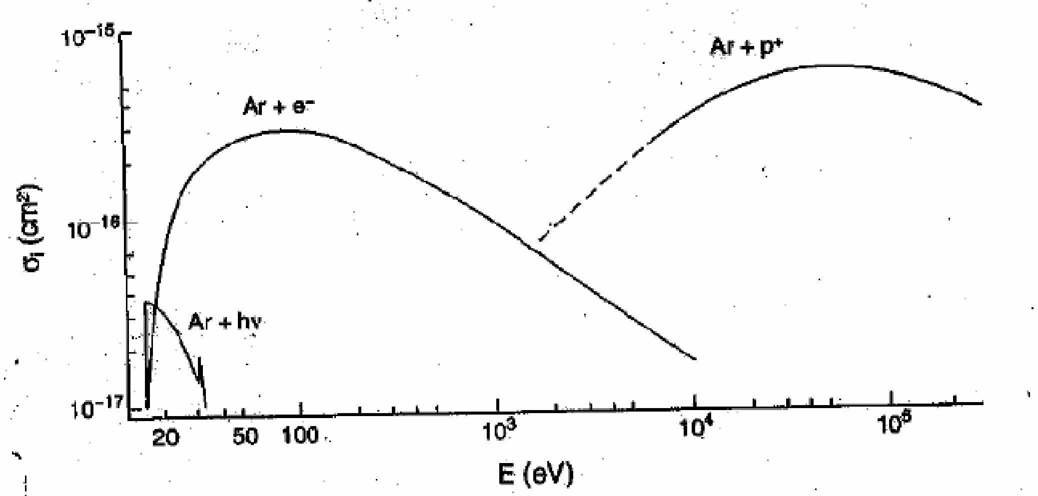
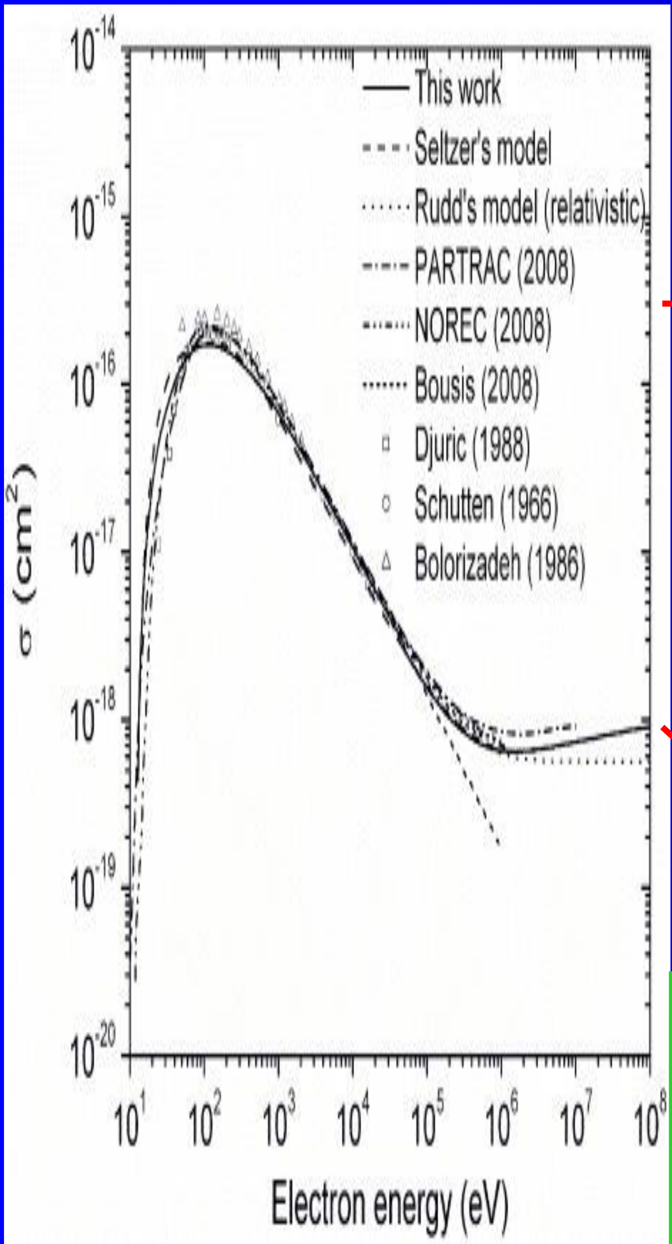
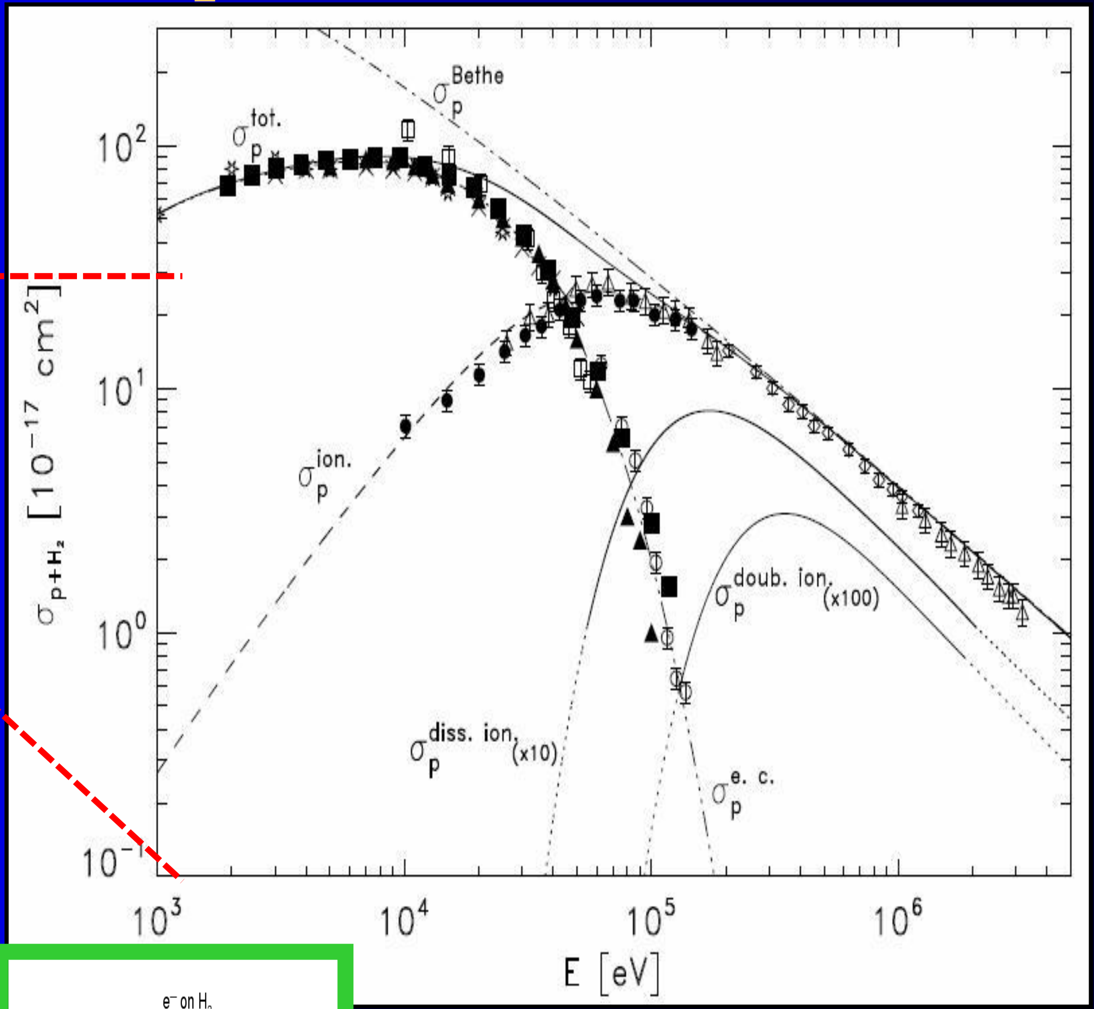
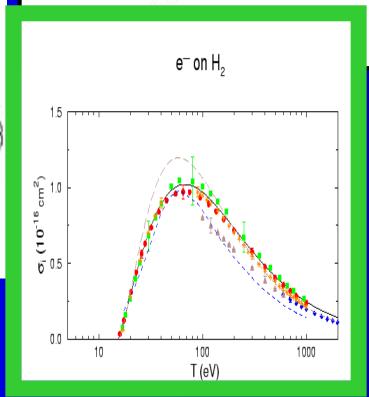


FIGURE 4
Ionization cross sections as functions of energy for ionizing collisions with fast electrons, protons, and photons. (From Winter, H., in *Experimental Methods in Heavy Ion Physics*, Springer-Verlag,

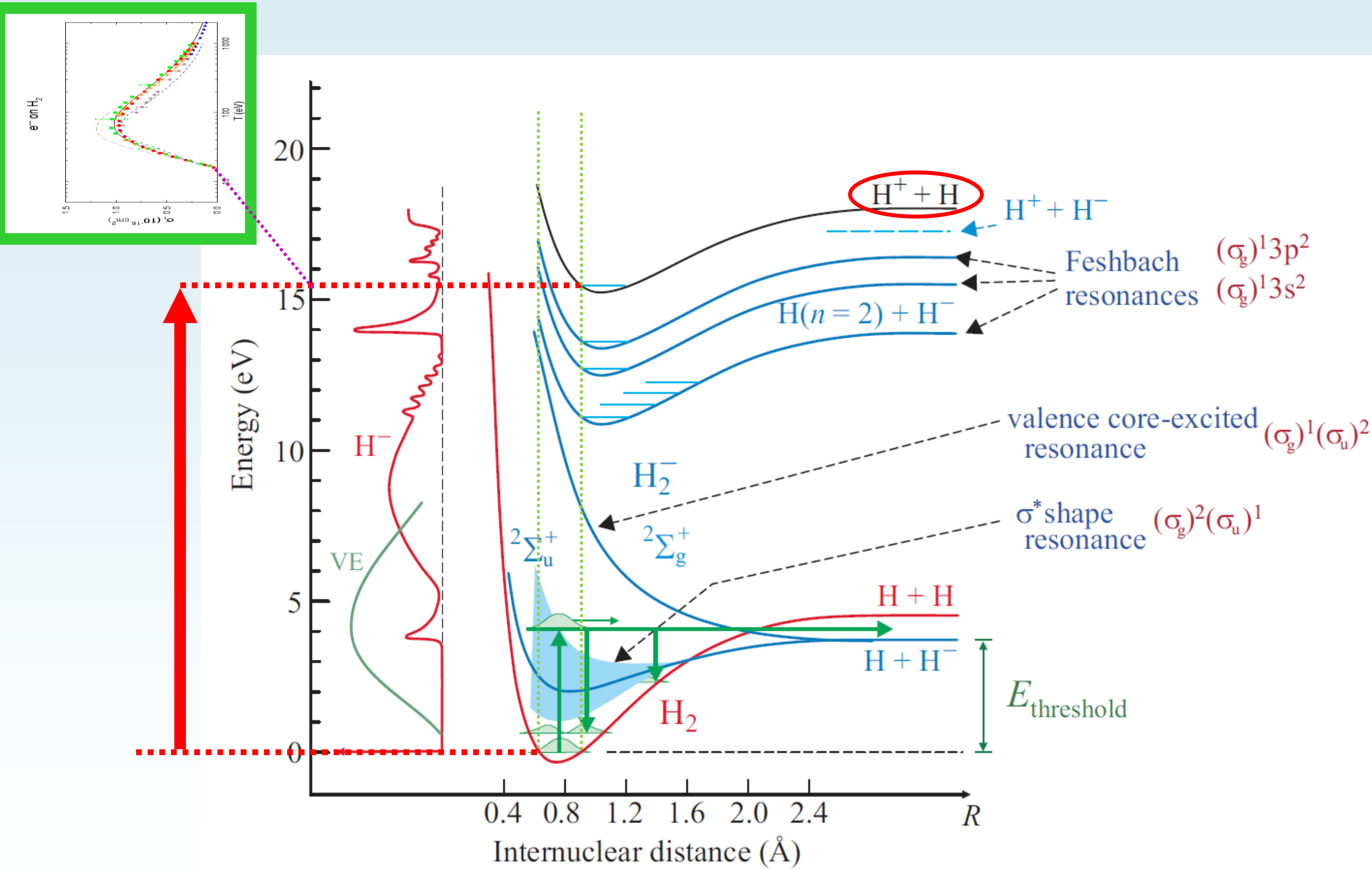
p + H_2 Ionization Cross Section







Padovani et al. 2009, A&A, 501, 619



e⁻ on H2
T (eV)
H+ + H
H+ + H−
Feshbach
resonances
(σg)13p2
(σg)13s2
H(n = 2) + H−
valence core-excited
resonance
(σg)1(σu)2
H2−
σ* shape
resonance
(σg)2(σu)1
2Σu+
2Σg+
H−
VE
H + H
H + H−
E threshold
H2
Energy (eV)
20
15
10
5
0
0.4
0.8
1.2
1.6
2.0
2.4
R
Internuclear distance (Å)

Cross sections for vibrational excitation, dissociation, ionization…H_2

H_2 + e
→ $H_2(v)$ + e ……. Vibrational excitation
→ H + H +e……. Dissociation
→ H_2^* + hν + e … Photon excitation
→ H_2^+ +e + e….. Ionization
→ H^+ + H + e + e Dissociative Ionization

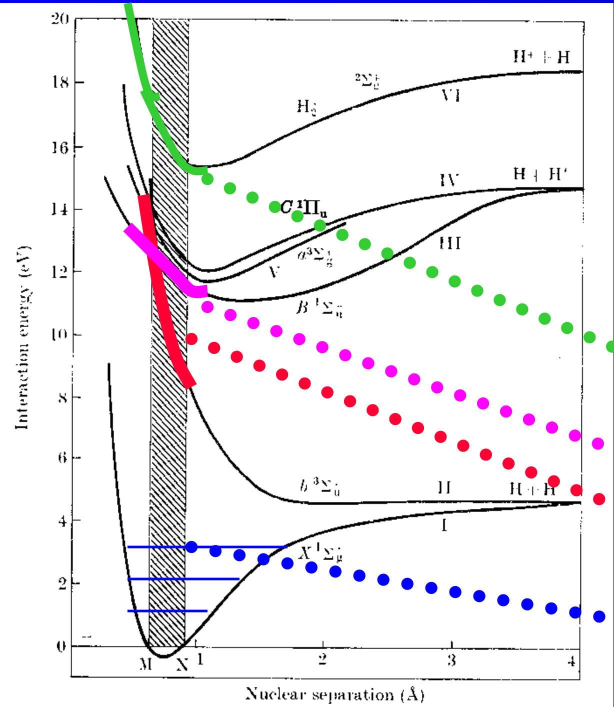


FIG. 13.1. Potential energy curves for electronic states of H_2 and H_2^+ lying within 20 eV of the ground state.

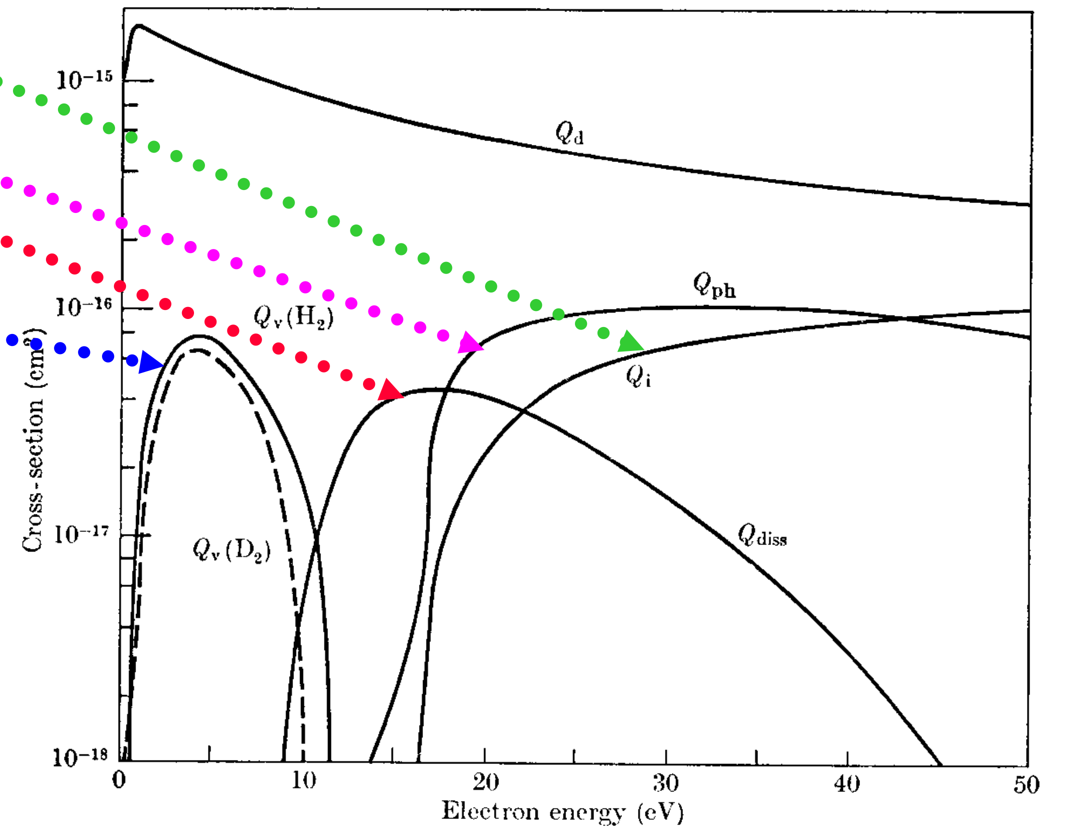
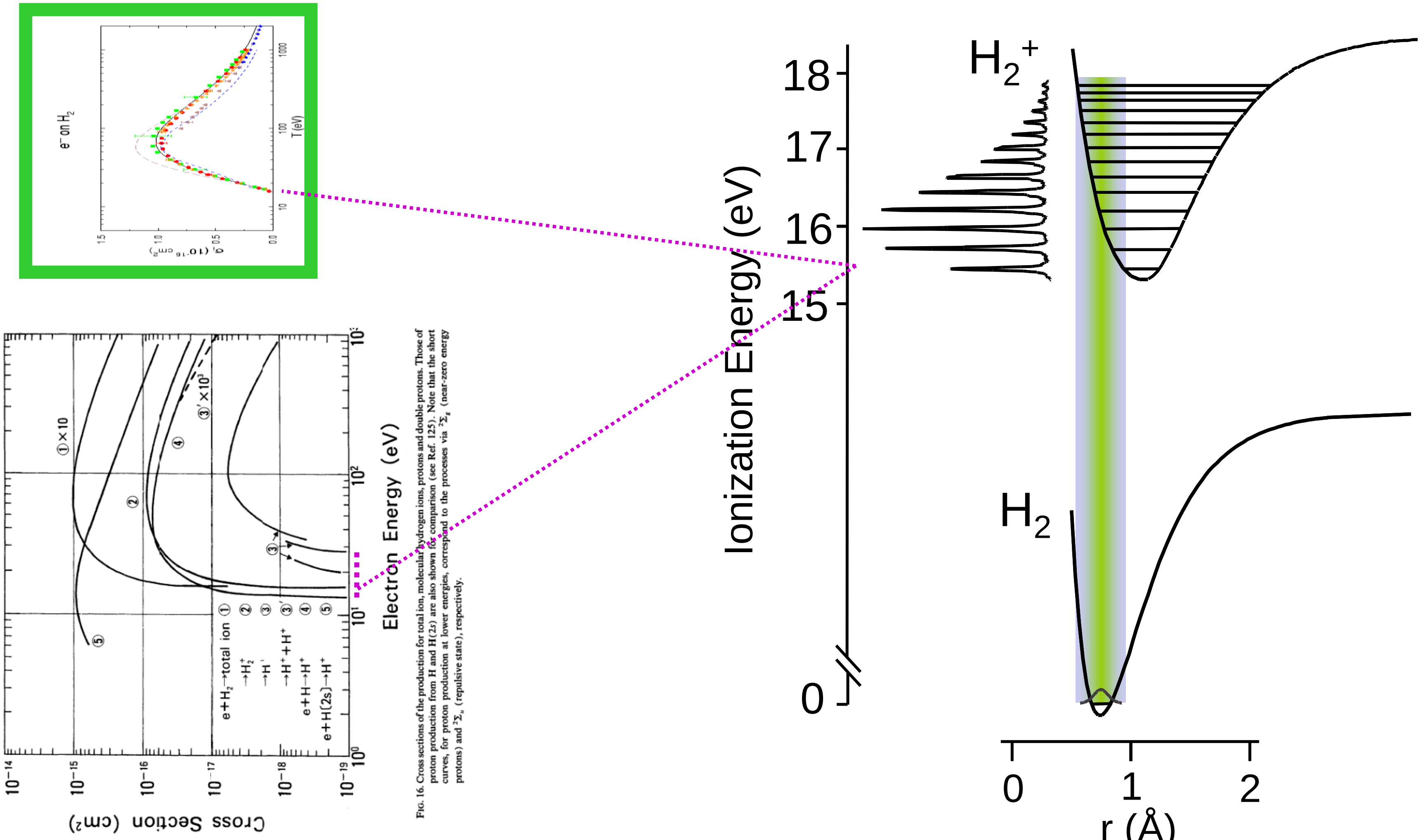


FIG. 13.37. Cross-sections assumed by Engelhardt and Phelps in their analysis of swarm data in H_2 and D_2 for electrons of characteristic energy greater than 1 eV. Q_d momentum-transfer cross-section, Q_i, ionization cross-section, Q_{diss} dissociation cross-section, Q_{ph} photon excitation cross-section, Q_v vibrational excitation cross-section (—— H_2, – – – D_2).

Potential Energy Surface Description of the Ionization of H_2



Details of interaction of electron with H_2 (1990)

CROSS SECTIONS FOR ELECTRON COLLISIONS WITH HYDROGEN

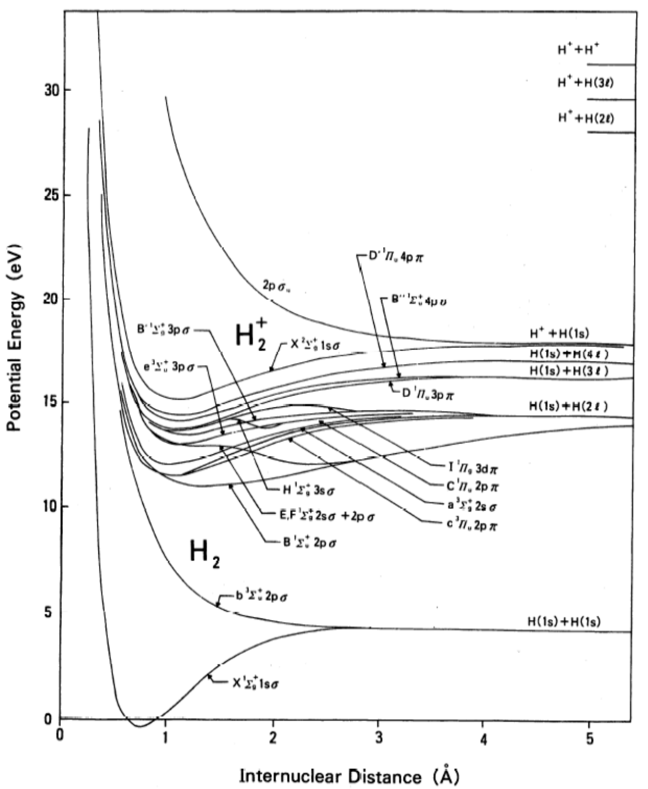


FIG. 1. Some important energy levels of molecular hydrogen and molecular ion (see Ref. 5).

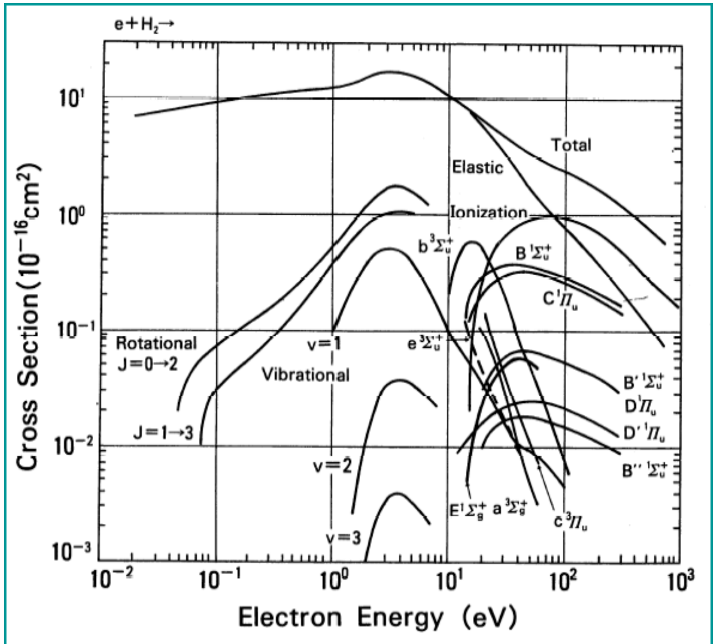


FIG. 2. Comparison of cross sections for various collision processes in neutral H_2. Also for comparison, cross sections of ionization of atomic hydrogen are shown. These data are taken at room temperatures.

Cross Sections and Related Data for Electron Collisions with Hydrogen Molecules and Molecular Ions[a)]

H. Tawara, Y. Itikawa,[b)] H. Nishimura,[c)] and M. Yoshino[d)]

National Institute for Fusion Science,[a)] Nagoya 464-01, Japan

(Received July 5, 1989; revised manuscript received November 1, 1989)

Data are compiled and evaluated for collision processes of excitation, dissociation, ionization, attachment, and recombination of hydrogen molecules and molecular ions (H_2^+, H_3^+) by electron impact as well as for properties of their collision products.

Key words: electron impact; hydrogen molecule; hydrogen molecular ion; scattering; elastic integral; vibrational excitation; rotational excitation; dissociation; ionization; photon emission; cross section.

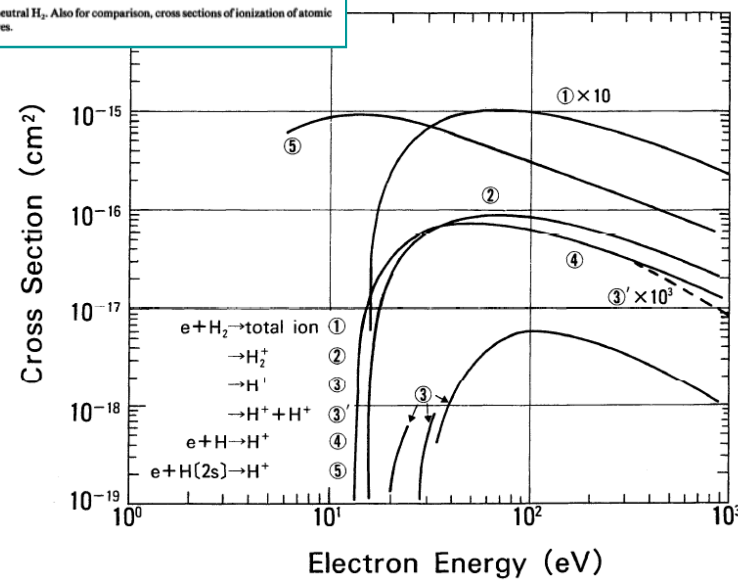


FIG. 16. Cross sections of the production for total ion, molecular hydrogen ions, protons and double protons. Those of proton production from H and H(2s) are also shown for comparison (see Ref. 125). Note that the short curves, for proton production at lower energies, correspond to the processes via ${}^2\Sigma_g$ (near-zero energy protons) and ${}^2\Sigma_u$ (repulsive state), respectively.

J. Phys. Chem. Ref. Data, Vol. 19, No. 3, 1990

Partial cross section for excitation

NO

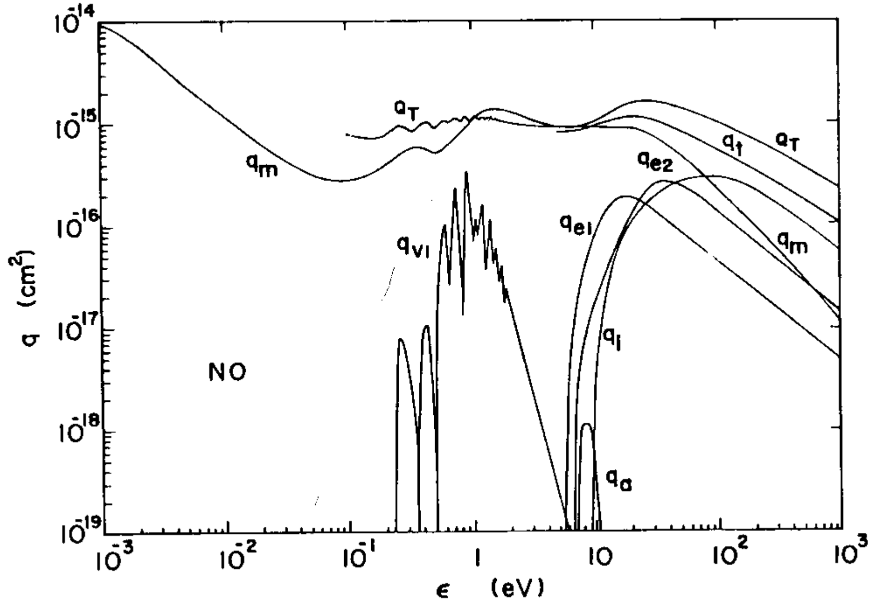


Fig. 4. Cross-section set for NO (1986).

NH_3

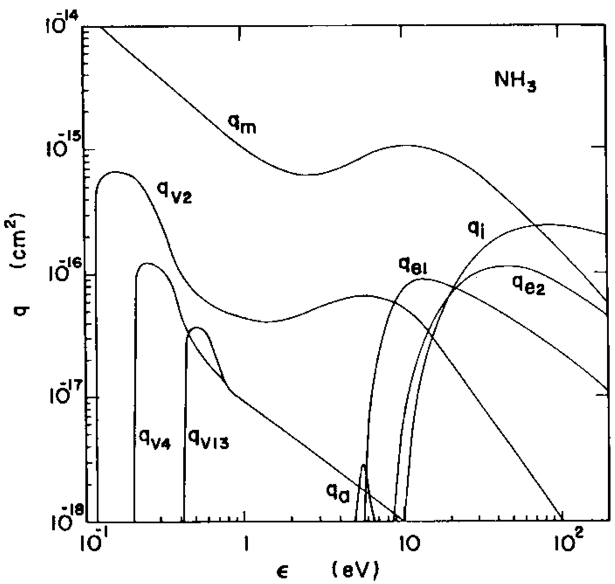
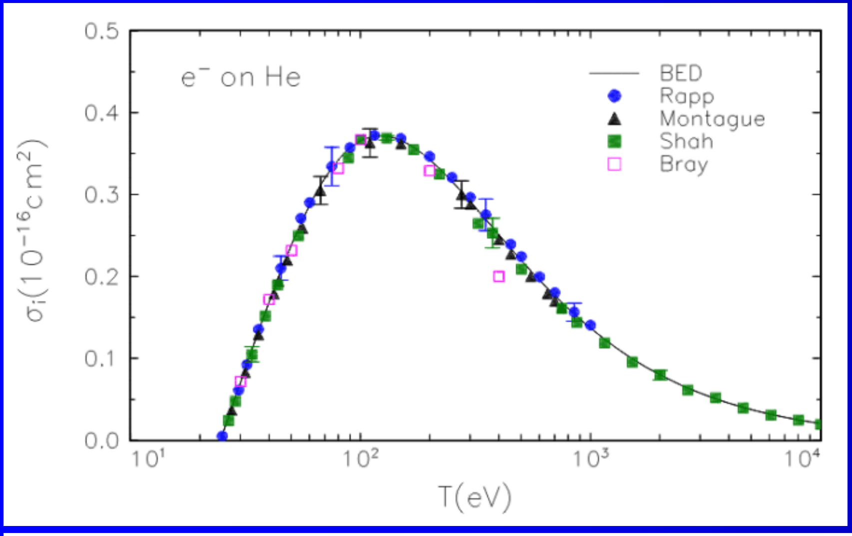
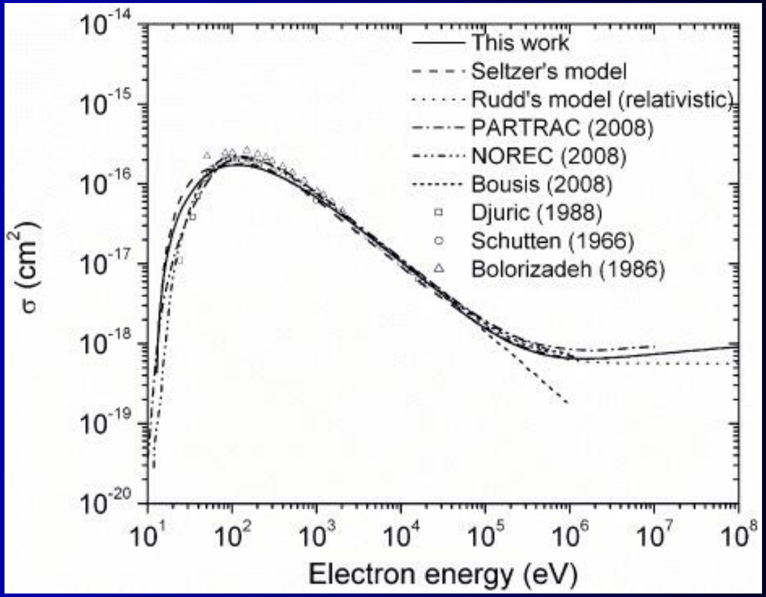


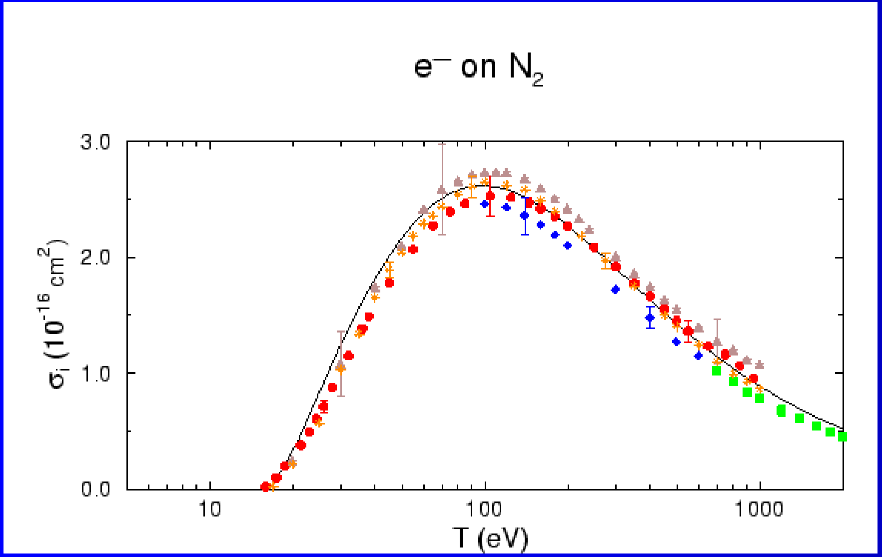
Fig. 6. Electron collision cross-section set for NH_3 (1986).

Ionization cross section He and N_2



Electron impact





New J. Phys. **11** (2009) 063047
doi:10.1088/1367-2630/11/6/063047
Cross sections for the interactions of 1 eV–100 MeV electrons in liquid water and application to Monte-Carlo simulation of HZE radiation tracks

Ianik Plante[1,2] and Francis A Cucinotta[1]

BEB W. Hwang, Y.-K. Kim and M.E. Rudd,
J. Chem. Phys. **104**, 2956 (1996).

Life is not so simple – Total ionization cross section

Electron Interactions with CF_4

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National Institute of Standards and Technology, Gaithersburg, Maryland 20899-0001

J. Phys. Chem. Ref. Data, Vol. 25, No. 5, 1996

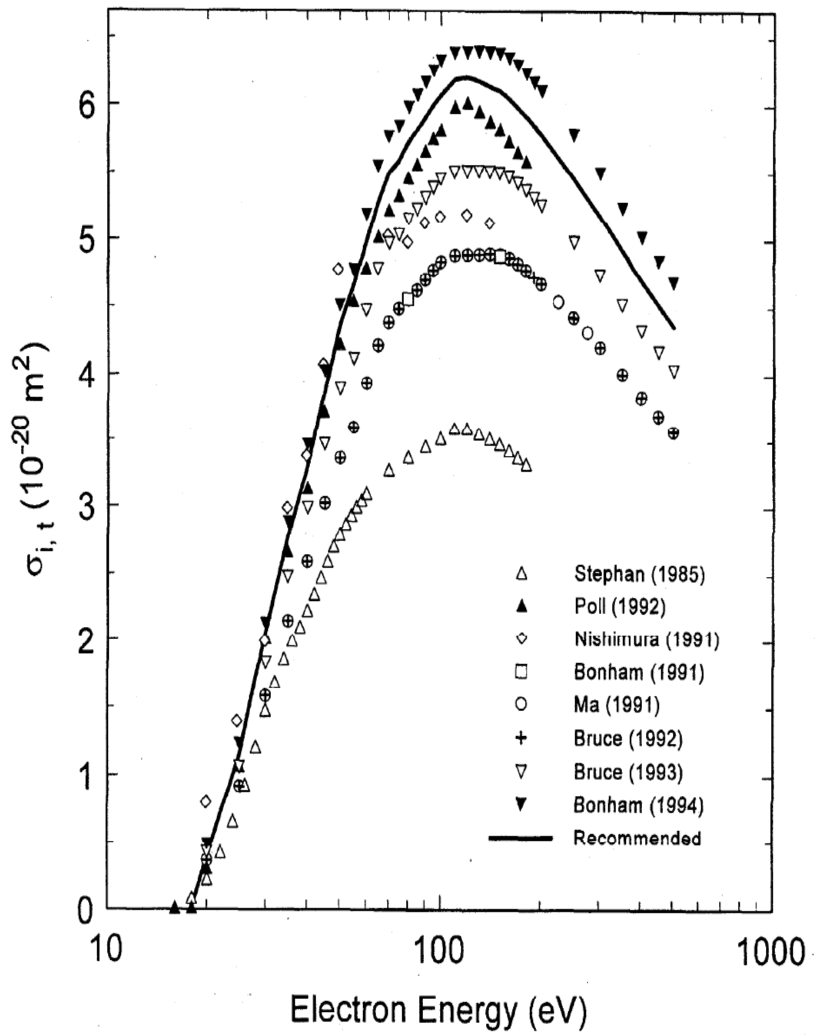


FIG. 17. Total ionization cross section $\sigma_{i,t}(\epsilon)$ as a function of electron energy for CF_4. Measured values: △, Ref. 43; ▲, Ref. 103; □, Ref. 69; ○, Ref. 98; +, Ref. 100; ▽, Ref. 104; ▼, data of Ref. 104 multiplied by 1.16 (per Bonham in Ref. 73); ◇, Ref. 106. Recommended: —, average of ▲ and ▼ (see Sec. 4.1 and Table 12).

Ionization cross section,
Different channels have different cross sections and dependencies on energy

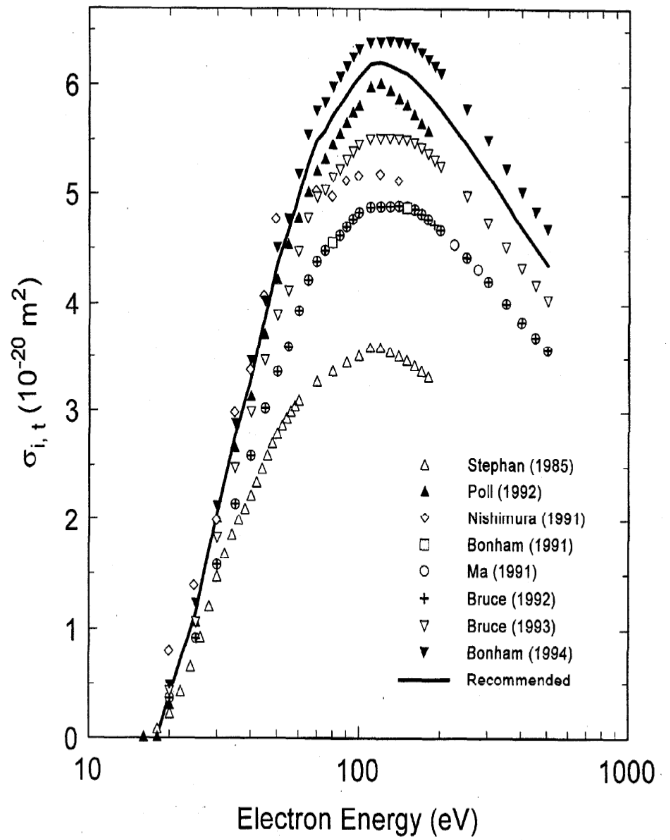


FIG. 17. Total ionization cross section $\sigma_{i,t}(\epsilon)$ as a function of electron energy for CF_4. Measured values: △, Ref. 43; ▲, Ref. 103; □, Ref. 69; ○, Ref. 98; +, Ref. 100; ▽, Ref. 104; ▼, data of Ref. 104 multiplied by 1.16 (per Bonham in Ref. 73); ◇, Ref. 106. Recommended: —, average of ▲ and ▼ (see Sec. 4.1 and Table 12).

J. Phys. Chem. Ref. Data, Vol. 25, No. 5, 1996

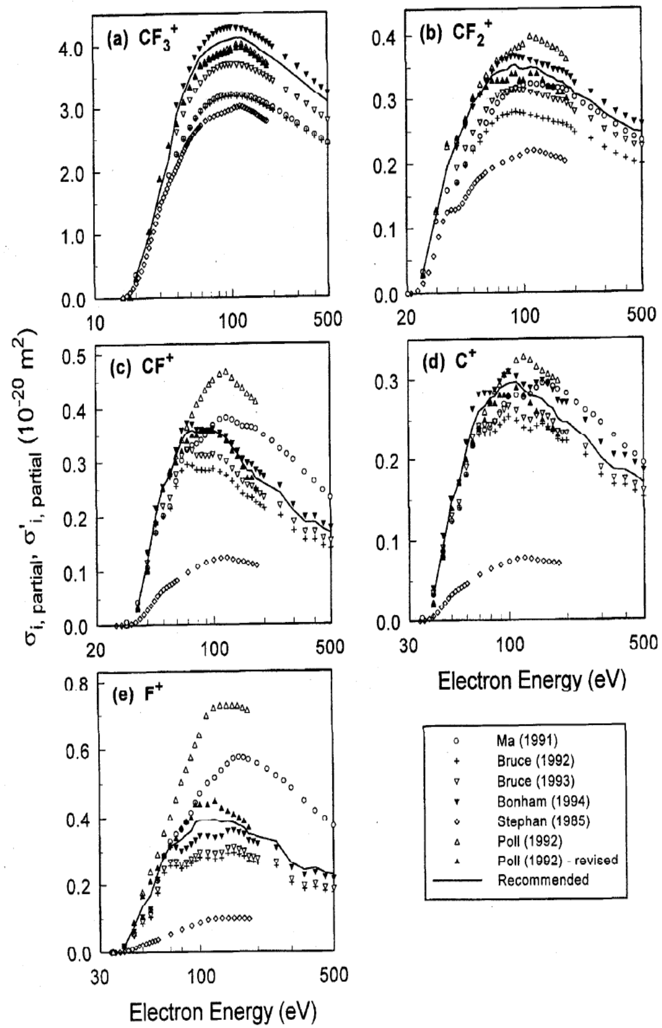


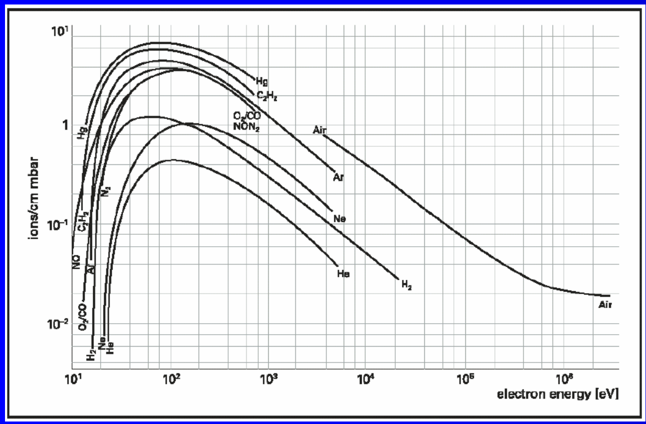
FIG. 19. Partial ionization cross section for the production of (a) CF_3^+, (b) CF_2^+, (c) CF^+, (d) C^+, and (e) F^+ by electron collision on CF_4. $\sigma'_{i,\,partial}(\epsilon)$: ◇, Ref. 43; △, Ref. 103; ○, Ref. 98. $\sigma_{i,\,partial}(\epsilon)$: +, Ref. 100; ▽, Ref. 104; ▼, Ref. 73; ▲, revised data of Ref. 103 (see text). —, average of ▼ and ▲ (see Sec. 4.2 and Table 15).

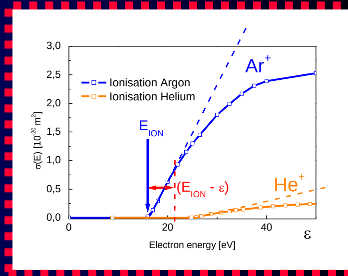
Electron Interactions with CF_4

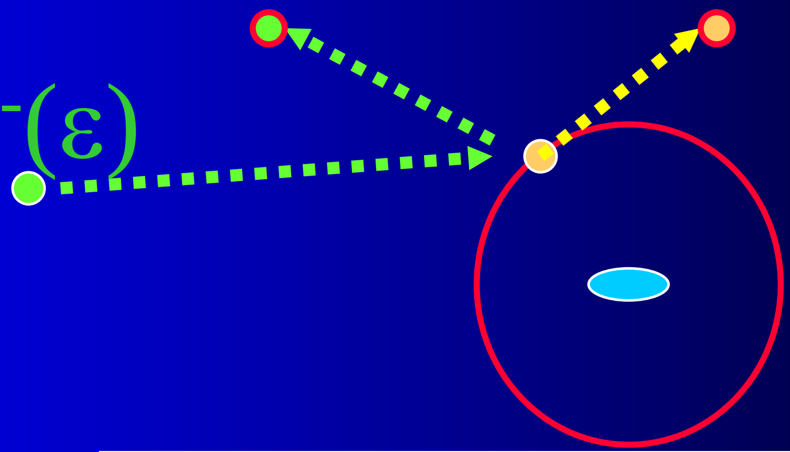
L. G. Christophorou,[a)] J. K. Olthoff, and M. V. V. S. Rao
National Institute of Standards and Technology, Gaithersburg, Maryland 20899-0001

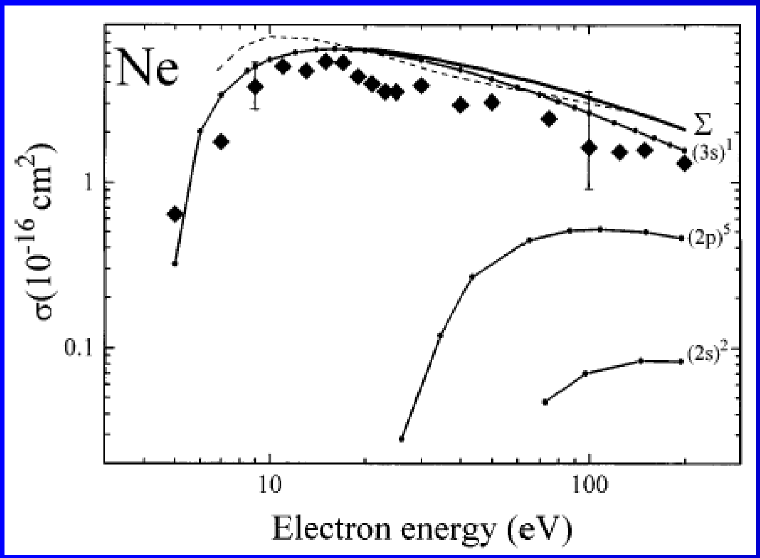
Thomson's formula

$$\sigma_j = C_j(\varepsilon - E_{ION})$$









Ionization if $\Delta\varepsilon > I$

Formula of Rutherford for coulomb force

$d\sigma = e^4 d\Theta / 4\varepsilon^2 \sin^4(\phi/2)$….. $\sigma_i = \pi e^4 / I \,.\, (\varepsilon - I)/\varepsilon^3$

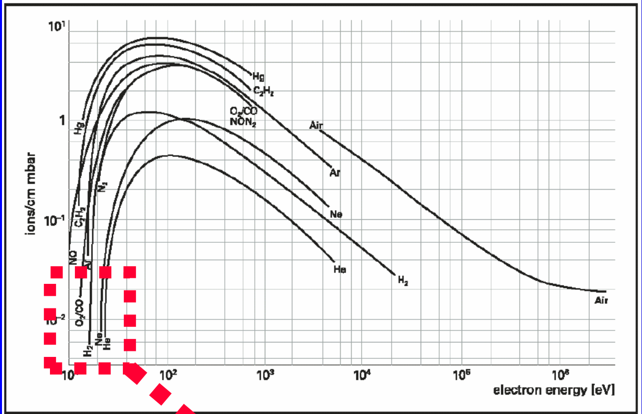
$$\sigma_i = 4\pi a_0^2 (I_H / \varepsilon)^2 \,.\, (\varepsilon - I)/I$$

➔ $\sigma_i = 4\pi a_0^2 (I_H / \varepsilon)^2 \,.\, (\varepsilon/I - 1) = f_{function}(\varepsilon/I)$

$\sigma_i = \Sigma\, \sigma_{in}$ **sum of the various subshell contributions**

Calculated ionization cross section of the $^3P_0$ state in Ne using the DM formalism. The full curves refer to the contributions from the various subshells and have been labeled appropriately. The sum of the various subshell contributions has been labeled by the symbol*6*. Also shown is the Born calculation of Ton-That and Flannery (broken curve, see text for details). The experimental data points (diamonds) are those of Johnston *et al* . Two typical error bars (combined systematic and statistical uncertainty) are shown for the experimental data.

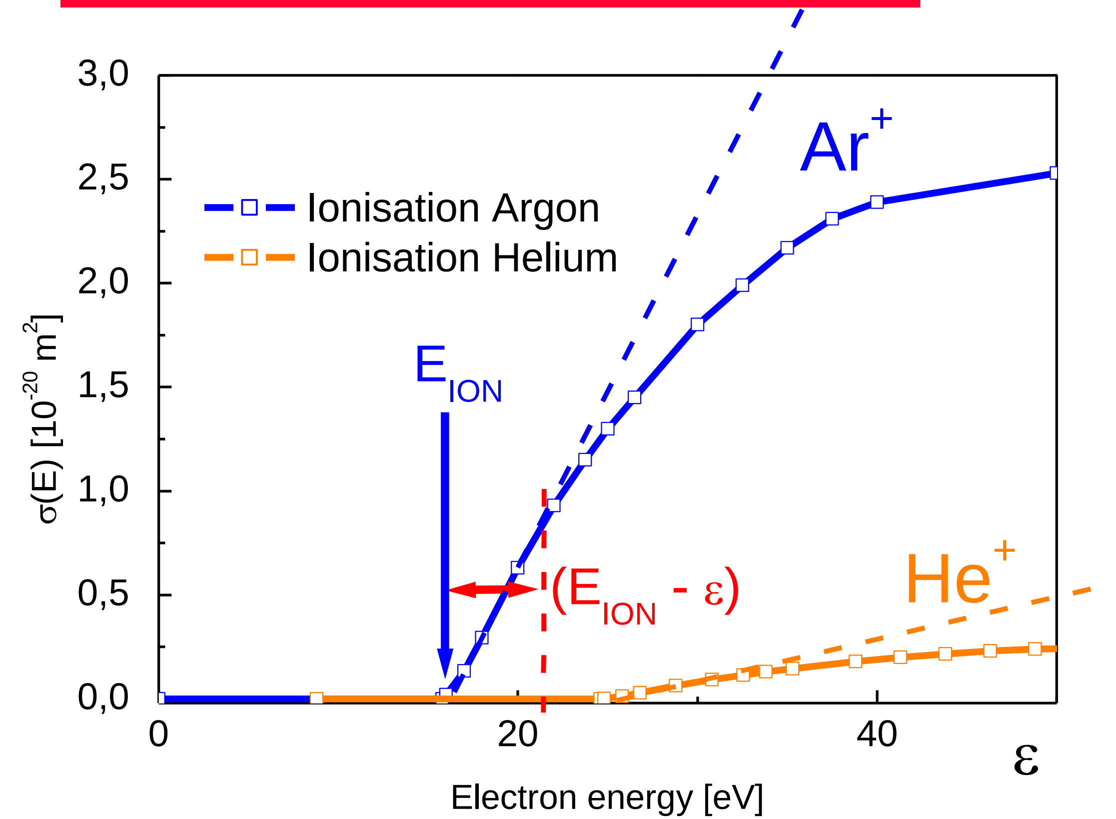
Near the threshold ➔ linear approximation



$$\sigma_i = 4\pi a_0^2 (I_H/\varepsilon)^2 \,.\, (\varepsilon - I)/I$$

➔ $\sigma_i = 4\pi a_0^2 (I_H/\varepsilon)^2 \,.\, (\varepsilon/I - 1) = f_{function}(\varepsilon/I)$

$$\sigma_j = C_j(\varepsilon - E_{ION})$$



Ionization cross section recent studies Ar - higher approximation

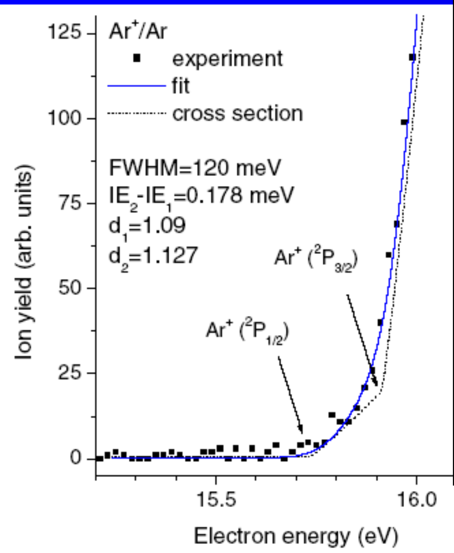


Figure 2. The ion yield curve Ar^+/Ar as measured in the present experiment. The full curve is the result of the fitting procedure, involving a convolution of the cross section (dotted curve; the arrows indicating the thresholds for the two spin states) and an electron energy distribution function with a width of 120 meV FWHM (for details see text).

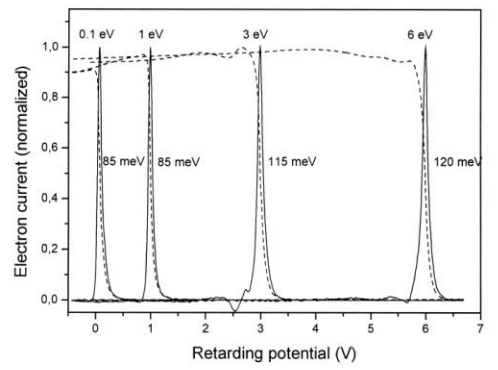


Fig. 11. Electron current versus retarding field for different electron energies (from 0.1 to 6 eV). Note that the alignment of the magnetic field is very crucial as, otherwise, the transmitted electron current varies significantly with energy. The alignment in the present case is still not perfect, as the coils used to generate the magnetic field have not Helmholtz geometry. Hence, the electron current shows some small variations with energy. In addition, the energy resolution of the monochromator, as determined by calculating the FWHM of the differentiated electron current, seems to deteriorate slightly at higher electron energies, that is, in this experimental run from ~85 meV FWHM at 0.1 eV to ~120 meV FWHM at 6 eV.

IE – ionization energy
EII – electron Impact Ionization

IE of Ar is 15.759+-0.001eV

IE_1 of $Ar^+(^2P_{1/2})$

IE_2 of $Ar^+(^2P_{3/2})$

$IE_2 - IE_1 = 0.178$eV

The measured Ar^+ ion yield is fitted with a function $I(U, \mathbf{p}, s)$:

$$I(U, \mathbf{p}, s) = \int \sigma_w(E, \mathbf{p}) \cdot f(E,U)\, dE + s \qquad (6)$$

where s is the background signal below the ionization threshold and the cross section σ_w for EII at the ionization threshold of Ar is assumed to have the form:

$$\sigma w(E, \mathbf{p}) = \begin{cases} 0 & \text{for } E < IE_1(Ar) \\ A_1(E - IE1)^{d1} & \text{for } E > IE_1 \text{ and } E < IE_2 \\ A_1(E - IE1)^{d1} + A_2(E - IE2)^{d2} & \text{for } E > IE_2 \end{cases}$$

Ionization cross sections H_2 – details near the threshold

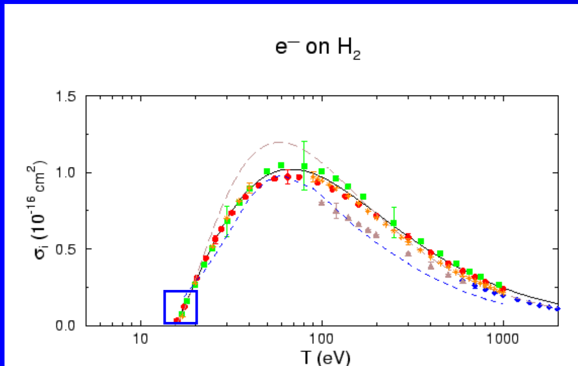


TABLE 13.6

Comparison of observed and calculated energy separation of various vibrational levels of H_2^+

	Energy separations (eV)					
Vibnl. levels	0–1	1–2	2–3	3–4	4–5	5–6
Calculated	0·269	0·254	0·238	0·223	0·208	0·192
Observed	0·272	0·263	0·233	0·237	0·21	0·20

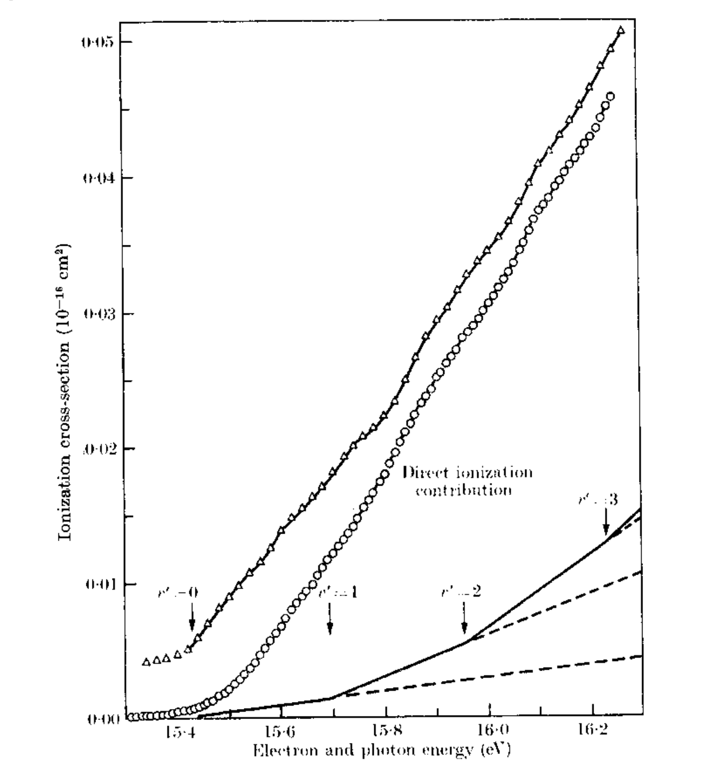


FIG. 13.21. Variation of the ionization cross-section of H_2 near the threshold as observed by McGowan, Fineman, Clarke, and Hanson, ○ experimental points. The integrated photo-ionization cross-section observed by Dibeler, Reese, and Krauss is shown for comparison, Δ experimental points. The estimated contribution from direct ionization is also shown.

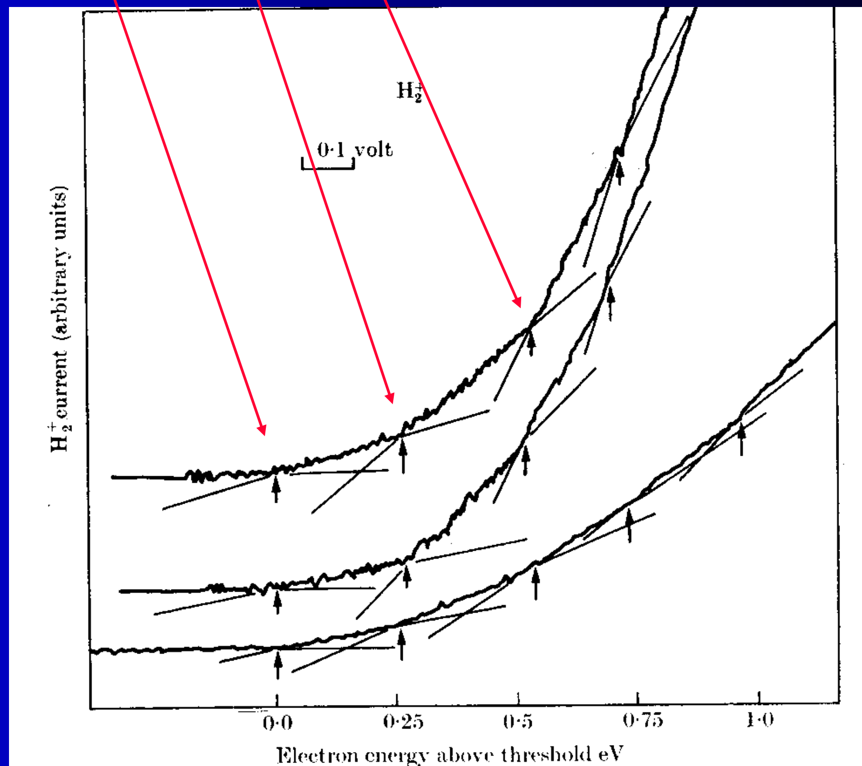


FIG. 13.19. Variation of the ionization cross-section of H_2 near the threshold as observed by Marmet and Kerwin.

Ion source

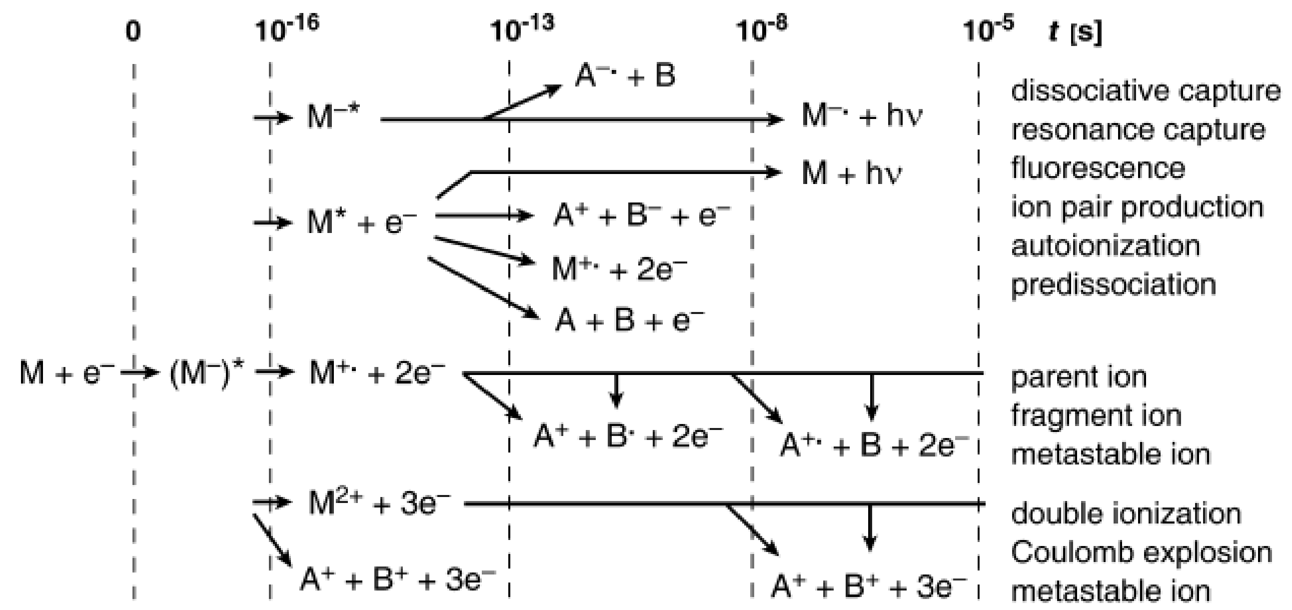
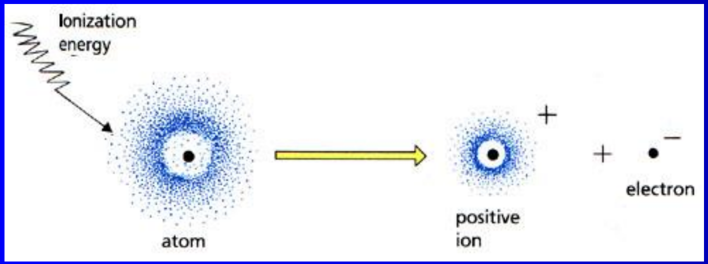
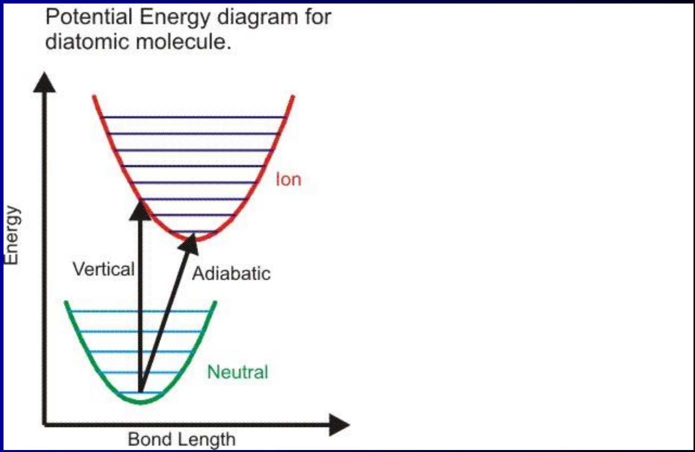


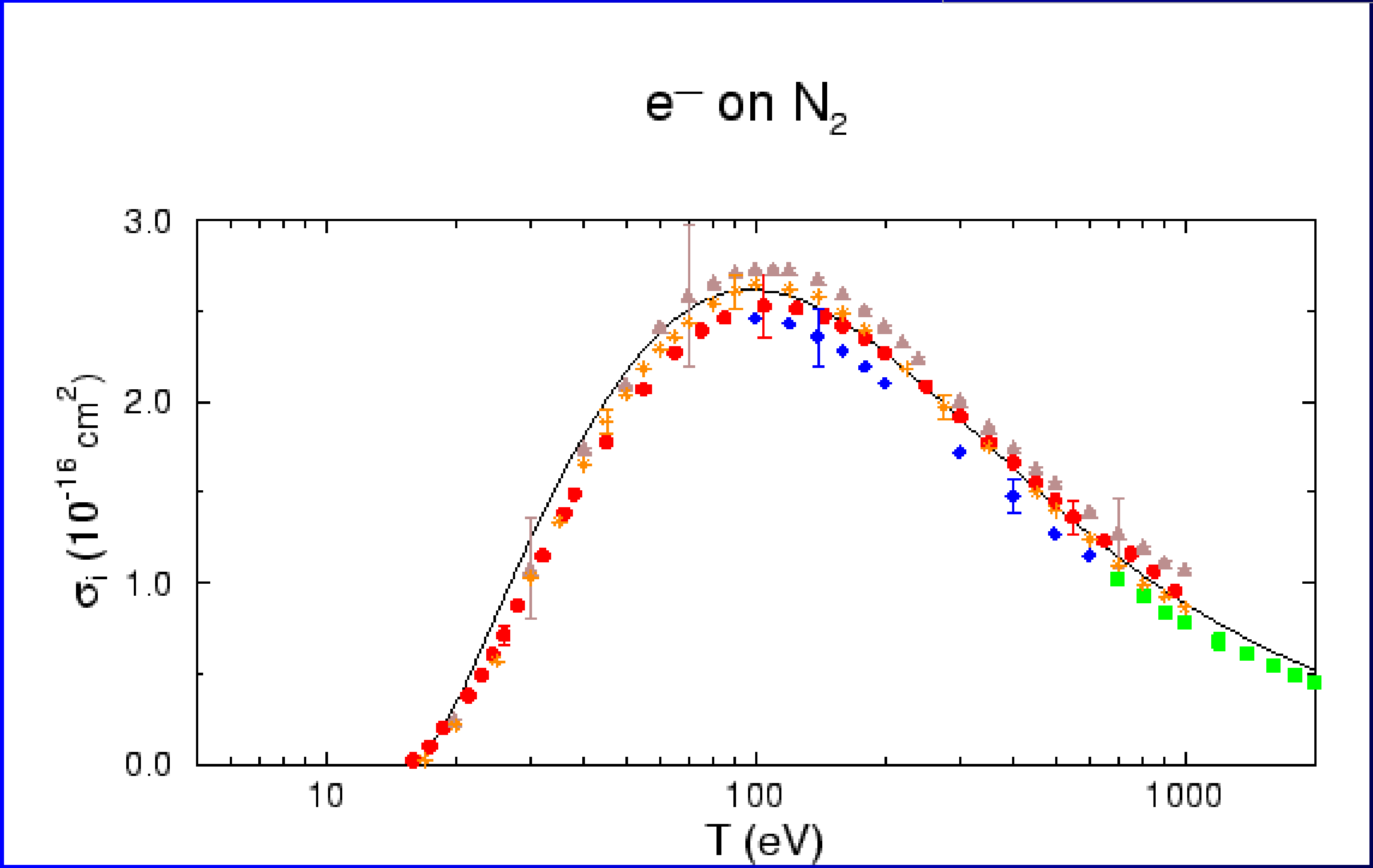
Fig. 2.10. Schematic time chart of possible electron ionization processes. Adapted from Ref. [39] with permission. © Wiley & Sons, 1986.





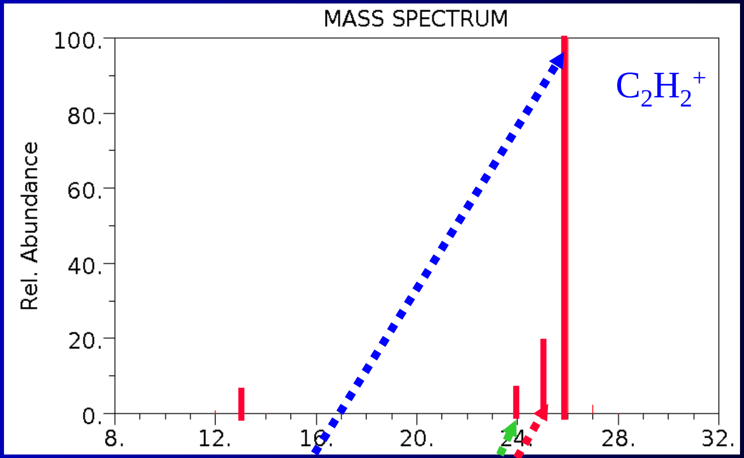
Ionization cross section N_2

BEB
W. Hwang, Y.-K. Kim and M.E. Rudd, J. Chem. Phys. **104**, 2956 (1996).



Ionization cross section -acetylene C_2H_2
Product channels

Pragmatic approach



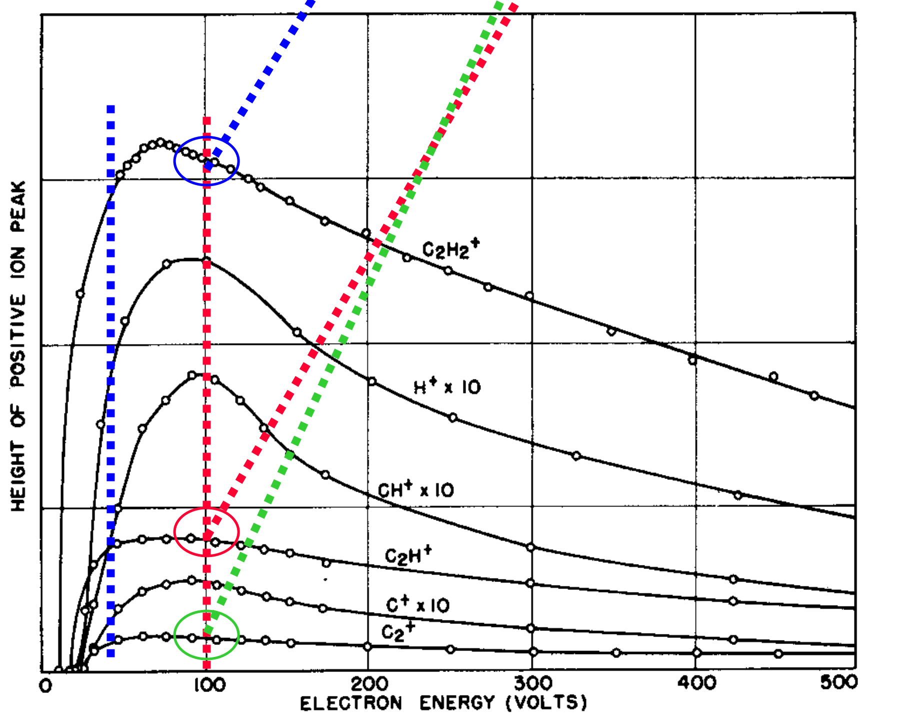
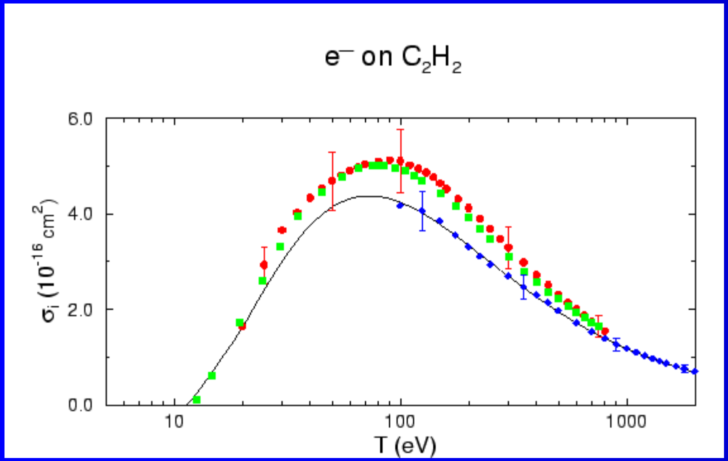
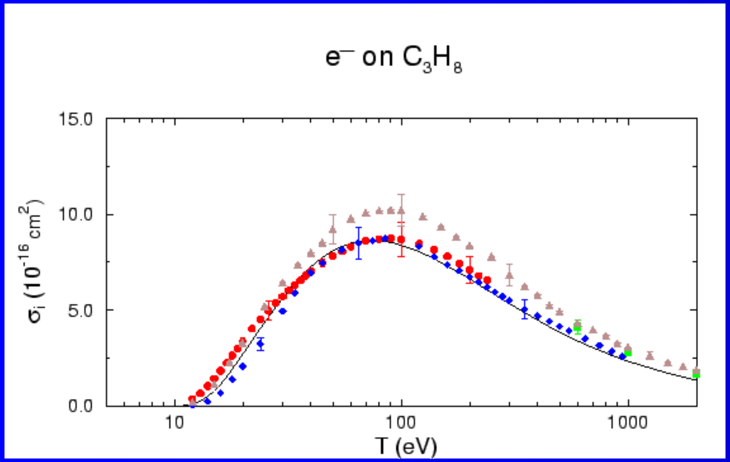
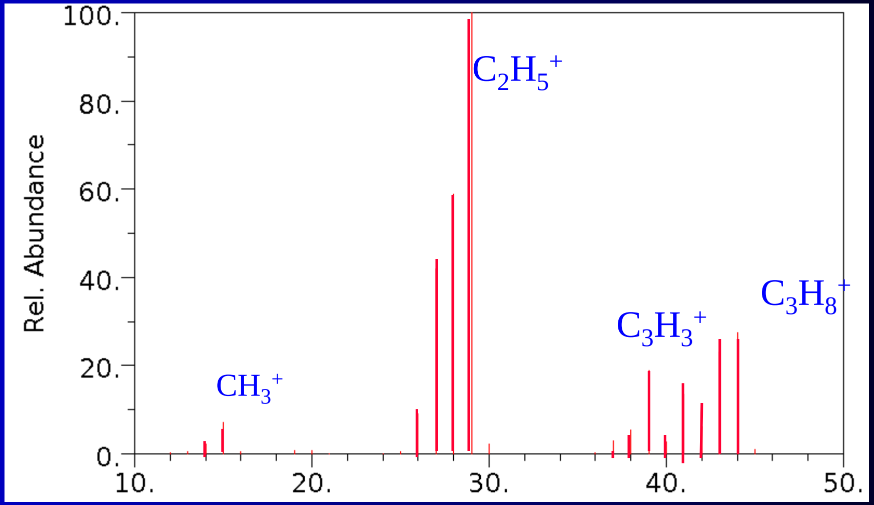


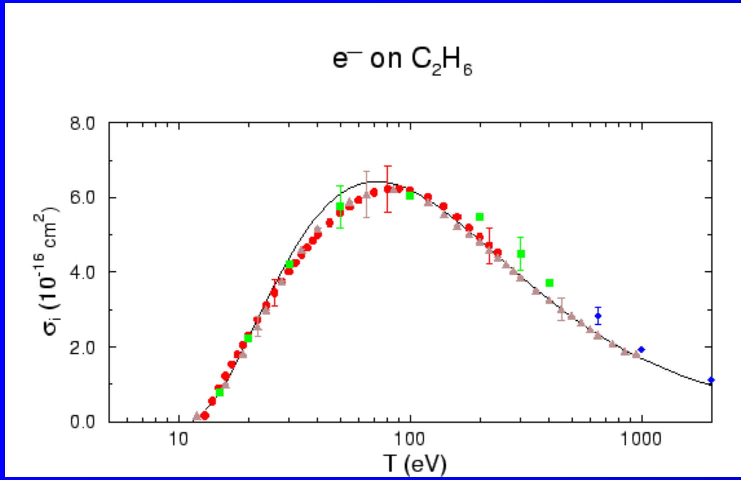
FIG. 6. Ionization efficiency curves for several ions from acetylene (493).

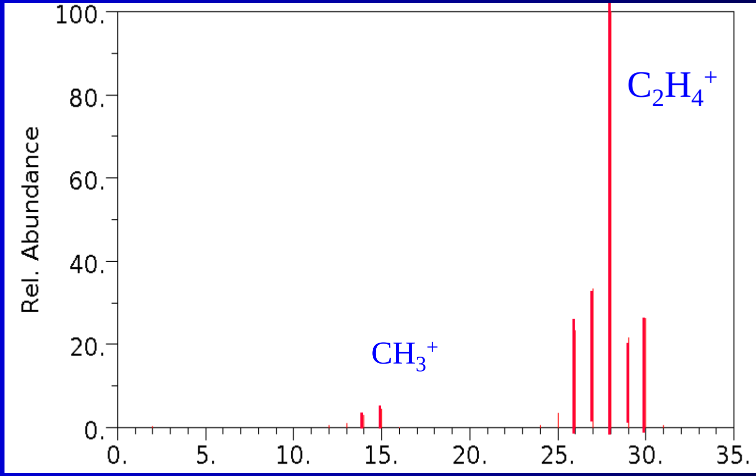


Ionization cross section data from http://webbook.nist.gov









How to recognize spectra ???

Ionization - EII of CH_4

Determination of ionization energies (IEs)

for EII of CH_4 for the following reactions:

$$e + CH_4 \rightarrow CH^+_4 + 2e \qquad (1)$$

$$\rightarrow CH^+_3 + H + 2e \qquad (2a)$$

$$\rightarrow CH^+_3 + H^- + e \qquad (2b)$$

$$\rightarrow CH^+_2 + H_2 + 2e \qquad (3)$$

$$\rightarrow CH^+ + H + H_2 + 2e \qquad (4a)$$

$$\rightarrow CH^+ + H^- + H_2 + e \qquad (4b)$$

$$\rightarrow C^+ + 2H_2 + 2e. \qquad (5)$$

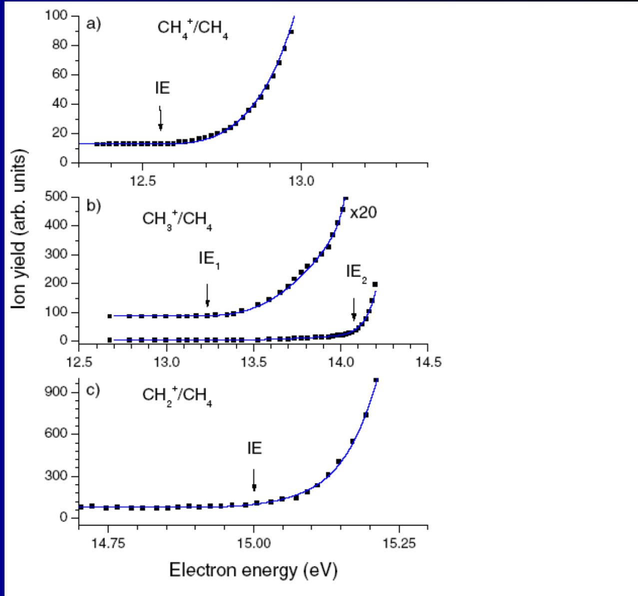


Figure A.1. Ion yield curve for CH_4^+, CH_3^+ and CH_2^+/CH_4 obtained through digitalization of the data from [3]. Full curves present fits through these data. Arrows indicate the estimated IEs derived by the fitting procedure.

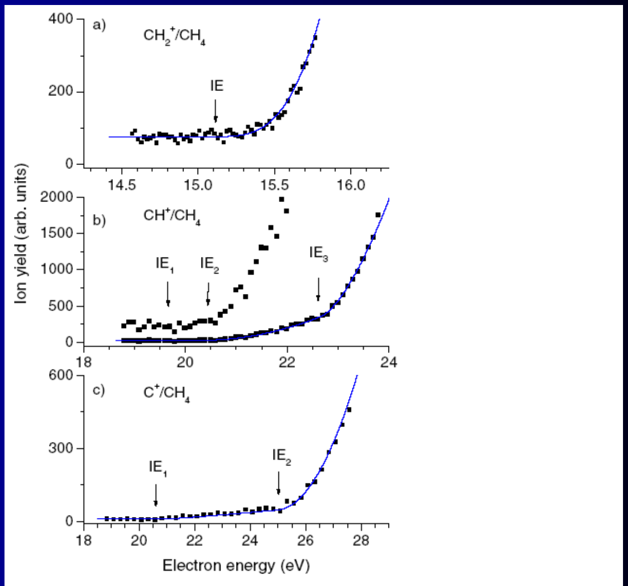
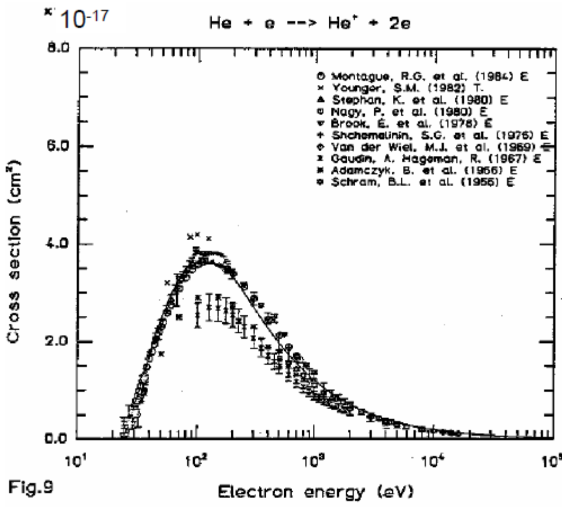


Figure 5. Ion yield curve for CH_2^+, CH^+ and C^+/CH_4 as measured at 293 K. Full curves present fits through the experimental data. Arrows indicate the IEs derived by the fitting procedure. Note that for the case of CH^+ only IE_2 and IE_3 have been derived from the present data; IE_1 has been calculated from the known EA of H (see text).

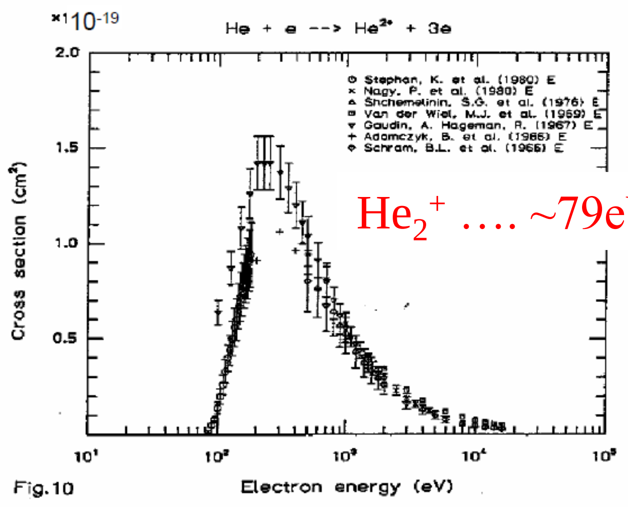
$$\sigma w(E, \mathbf{p}) = \begin{cases} 0 & \text{for } E < IE_1(\mathrm{Ar}) \\ A_1(E - IE1)^{d1} & \text{for } E > IE_1 \text{ and } E < IE_2 \\ A_1(E - IE1)^{d1} + A_2(E - IE2)^{d2} & \text{for } E > IE_2 \end{cases}$$

Ionization of He

Single-ionisation: He + e → He^+ + 2e



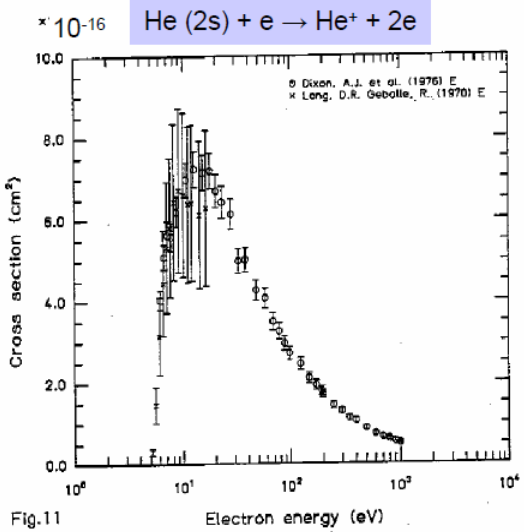
Multi-ionisation: He + e → He^{2+} + 3e



He_2^+ …. ~79eV

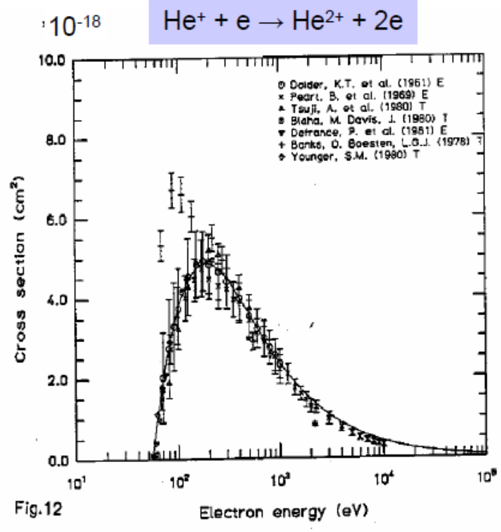
Ionization of the excited state

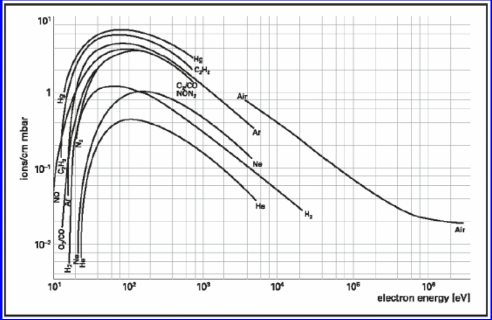
He (2s) + e → He^+ + 2e



Ionization of singly charged He

He^+ + e → He^{2+} + 2e





Multiple ionization

Multiple ionization of helium and krypton by electron impact close to threshold: appearance energies and Wannier exponents

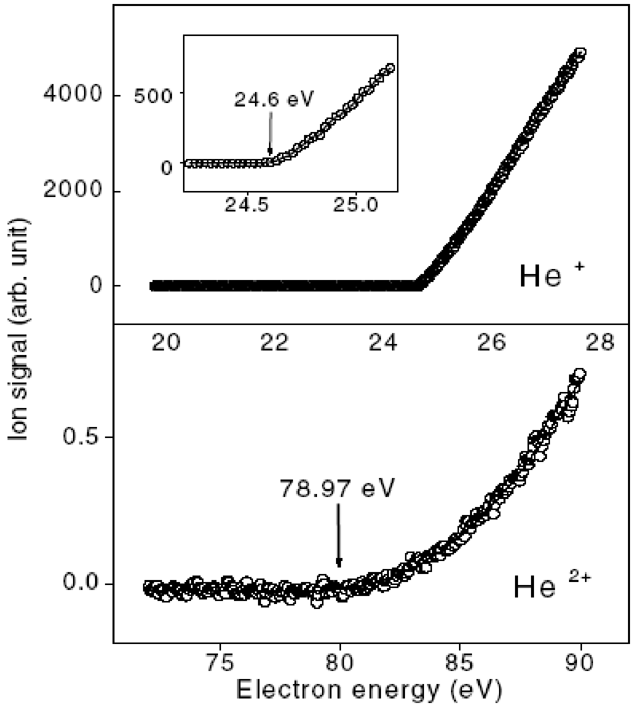


Figure 1. Ion signal as a function of electron energy for the formation of He^+ ions (top) and He^{2+} ions (bottom) in the near-threshold region. The measured data are shown as open circles, the fits are shown as solid curves. The AEs, which are indicated, are the AEs for the individual data sets shown and may differ from the AE values listed in table 1 which were obtained from a comprehensive analysis of many individual data sets.

Table 1. AE values in eV for the formation of He^+ and He^{2+} ions in comparison with other measured or calculated AE values.

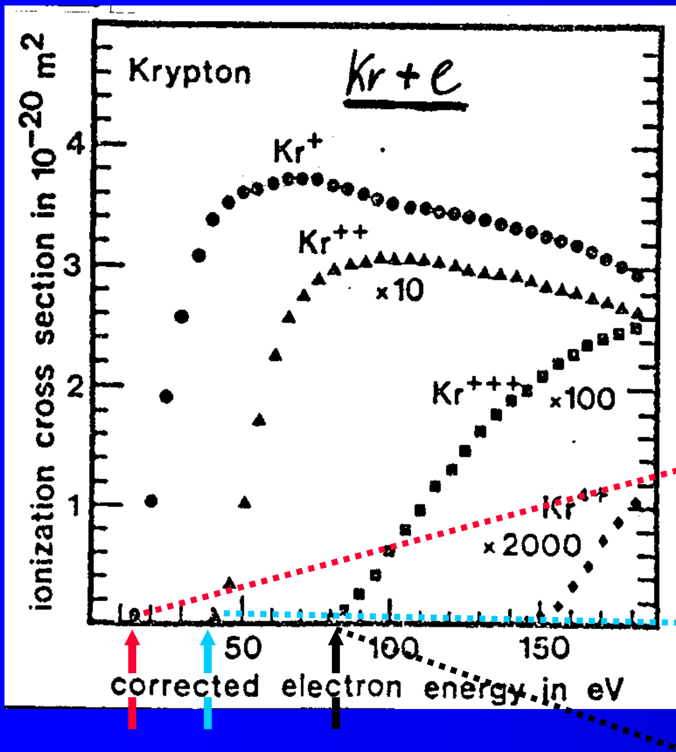
	Spectroscopic value [1]	Redhead [45]	This work
He^+	24.59	—	24.6 ± 0.15
He^{2+}	79.00	77.58	79.05 ± 0.3

J. Phys. B: At. Mol. Opt. Phys. **35** (2002) 4685–4694

He2+ …. ~79eV

Multiple ionization

Multiple ionization of helium and krypton by electron impact close to threshold: appearance energies and Wannier exponents



J. Phys. B: At. Mol. Opt. Phys. **35** (2002) 4685–4694

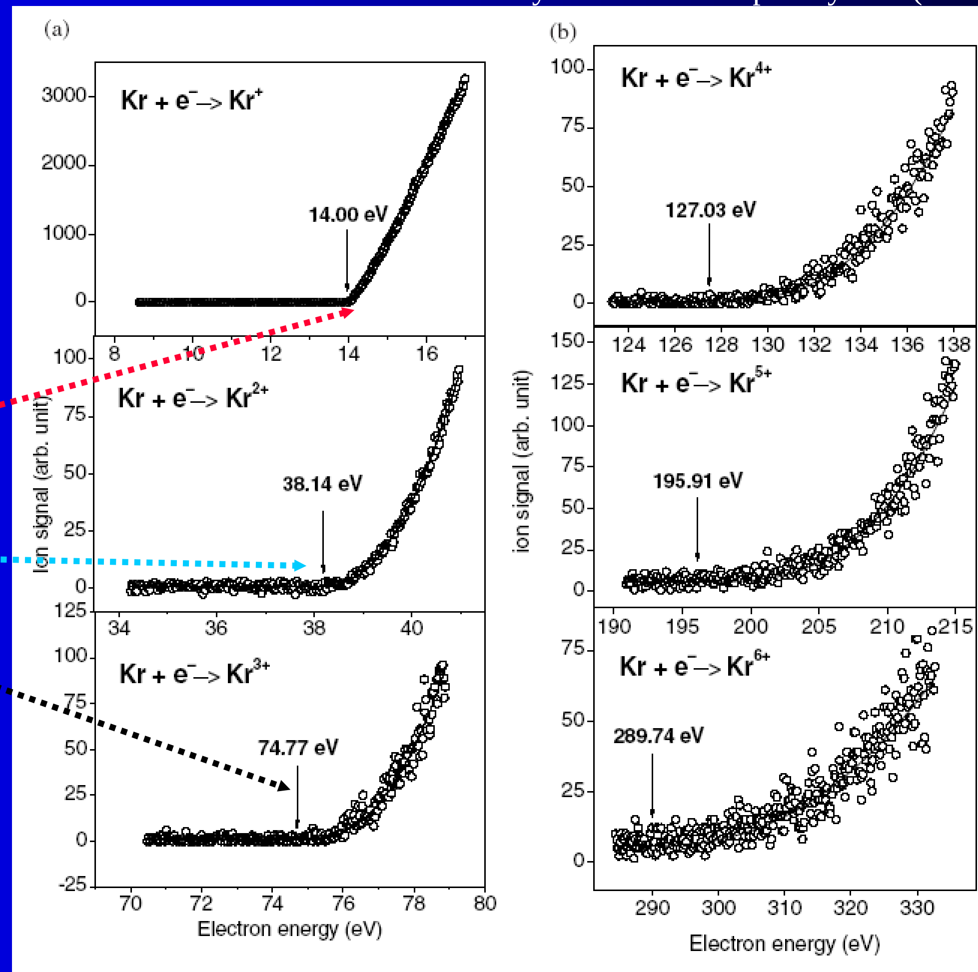
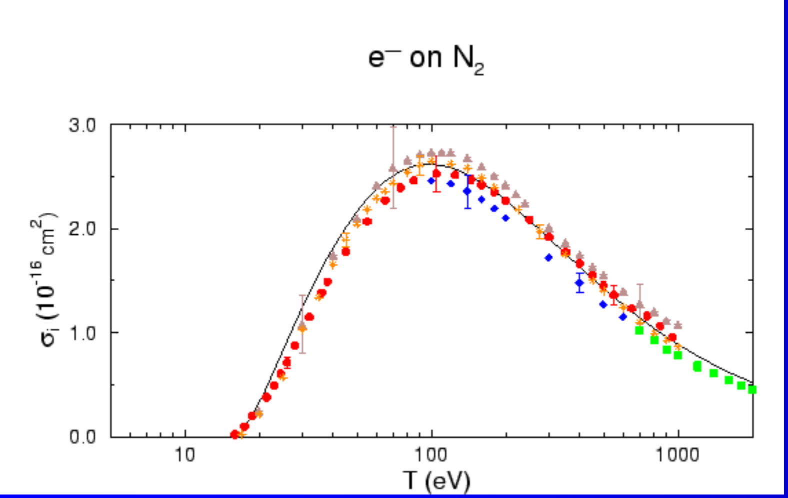
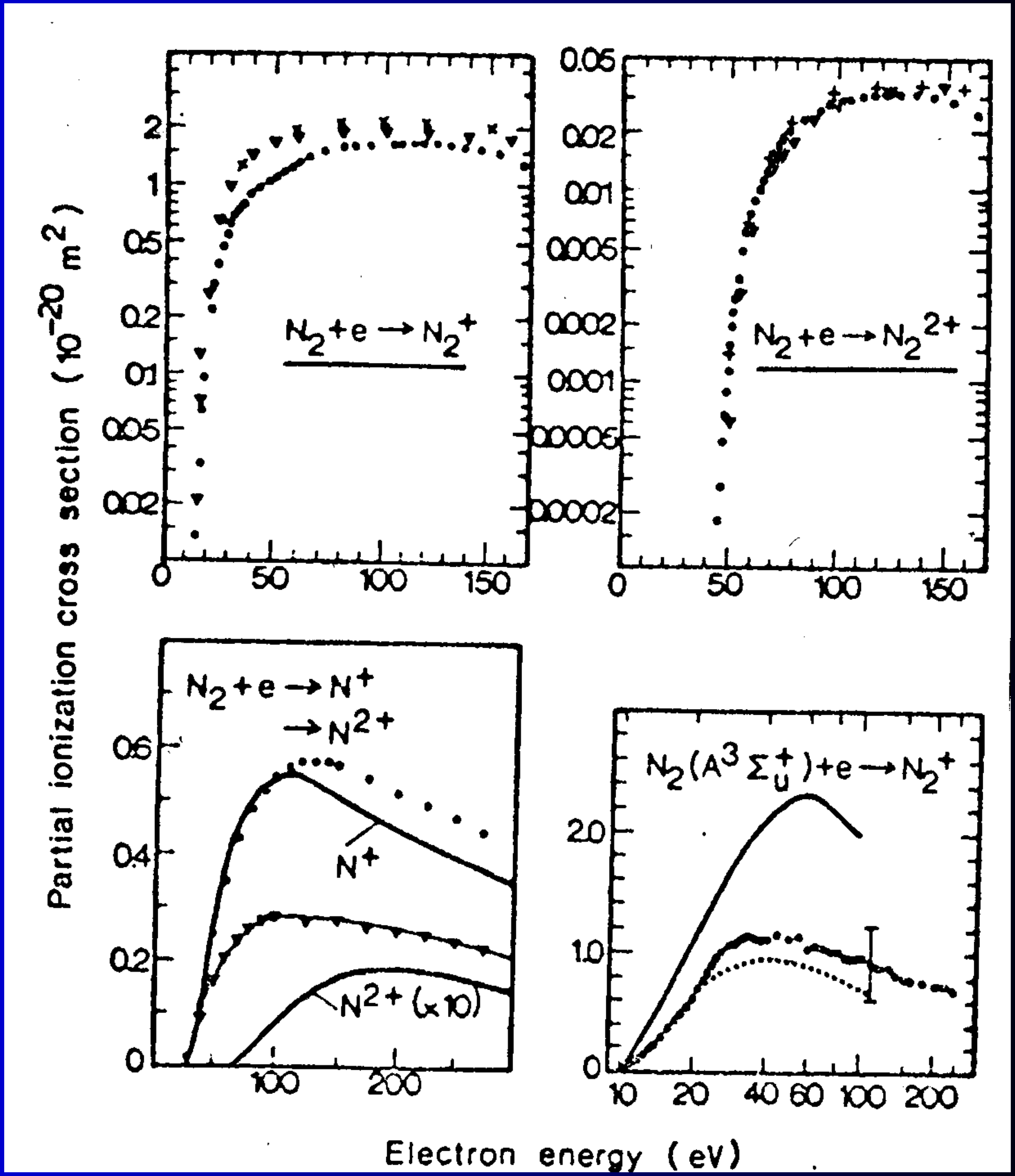


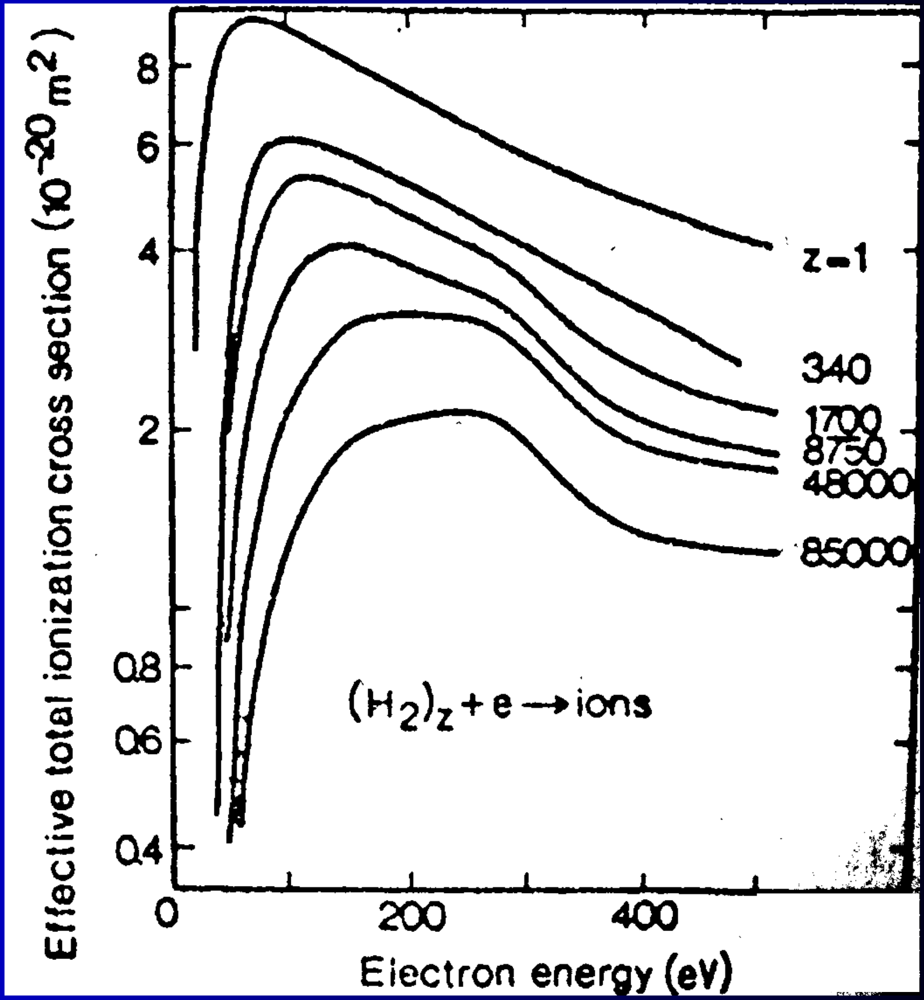
Figure 2. Ion signal as a function of electron energy for the formation of Kr^{n+} ions (n = 1–6) in the near-threshold region. The measured data are shown as open circles, the fits are shown as solid curves. The AEs, which are indicated, are the AEs for the individual data sets shown and may differ from the AE values listed in table 2 which were obtained from a comprehensive analysis of many individual data sets.

Multiple ionization





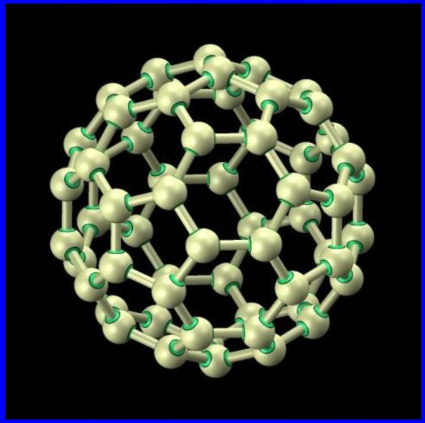
Ionization of clusters

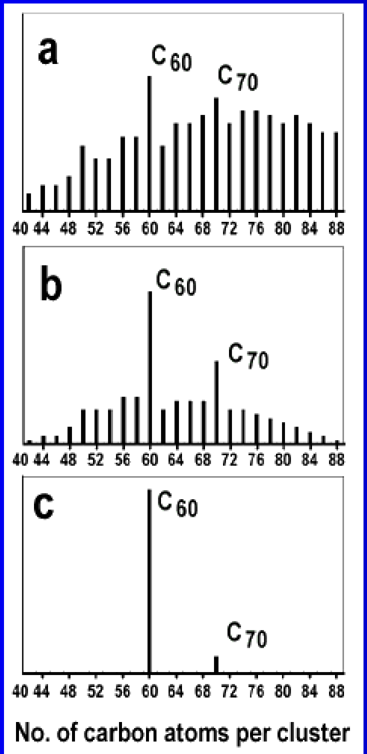


$(H_2)_Z + e \rightarrow$ ions

$\sigma_{\text{average total}} = Z.\ \sigma_{\text{effective}}$

Ionization of C60 Fulleren





$$e^- + C_{60} \longrightarrow C_{60}^{+} + 2e^-$$

$$e^- + C_{60}^{+} \longrightarrow C_{60}^{2+} + 2e^-$$

$$e^- + C_{60}^{2+} \longrightarrow C_{60}^{3+} + 2e^-$$

$$e^- + C_{60}^{3+} \longrightarrow C_{60}^{4+} + 2e^-$$

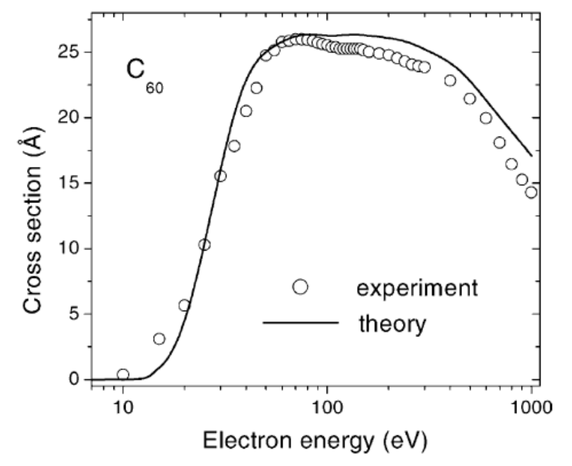


Fig. 6. Cross-section for the formation of C_{60}^{+} ions following electron-impact single ionization of C_{60}. The experimental data (○) are from Ref. [18], the solid line represents the present calculation.

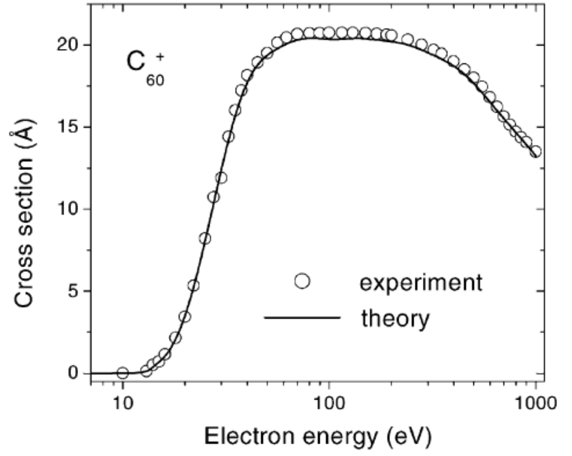
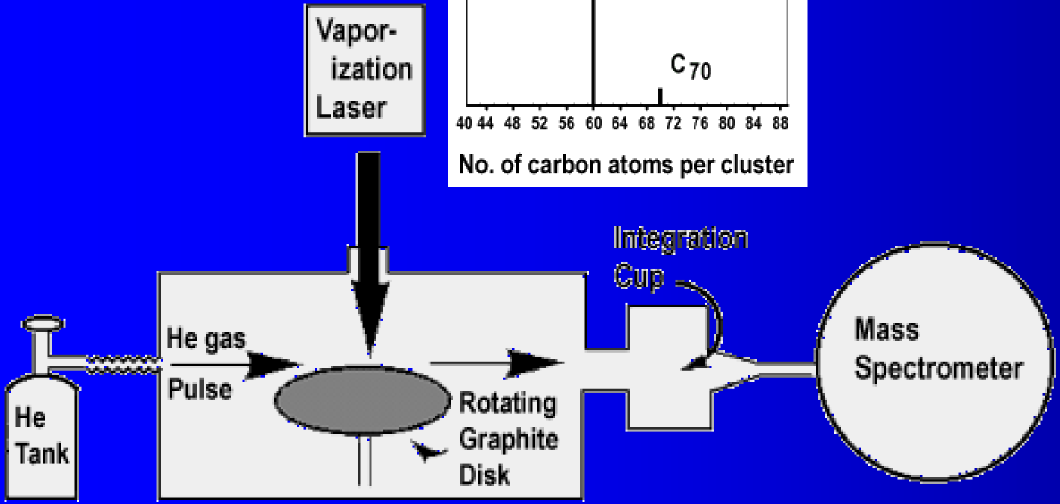


Fig. 3. Cross-section for the formation of C_{60}^{2+} ions following electron-impact single ionization of C_{60}^{+}. The experimental data (○) are from Ref. [23], the solid line represents the present calculation.



Distribution of carbon clusters produced under various experimental conditions.

a) Low helium density over graphite target at time of laser vaporization.

b) High helium density over graphite target at time of laser vaporization.

c) Same as b), but with addition of "integration cup" to increase time between vaporization and cluster analysis.

Electron-Impact Induced Fragmentation of Fullerene Ions

The measurements were performed employing the electron-ion crossed-beam setup. A commercially available powder of fullerenes was evaporated with an electrically heated oven. The neutral vapor was introduced into a 10 GHz Electron Cyclotron Resonance Ion Source (ECRIS). The extracted ion beam was collimated to 2x2 mm^2 after mass to charge analysis and crossed with an intense electron beam. The energy of the electrons can be varied between 10 and 1000 eV. After the electron-ion interaction the fragment ions $C_{58}{}^{q+}$ were separated from the incident ion beam of $C_{60}{}^{q+}$ by a 90^0 magnet and detected by a single-particle detector. The flight time between the interaction of the $C_{60}{}^{q+}$ ions and the analysis of the product ions is in the order of 10 μs. The current of the parent ion beam was measured simultaneously in a Faraday cup.

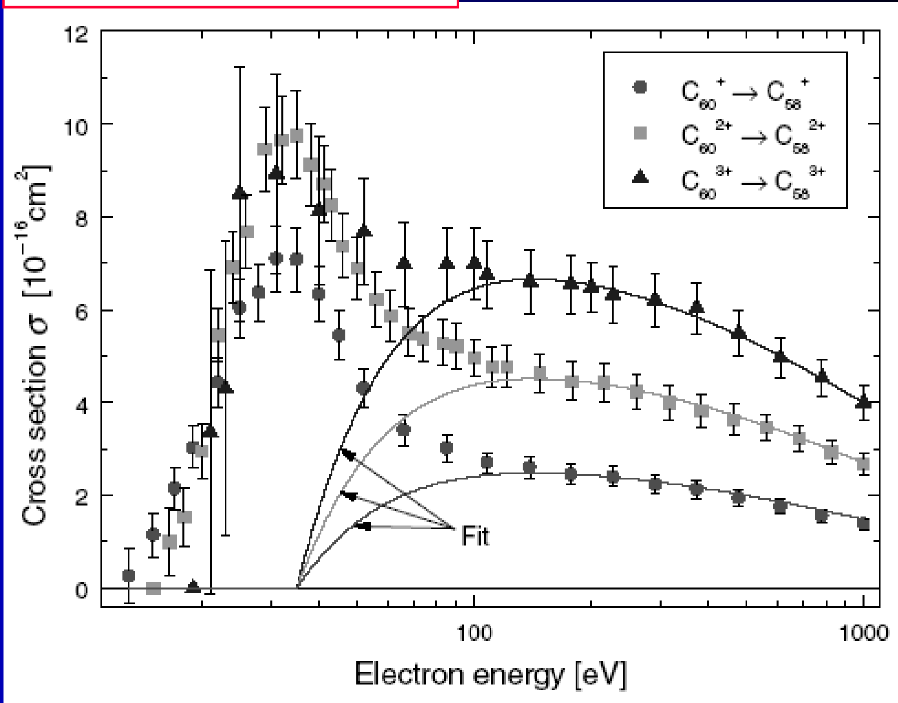
Binding energy value of about 11 eV

$$e^- + C_{60}{}^{+} \rightarrow C_{58}{}^{+} + C_2 + e^-$$

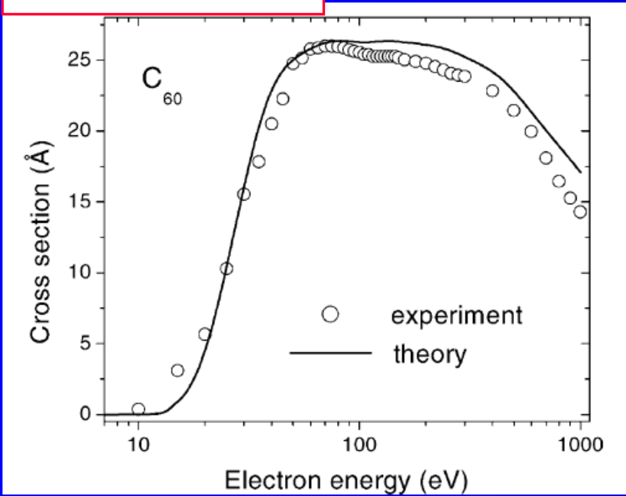
$$e^- + C_{60}{}^{2+} \rightarrow C_{58}{}^{2+} + C_2 + e^-$$

$$e^- + C_{60}{}^{3+} \rightarrow C_{58}{}^{3+} + C_2 + e^-$$

FRAGMENTATION



IONIZATION



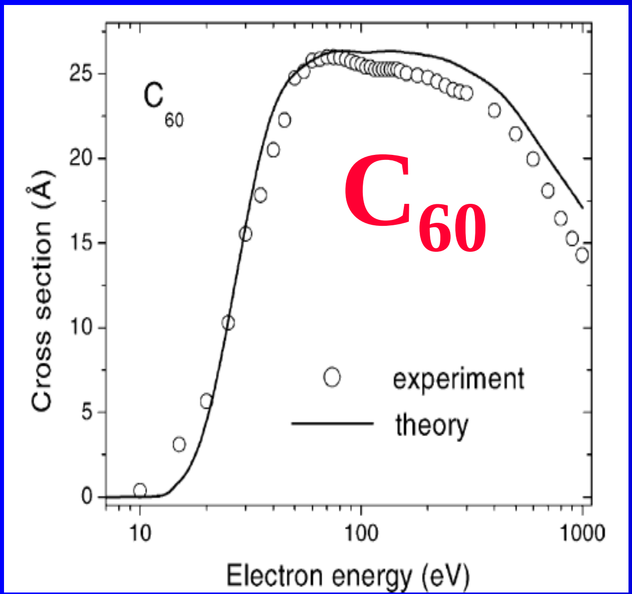
Absolute cross sections s for the electron-impact induced C_2 fragmentation of $C_{60}{}^{q+}$ ions.

Electron-Impact Induced Ionization of Fullerene Ions

IONIZATION

A semi-empirical concept for the calculation of electron-impac
ionization cross-sections of neutral and ionized fullerenes

International Journal of Mass Spectrometry 223–224 (2003) 1–8



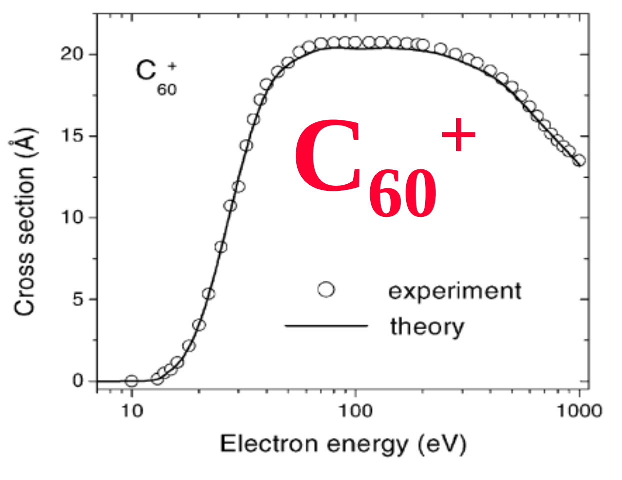


Fig. 3. Cross-section for the formation of C_{60}^{2+} ions following electron-impact single ionization of C_{60}^{+}. The experimental data (○) are from Ref. [23], the solid line represents the present calculation.

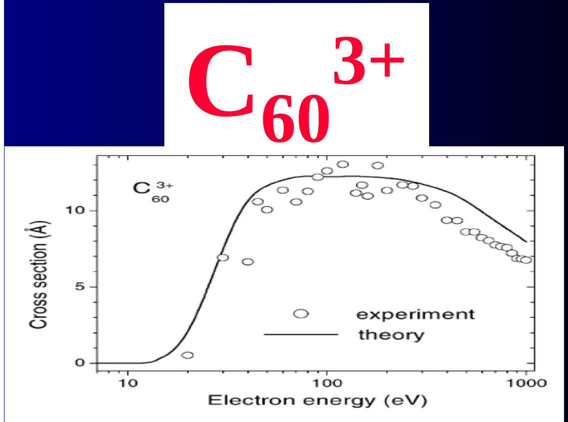
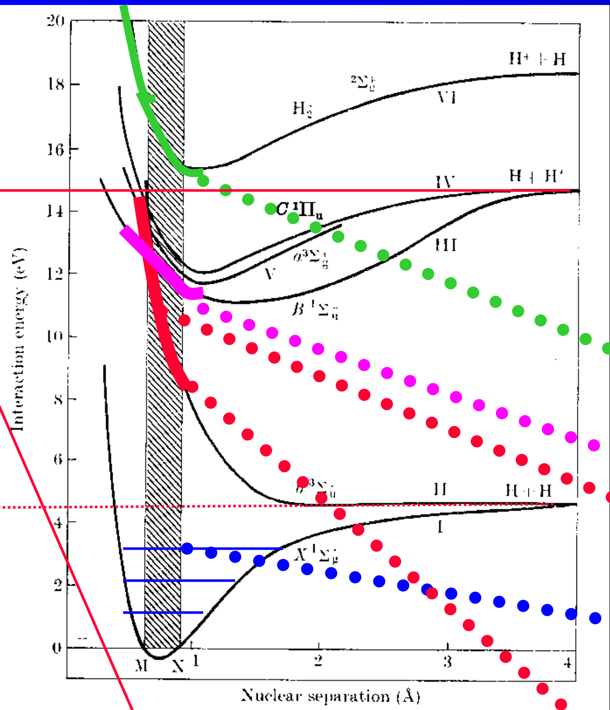


Fig. 4. Cross-section for the formation of C_{60}^{4+} ions following electron-impact single ionization of C_{60}^{3+}. The experimental data (○) are from Ref. [23], the solid line represents the present calculation.

Cross sections for vibrational excitation, dissociation, ionization…H_2

$H_2 + e$	→ $H_2(v) + e$ …….	Vibrational excitation
	→ $H + H + e$…….	Dissociation
	→ $H_2^* + h\nu + e$ …	Photon excitation
	→ $H_2^+ + e + e$…..	Ionization
	→ $H^+ + H + e + e$	Dissociative Ionization



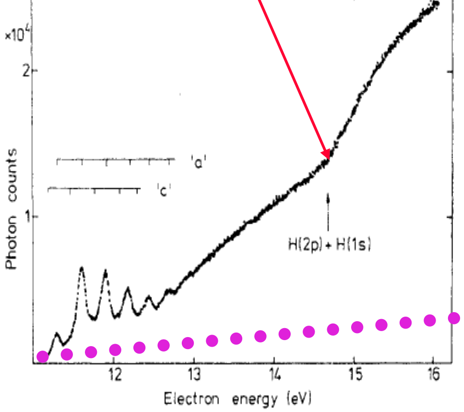


Figure 3. Optical excitation function for VUV photons measured with channeltron and MgF_2 window (1120–1300 Å); pressure 4×10^{-7} bar; collection time 7 h; 4·9 meV/channel. Energy positions of known resonances are indicated. The dissociation energy for H(2p)+H(1s) is marked by an arrow.

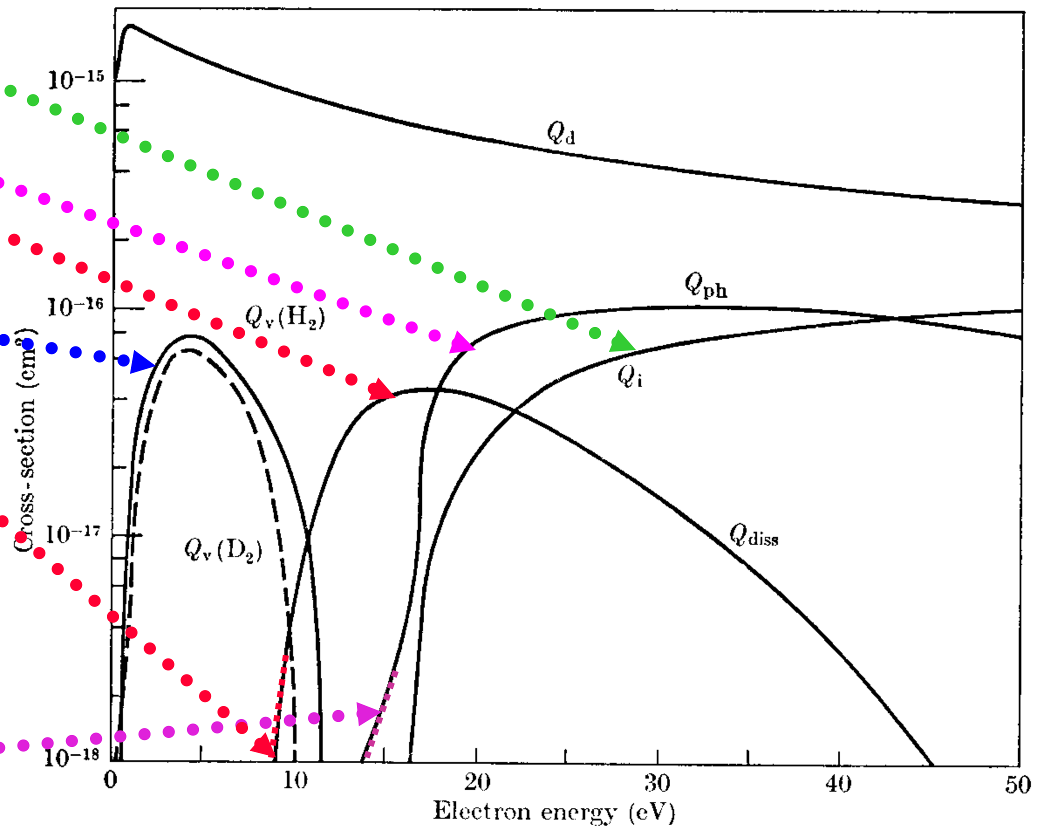


FIG. 13.37. Cross-sections assumed by Engelhardt and Phelps in their analysis of swarm data in H_2 and D_2 for electrons of characteristic energy greater than 1 eV. Q_d momentum-transfer cross-section, Q_i, ionization cross-section, Q_{diss} dissociation cross-section, Q_{ph} photon excitation cross-section, Q_v vibrational excitation cross-section (—— H_2, – – – D_2).

Cross sections for ionization…H_2

$H_2 + e$

→ $H_2(v) + e$ ……. **Vibrational excitation**

→ $H + H + e$……. **Dissociation**

→ $H_2^* + h\nu + e$ … **Photon excitation**

→ $H_2^+ + e + e$….. **Ionization**

→ $H^+ + H + e + e$

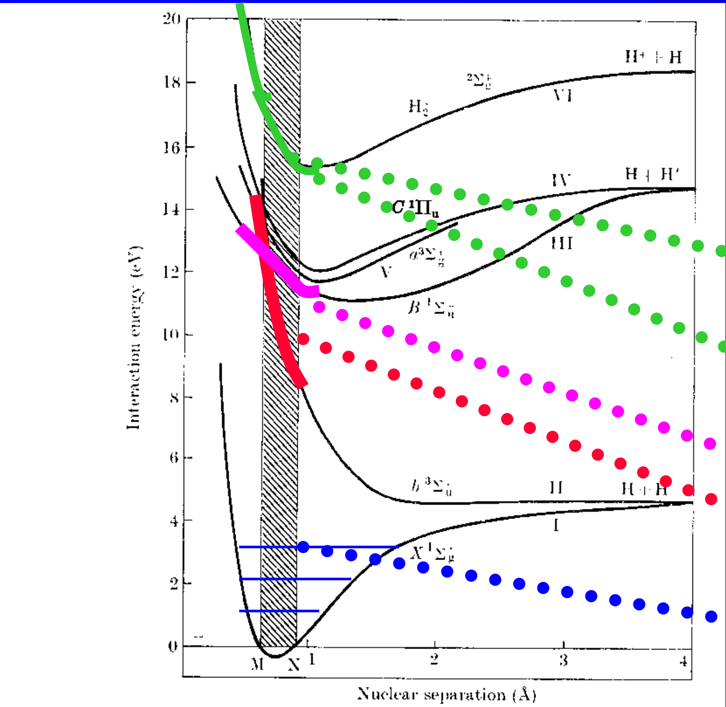


Fig. 13.1. Potential energy curves for electronic states of H_2 and H_2^+ …

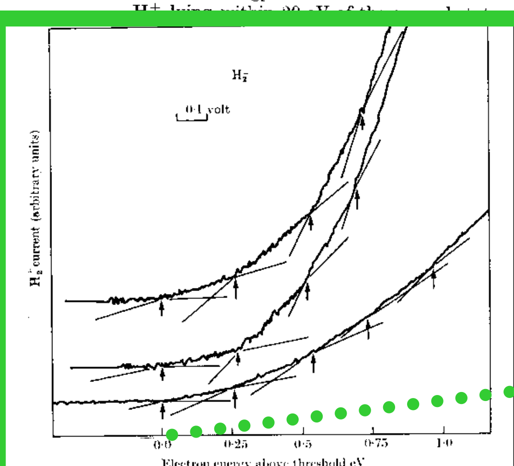


Fig. 13.19. Variation of the ionization cross-section of H_2 near the threshold as observed by Marmet and Kerwin.

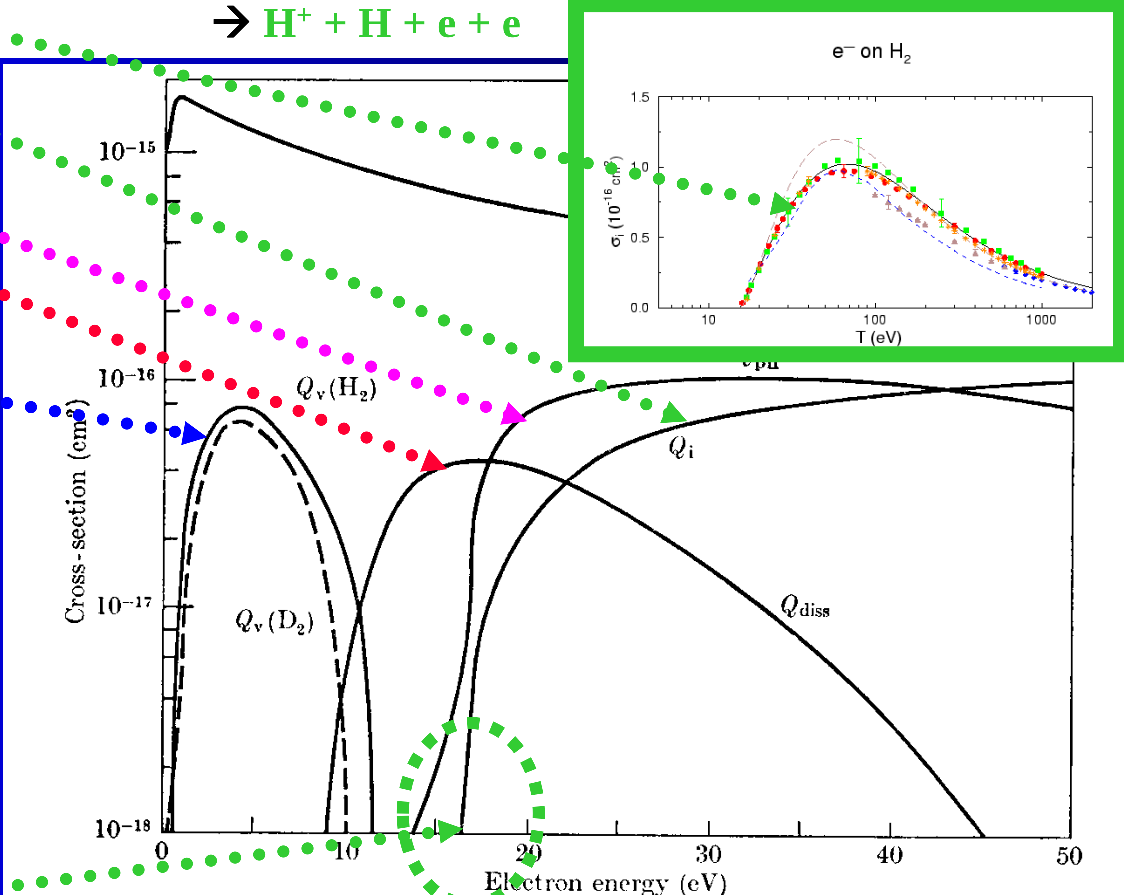
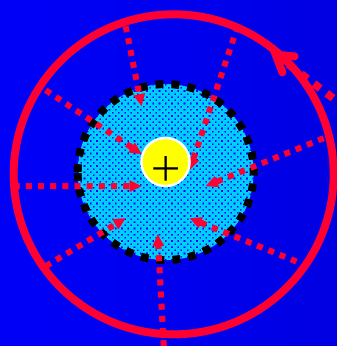
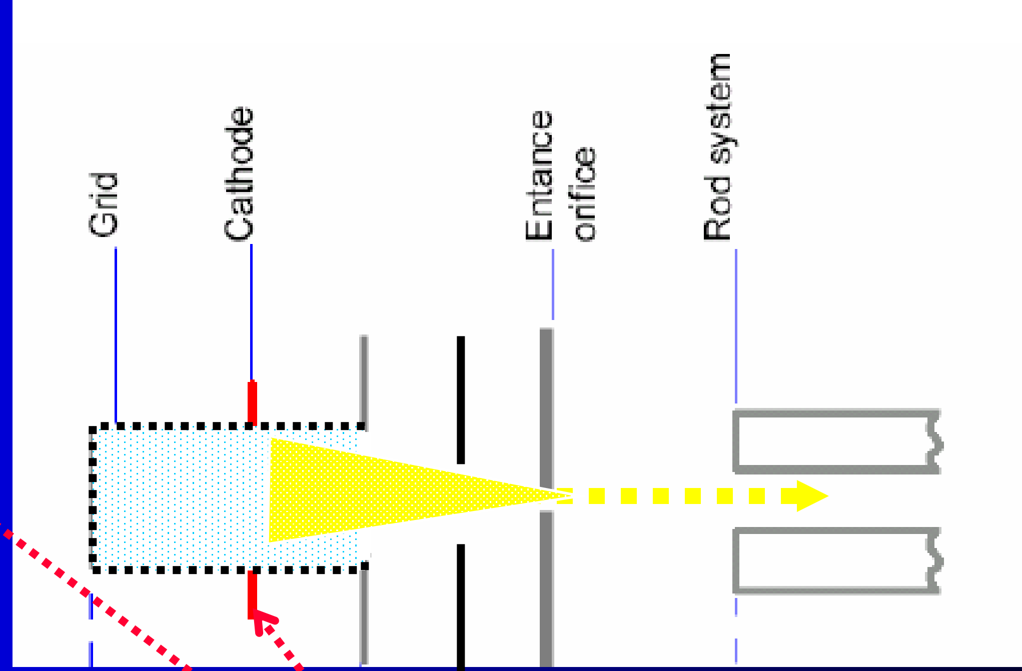


Fig. 13.37. Cross-sections assumed by Engelhardt and Phelps in their analysis of swarm data in H_2 and D_2 for electrons of characteristic energy greater than 1 eV. Q_d momentum-transfer cross-section, Q_i, ionization cross-section, Q_{diss} dissociation cross-section, Q_{ph} photon excitation cross-section, Q_v vibrational excitation cross-section (—— H_2, – – – D_2).

High efficiency
Grid ion source



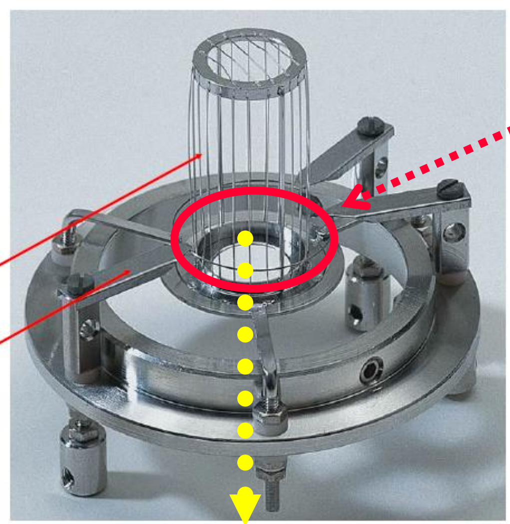


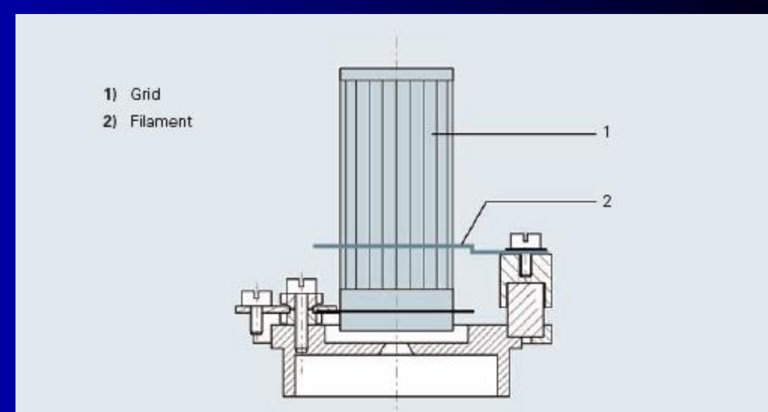
Ion optics **Mass filter**

Filament

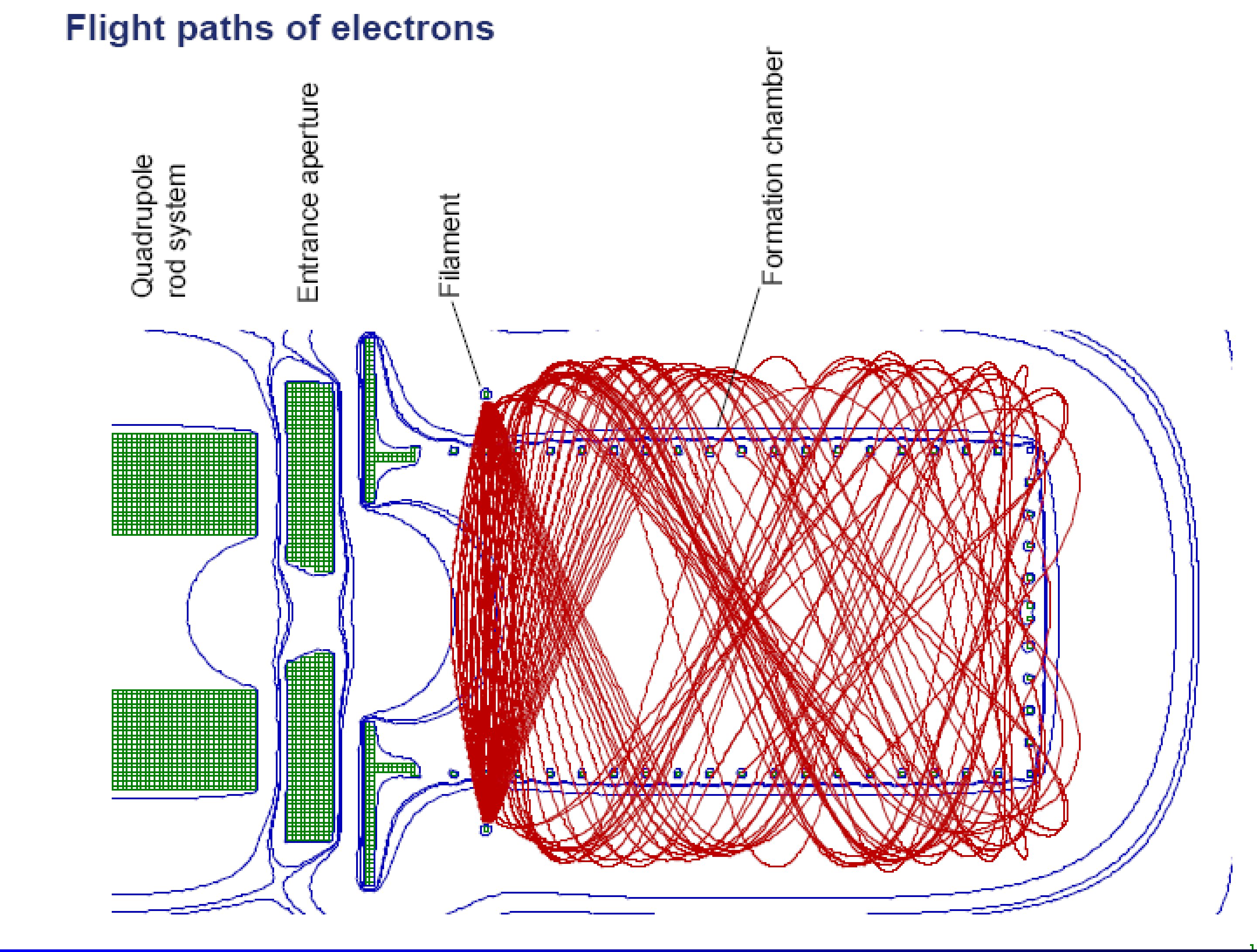
Grid ion source

- Open design
- Two filaments (W)
- Low degassing rate
  - mimimum amount of material
  - Pt-Ir wires for formation chamber
  - Molybdenum filament holders
- Easy to degas via electron bombardment
- Filaments on positive potential

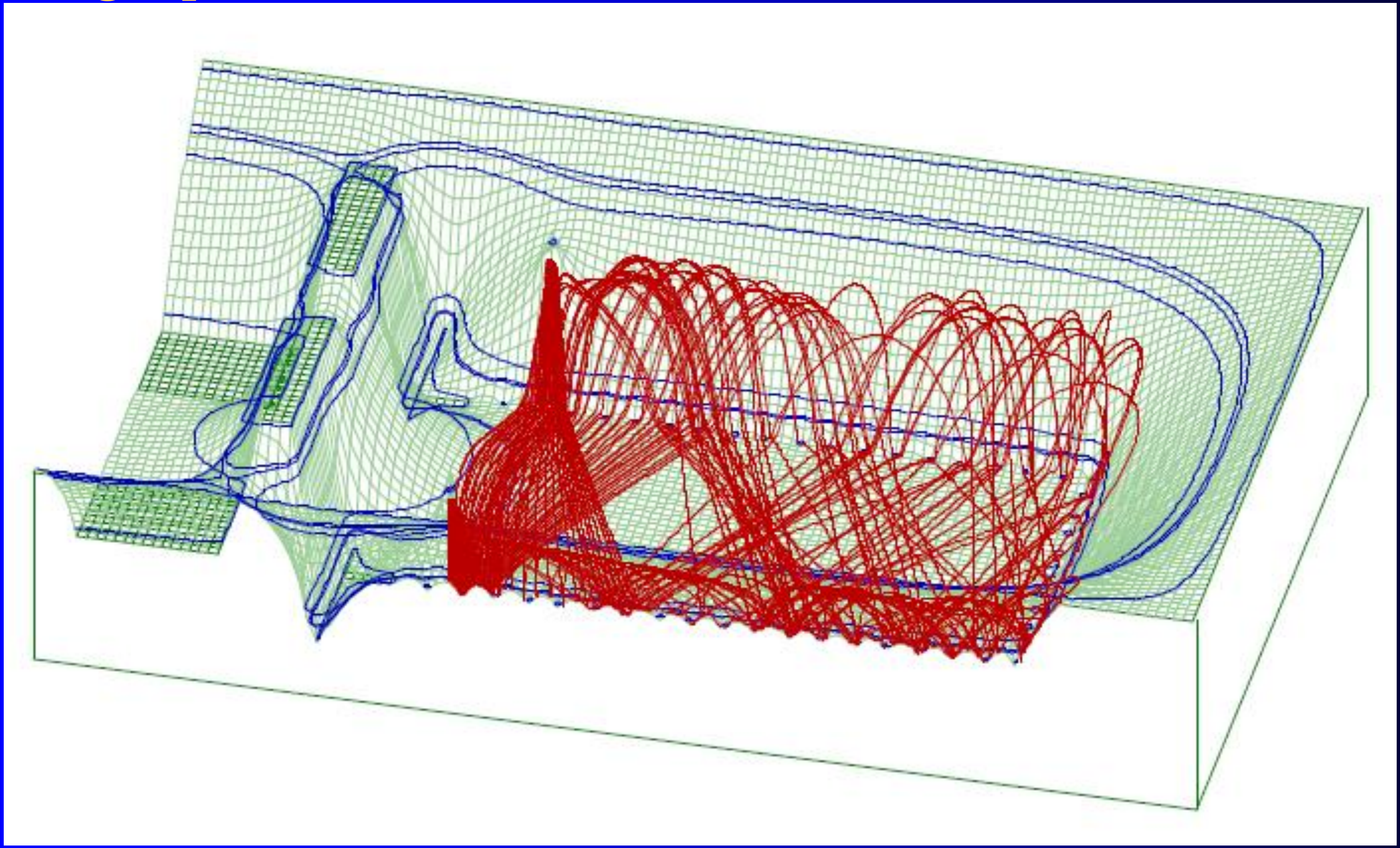




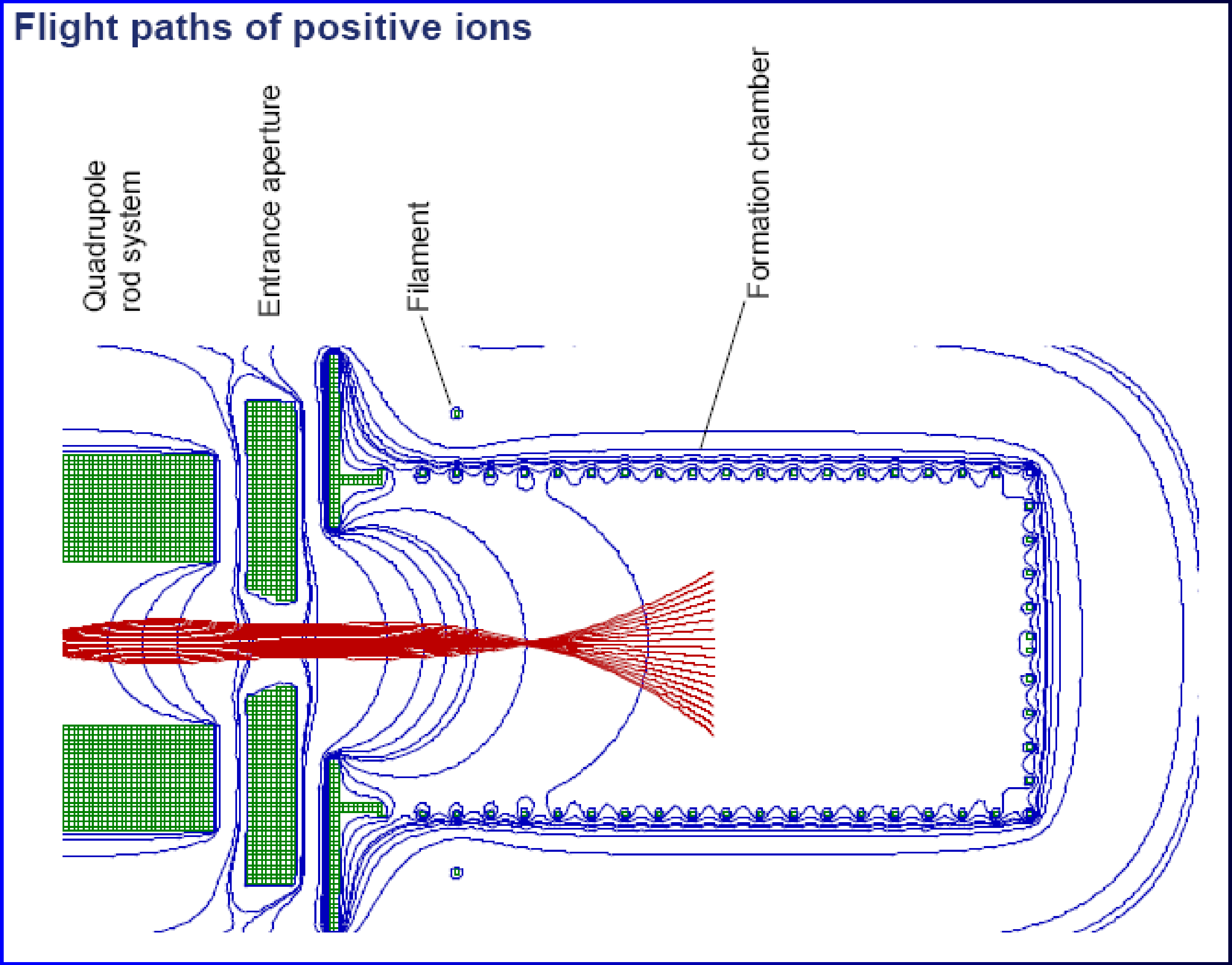
Flight paths of electrons



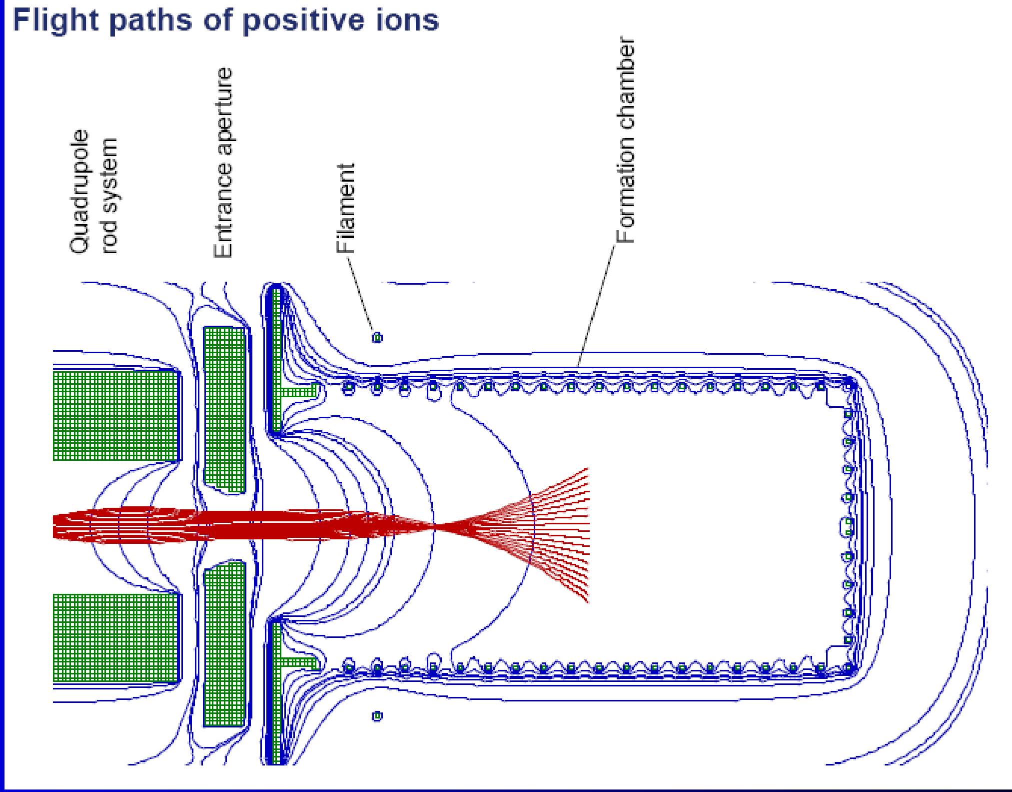
Flight paths of electrons 3D

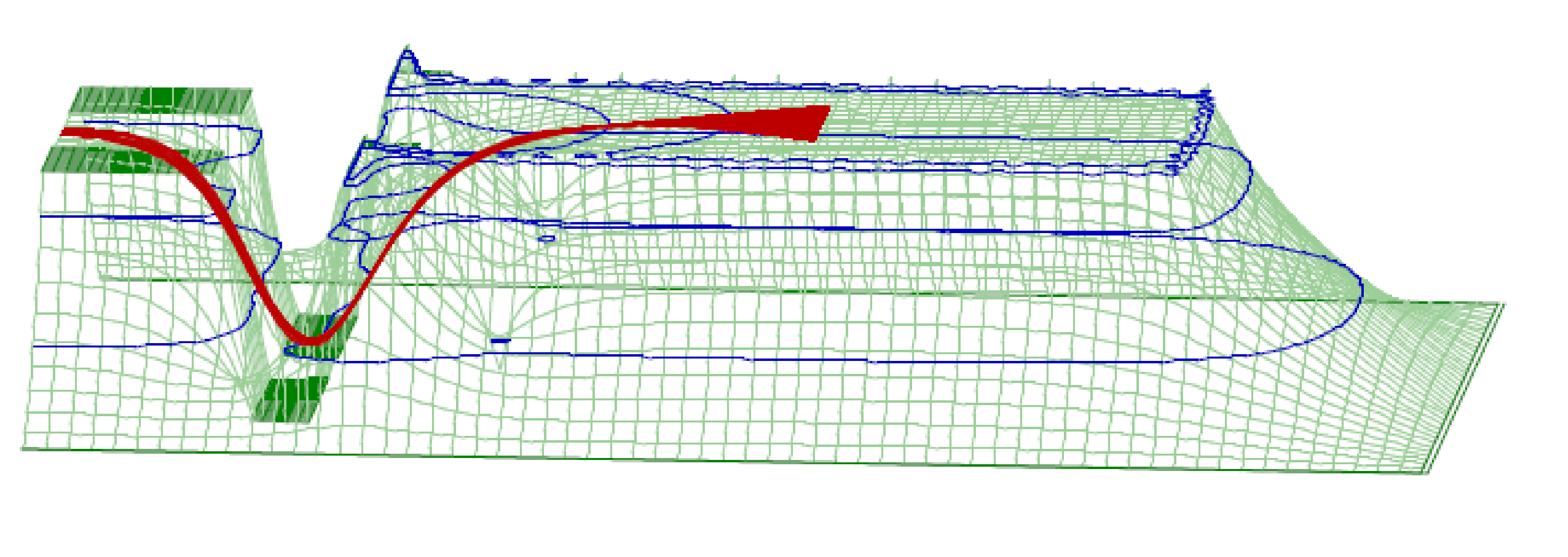


Flight paths of positive ions

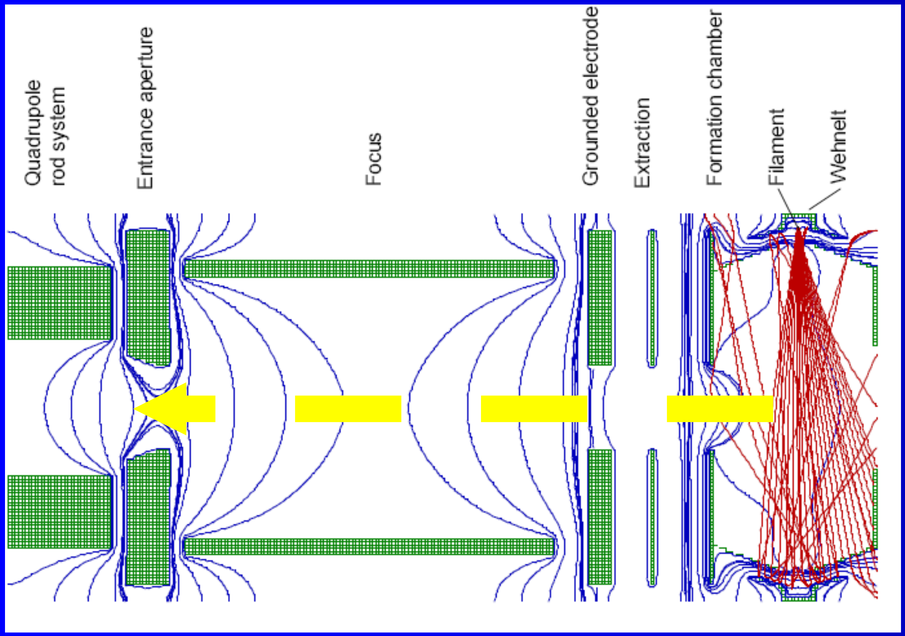


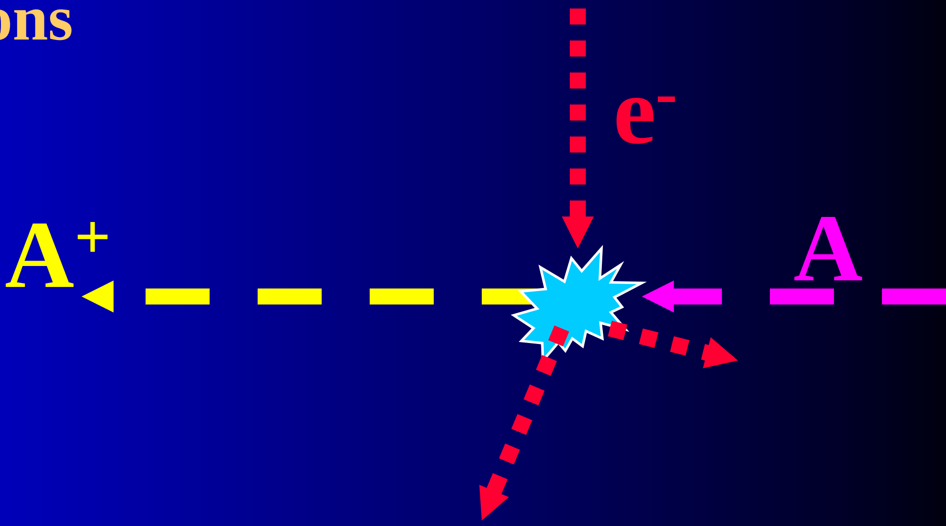
Flight paths of ions 3D



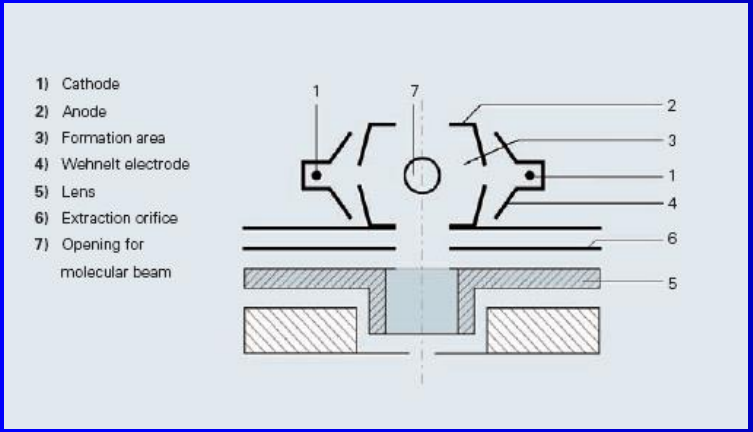


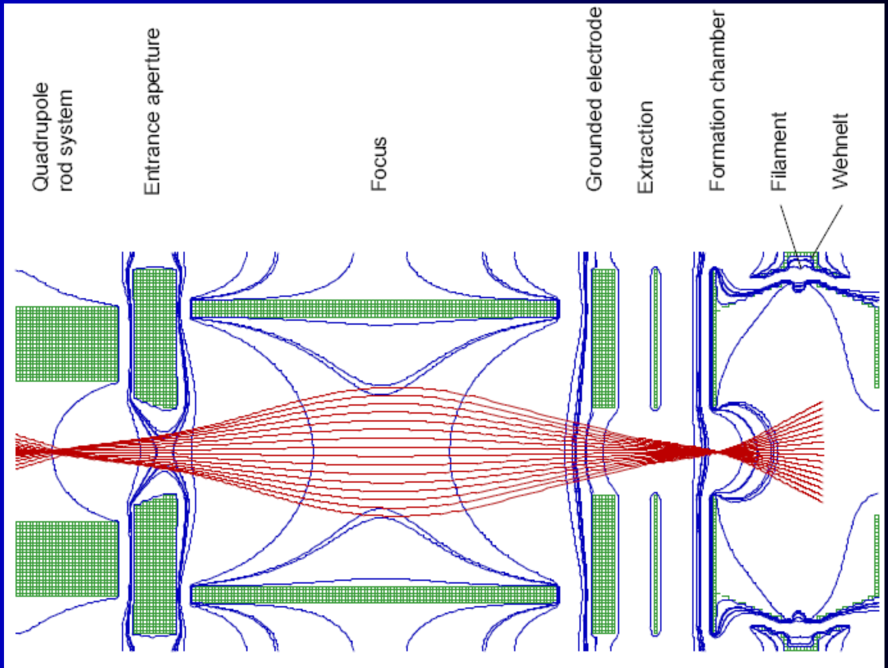
Cross Beam ion Source, calculations



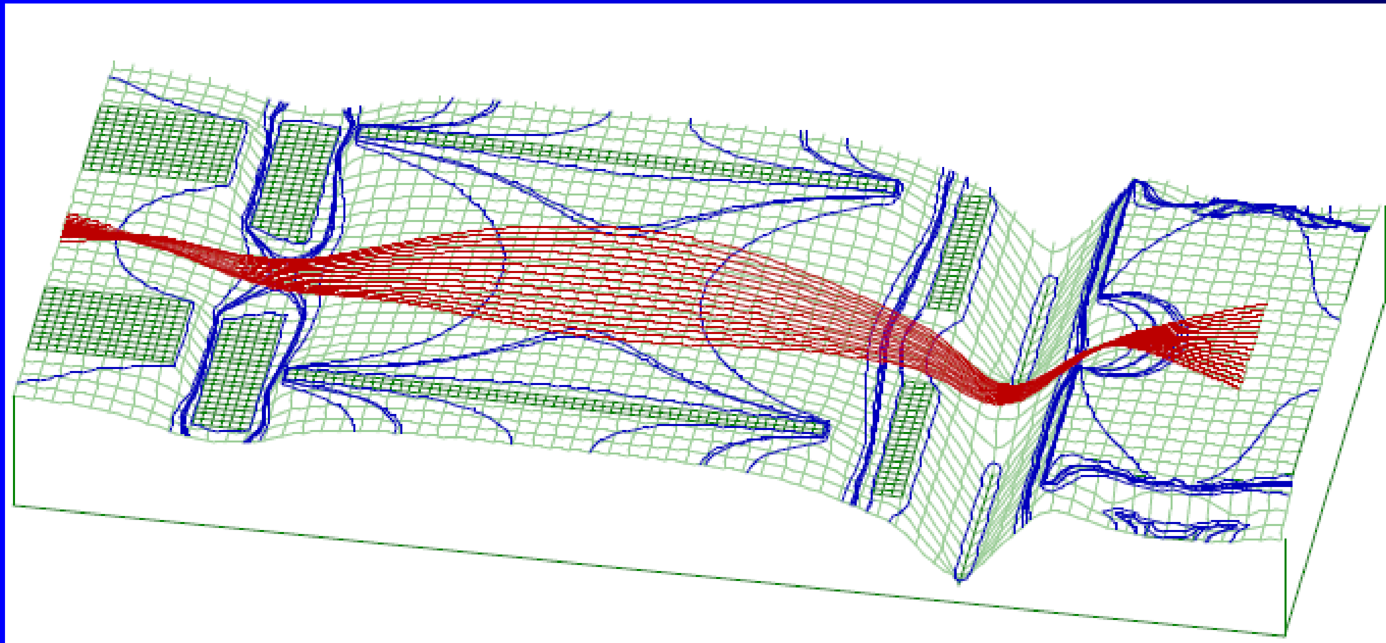


Crossbeam ion source





Cross Beam ion Source



Cross Beam ion source
with magnets

- Two filaments
- Easy to degas
- Good ion focussing
- Bakeable to 300°C

Mass spectrometer

16 mm rod system for highest resolution, stability and transmission (e.g. He/D_2 separation)

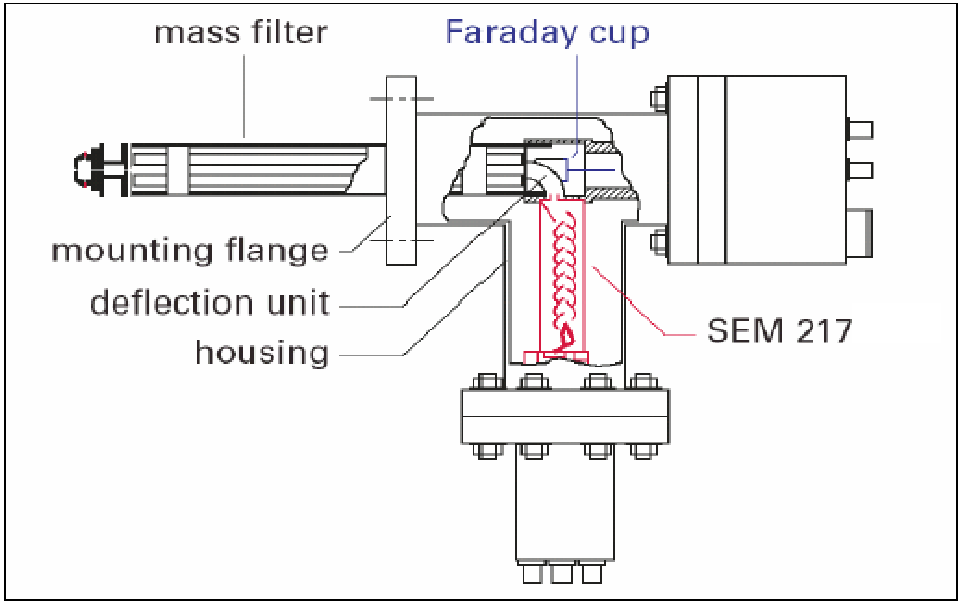
8 mm rod system for High-End RGA and analytical applications

6 mm rod system for common RGA

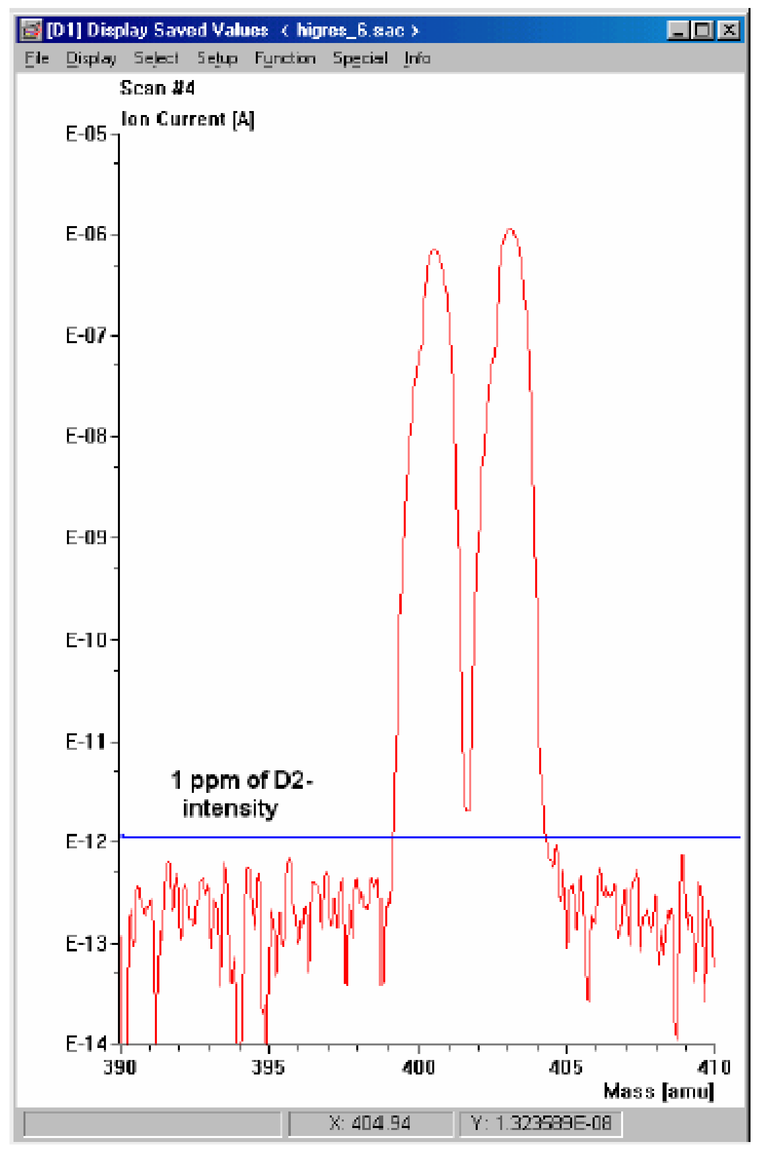
90° off axis arrangement

efficient suppression of

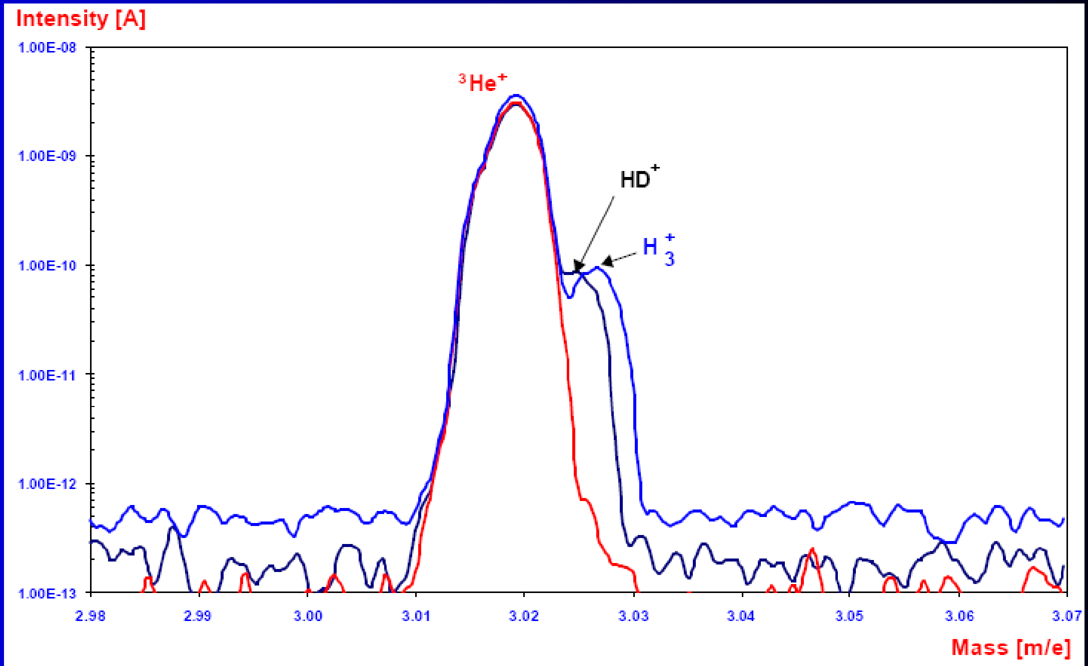
- photons
- fast neutral particles
- stray ions



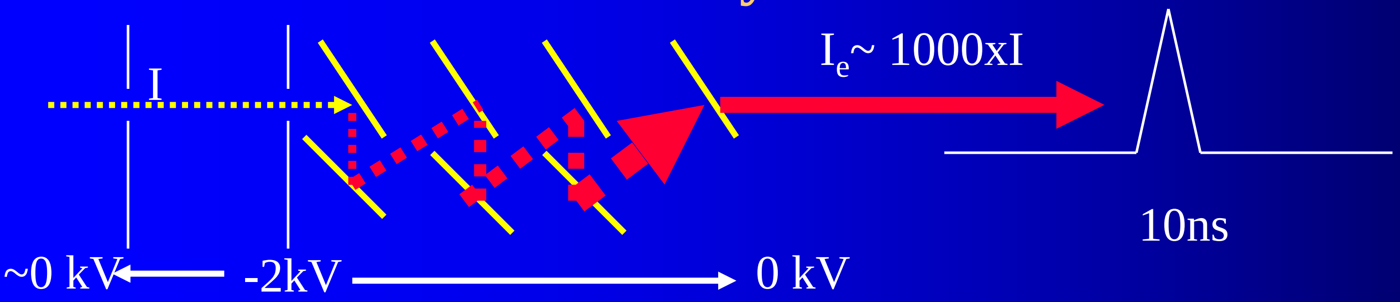
High Resolution Mass Spectrum



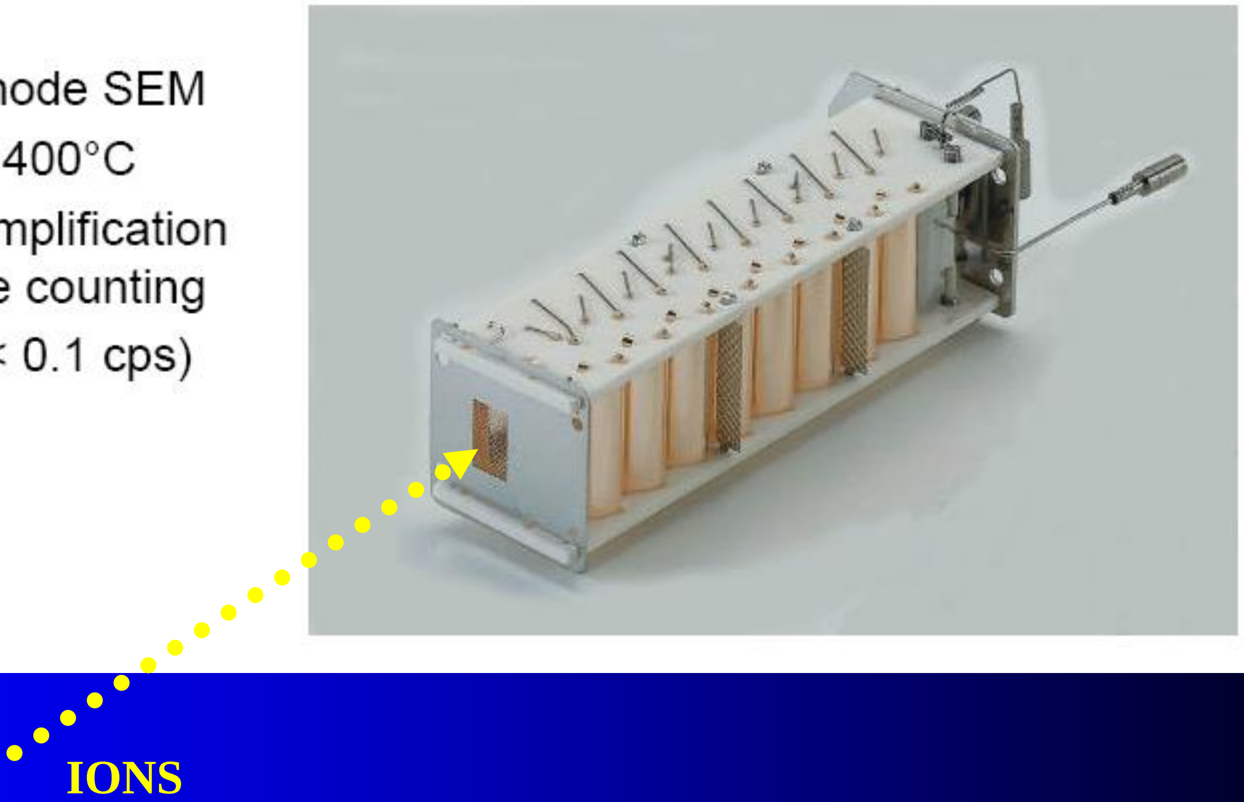
3	3He+	3.016030
	T+	3.016050
	HD+	3.021825
	H3+	3.023475
4	4He+	4.002600
	HT+	4.023875
	D2+	4.028204
	H2D+	4.029650



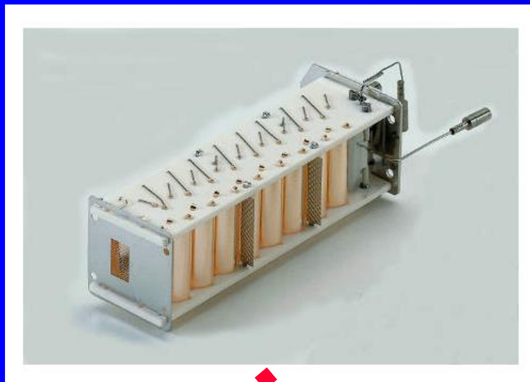
Ion detector – Discrete dynode SEM



- Ion Detection
  - Discrete Dynode SEM
  - Bakeable to 400°C
  - for analog amplification and for pulse counting
  - Low noise (< 0.1 cps)



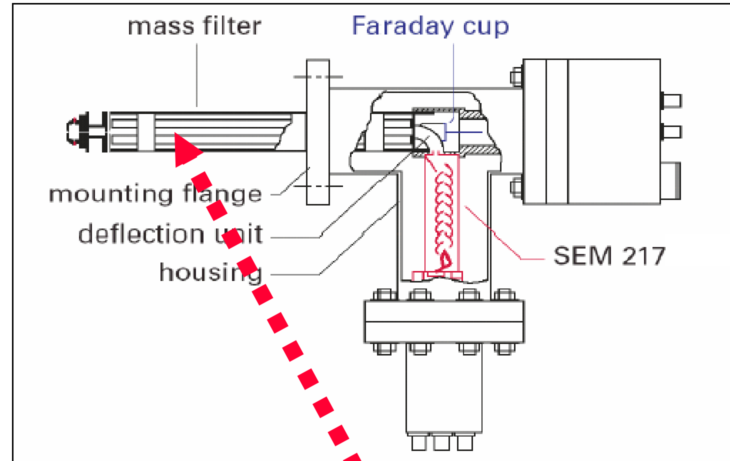
QMA



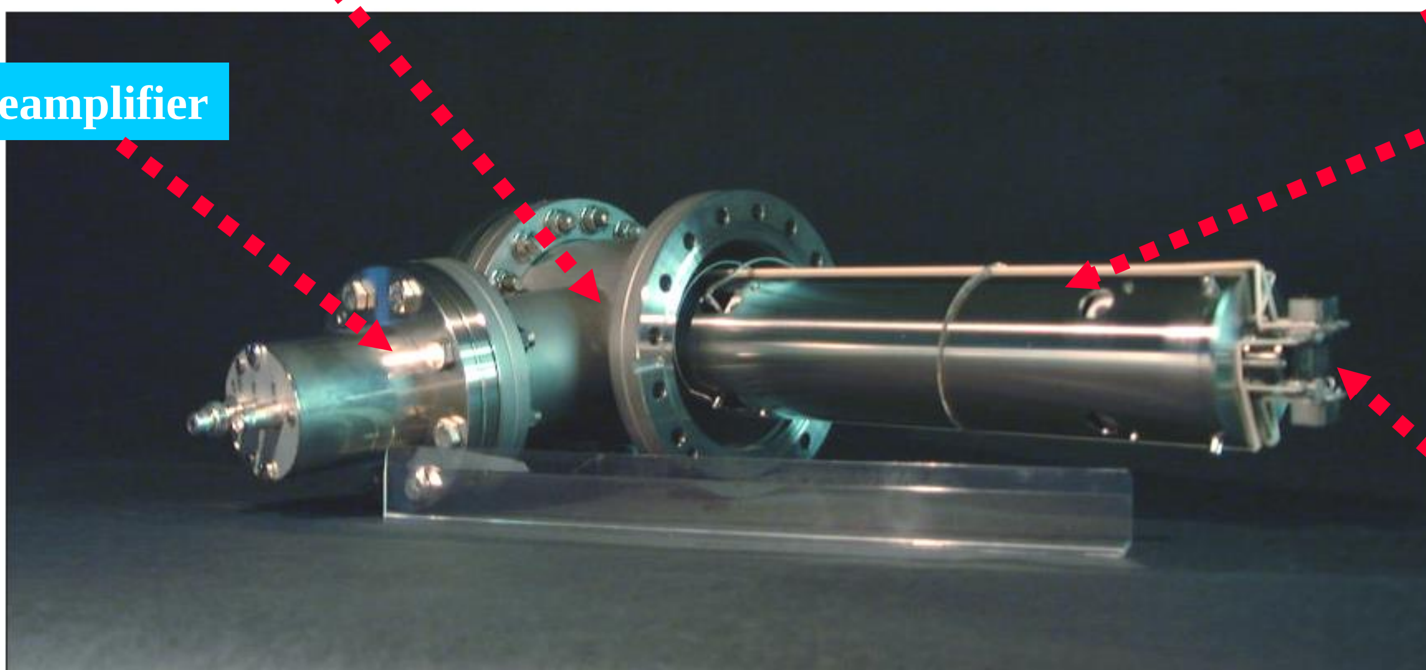
90° off axis arrangement

efficient suppression of

- photons
- fast neutral particles
- stray ions



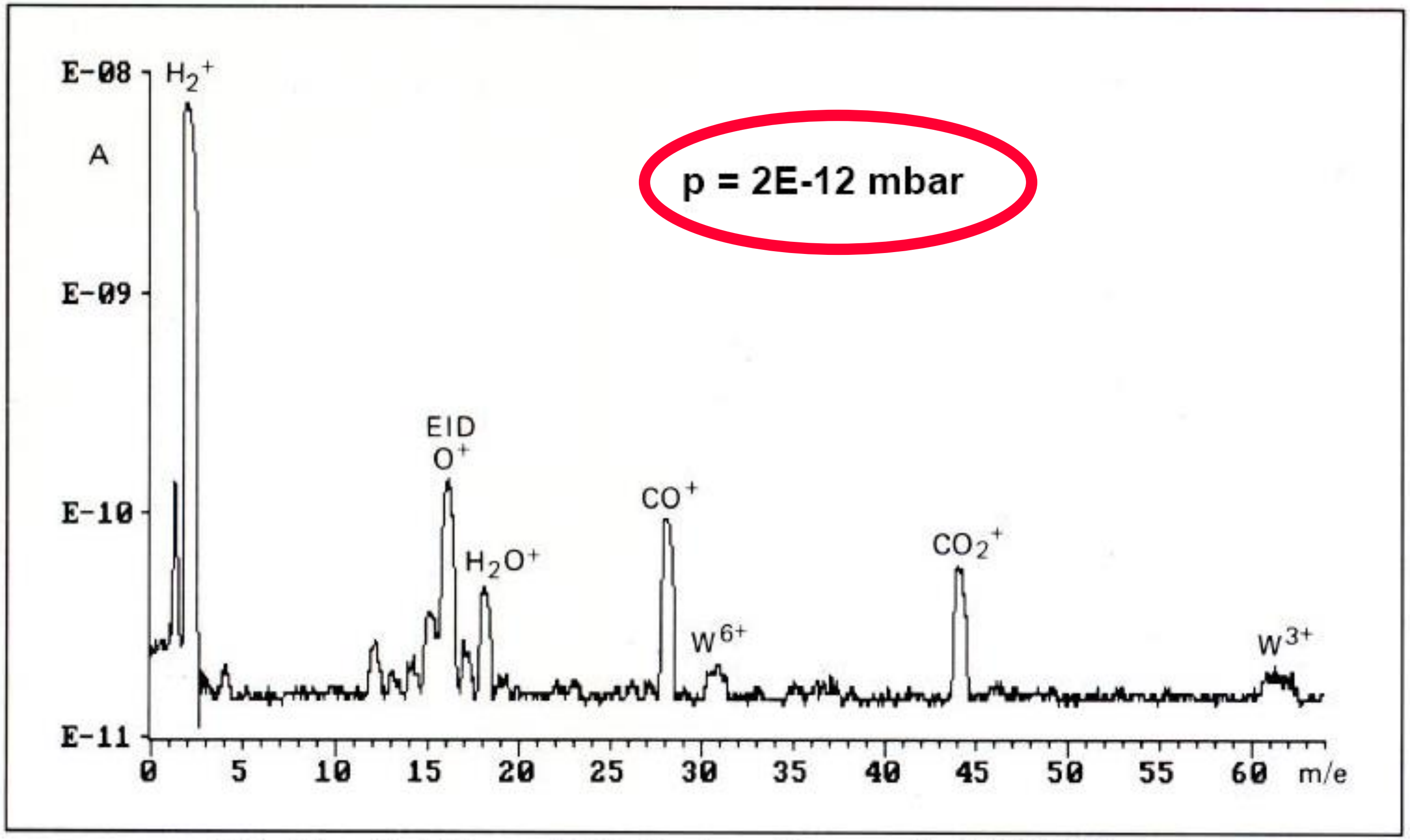
QMA 410 with Cross Beam ion source and 90° off axis SEM



Preamplifier

Cross Beam SOURCE

Mass spectrum

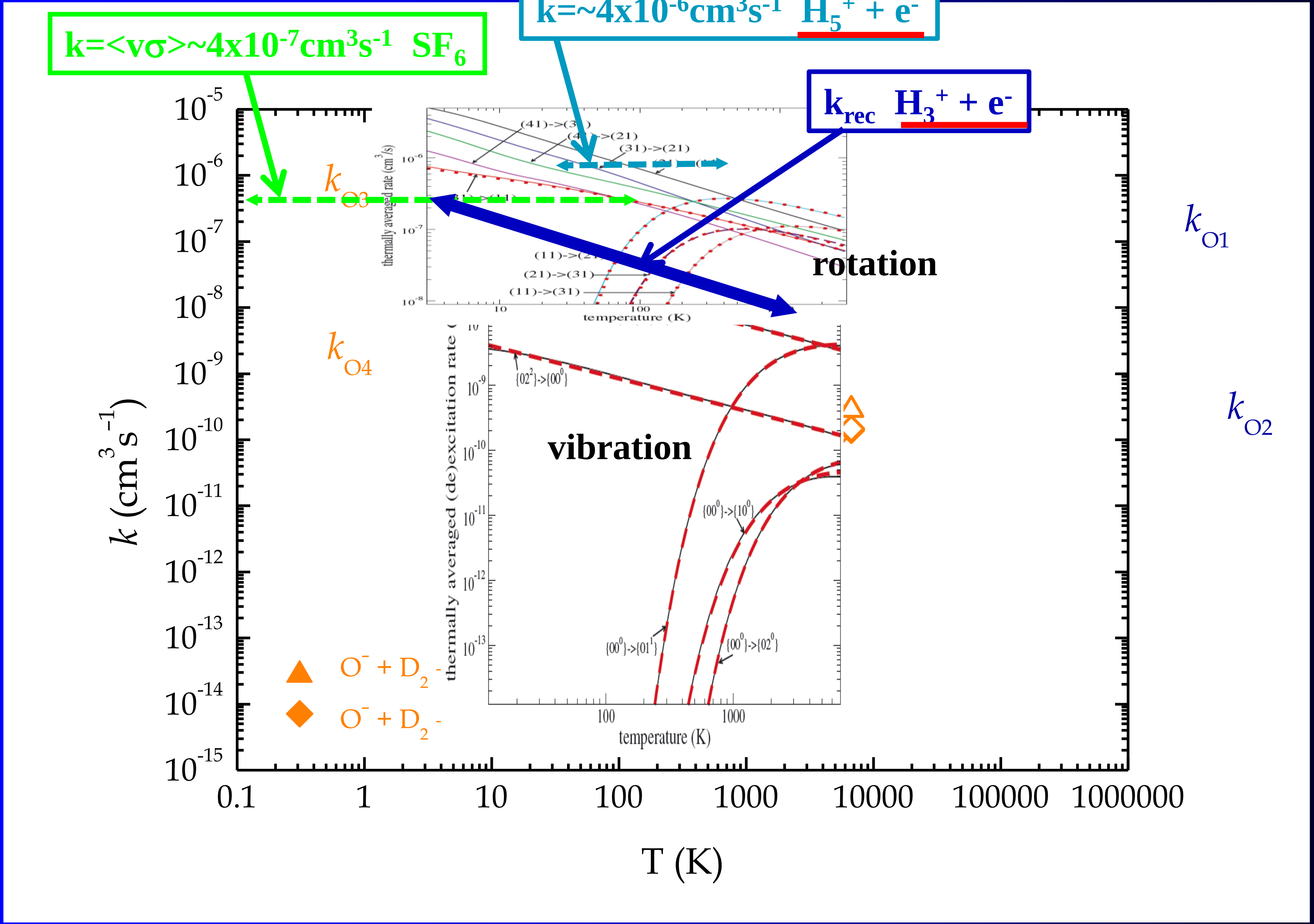


W.K. Huber, N. Müller, and G.Rettinghaus, Vacuum, 41, 2103 (1990)

Typical UHV spectrum

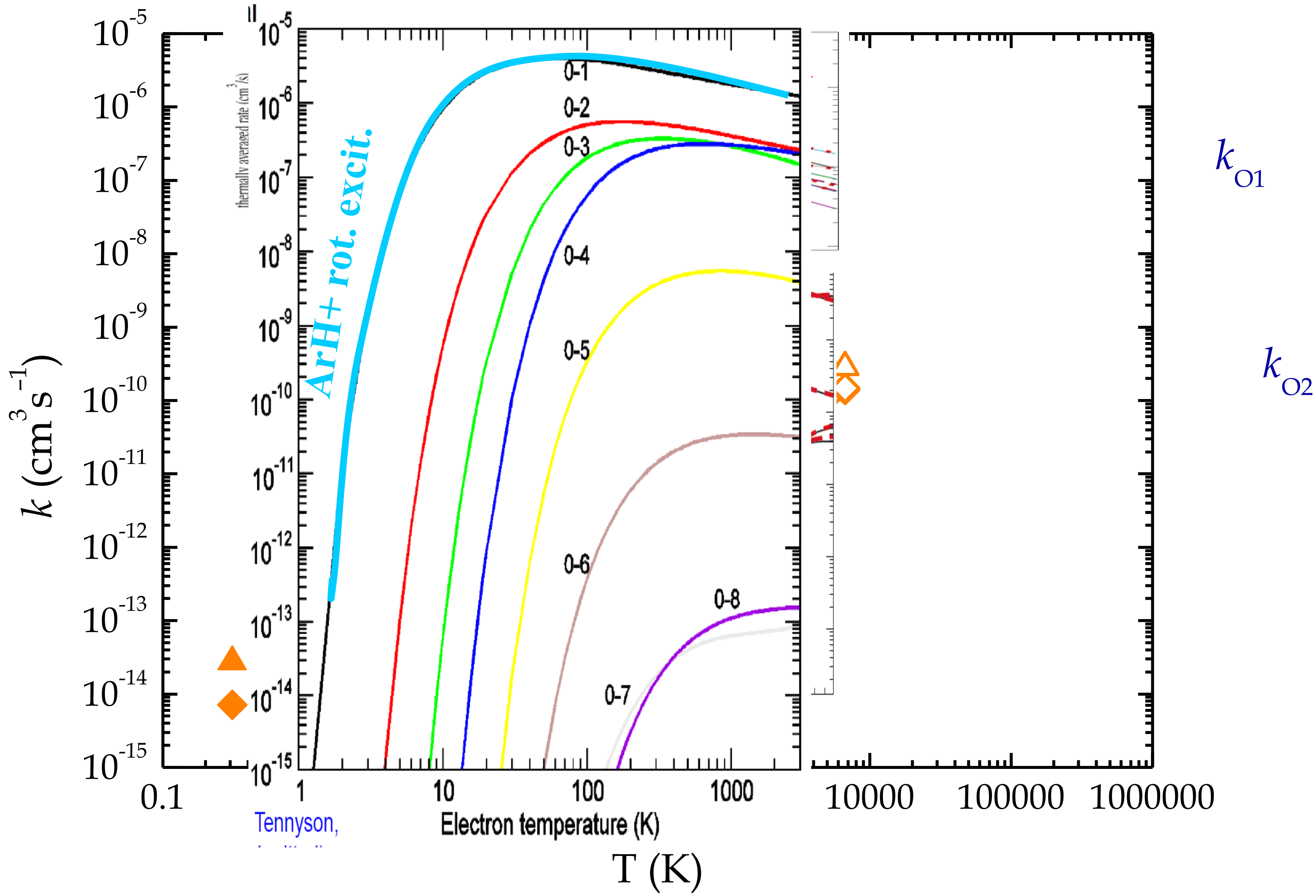
E/k←→T
1eV ~ 11 400 K
1K ~ 9x10^{-5}eV

Electron impact rot. vibr. exciattion/deexcitation H_3^+



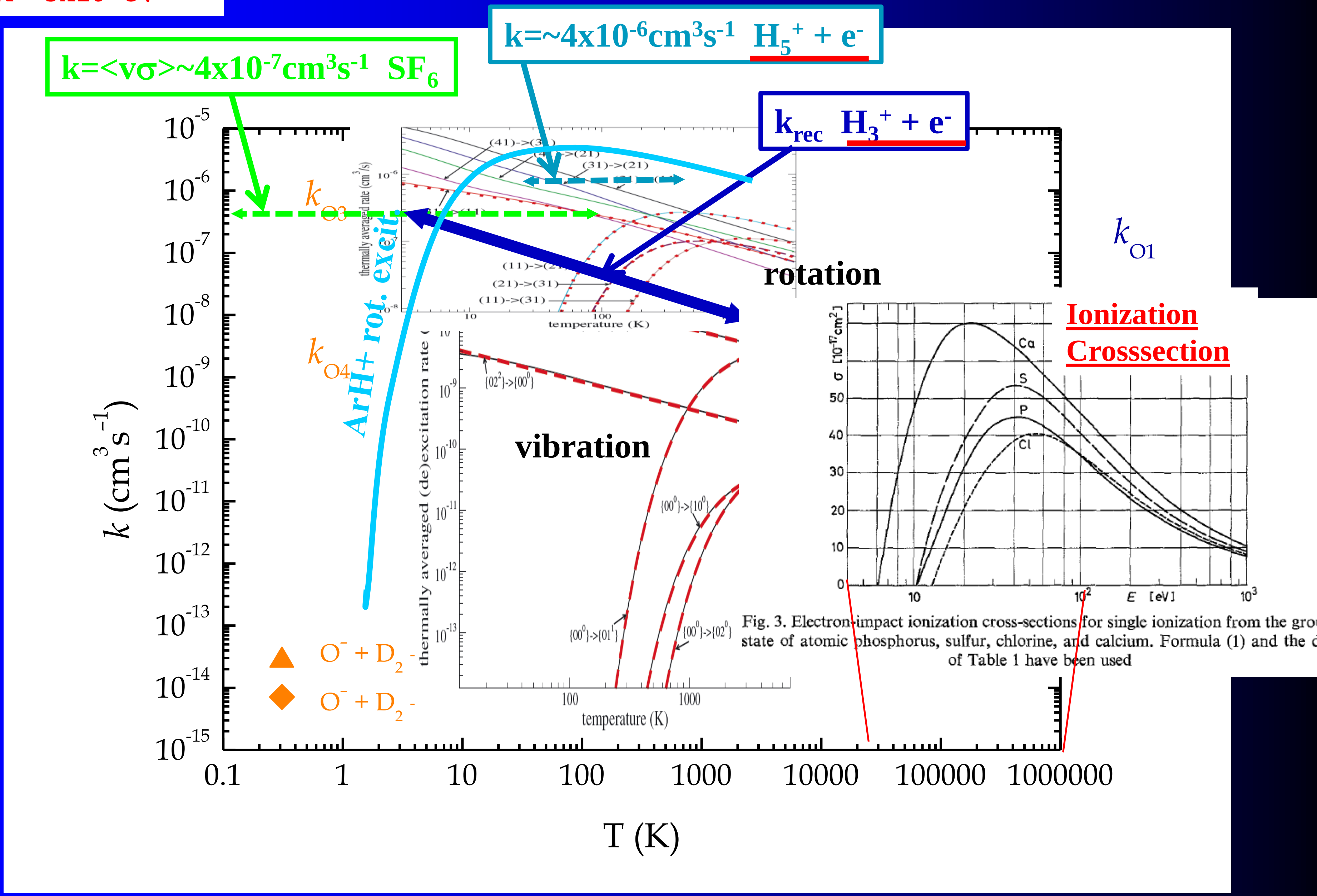
E/k←→T
1eV ~ 11 400 K
1K ~ 9×10^{-5} eV

Electron impact rotational excitation of ArH^+



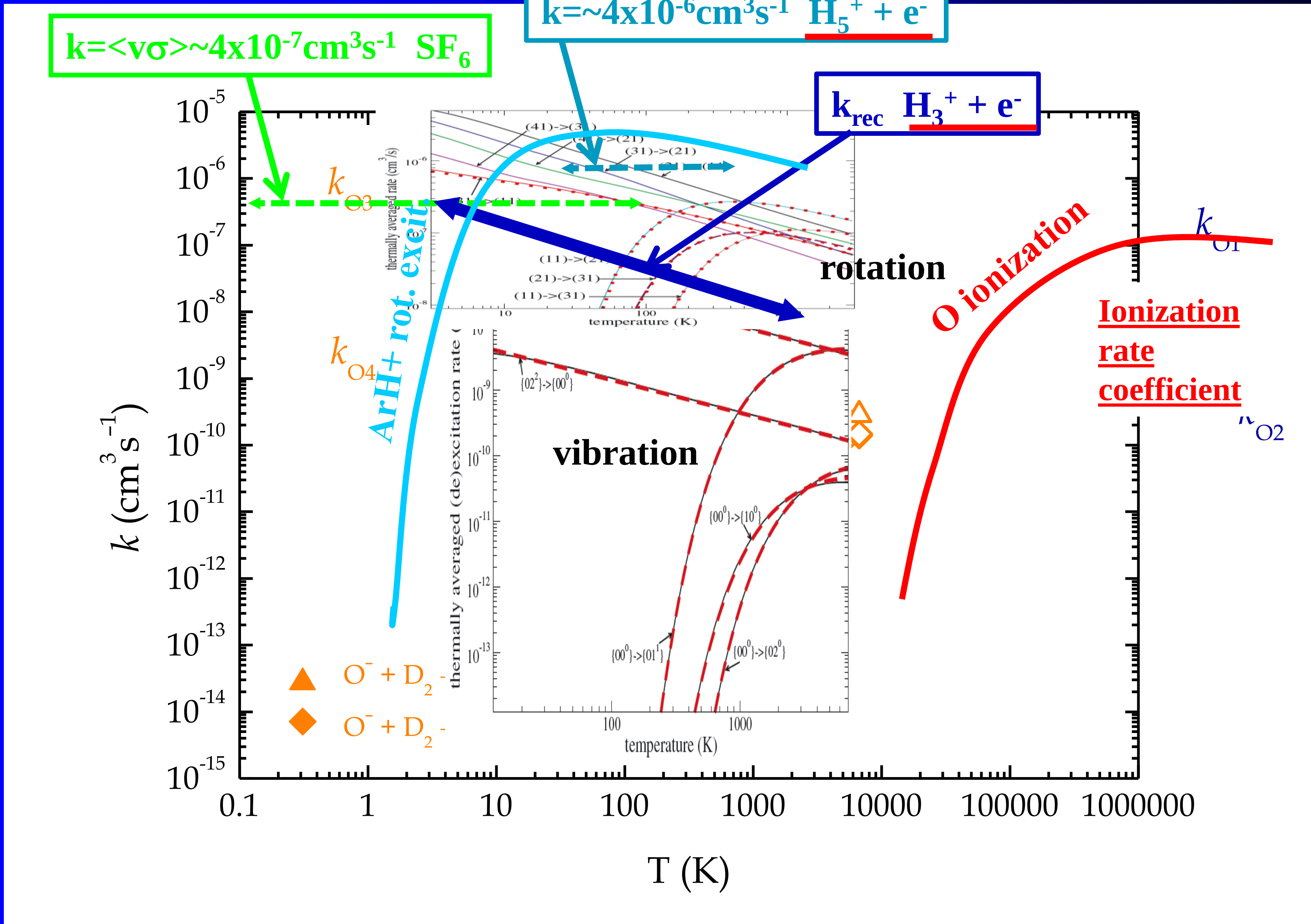
$E/k \leftrightarrow T$
1eV ~ 11 400 K
1K ~ 9x10^{-5}eV

Electron impact rot. vibr. exciattion/deexcitation H_3^+



E/k←→T
1eV ~ 11 400 K
1K ~ 9x10^{-5}eV

Electron impact rot. vibr. exciattion/deexcitation H_3^+



E/k←→T
1eV ~ 11 400 K
1K ~ $9x10^{-5}$eV

Electron impact rot. vibr. exciattion/deexcitation H_3^+

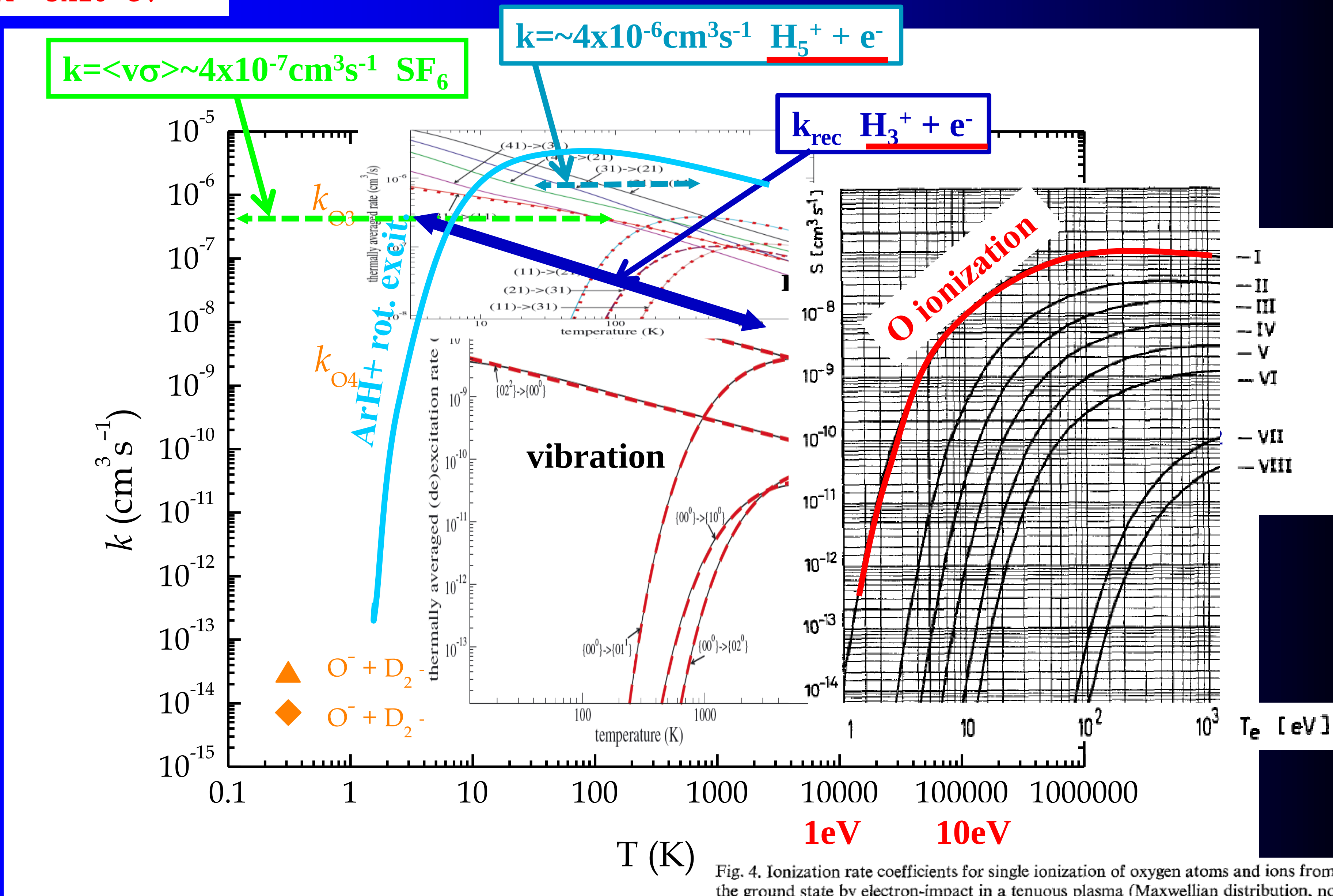


Fig. 4. Ionization rate coefficients for single ionization of oxygen atoms and ions from the ground state by electron-impact in a tenuous plasma (Maxwellian distribution, no lowering of ionization potential, no collision limit)

See You next week