Chapter VI:
Ionizations and excitations

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Introduction (1)

- Ionizations created by charged particles (incident particles or particles created by radiations indirectly ionizing) along their trajectory have a fundamental role in the detection principle
- In gases and liquids → creation of electrons and positive ions after the ionization of atoms or molecules (in the following → « atoms » to simplify)
- In some solids → creation of conduction electrons and holes
- In both cases → ions pair

Introduction (2)

- Electrons and ions created the incident charged particle itself are primary ionizations

- If enough energy is transferred to the electron → this electron can also create ion-electron pairs → these pairs are called secondary ionizations

Ionization and excitation in gases

- The energy lost by a charged particle travelling inside a gas is splitted (essentially) into 2 types of interaction →
  1. Ionization → one or more electrons are pulled out from the atom → process possible if the transferred energy is larger than the ionization energy (typical cross section for noble gases → $\sigma_i \approx 10^{-16}$ cm^2)
  2. Excitation → the atom is brought to an excited without direct creation of an ions pair → resonant process for which the transferred energy is specific (typical cross section for noble gases at the resonance → $\sigma_{ex} \approx 10^{-17}$ cm^2) → at the end: thermal dissipation of the energy
- Even if $\sigma_i > \sigma_{ex}$ → the excitation process is often dominating because interactions with weak transferred energy are more probable and the ionization energy is larger than the excitation energy

Mean energy for one electron-hole pair

We define the mean energy needed for the production of one electron-hole pair, W:

$$W = \frac{E_{abs}}{N_i}$$

where N_i is the number of ions pairs produced in the target material by the ionizing particle. E_{abs} is the energy lost by the particle in the target (if the particle is stopped inside the target E_{abs}= T, its kinetic energy). W is typically about two times larger than the ionization energy since some energy is also lost to excitations.

Determination of *W* (1)

- The precise calculation of *W* is a very complex problem → transport in the gas of the primary particle and of secondary particles → knowledge of the scattering cross sections for the primary particle but also for all created electrons → information are generally unknown or incomplete
- If the charged particle is stopped in the gas →

$$E = N_i \langle E_i \rangle + N_{ex} \langle E_{ex} \rangle + N_i \langle \epsilon \rangle$$

- In this expression → N_i: mean number of created ion-e^- pairs, N_{ex}: mean number of produced excitations, E_i: mean energy needed to create one ionization, E_{ex}: mean energy needed to create one excitation, ϵ: mean energy of the electrons having an energy smaller than the excitation energy (subexcitation electrons)

Determination of *W* (2)

- The subexcitation electrons are the electrons having not enough energy to produce excited atom (and thus also ionizations) → the number of these electrons is equal to the number of ions and thus to the number of ion-e^- pairs (N_i) → conservation of the total electric charge
- If one electron initially ejected from an atom has enough energy to ionize or to excite another atom → it will lose energy → it will finally become a subexcitation electron
- These electrons constitute the measured ionization current (see below)

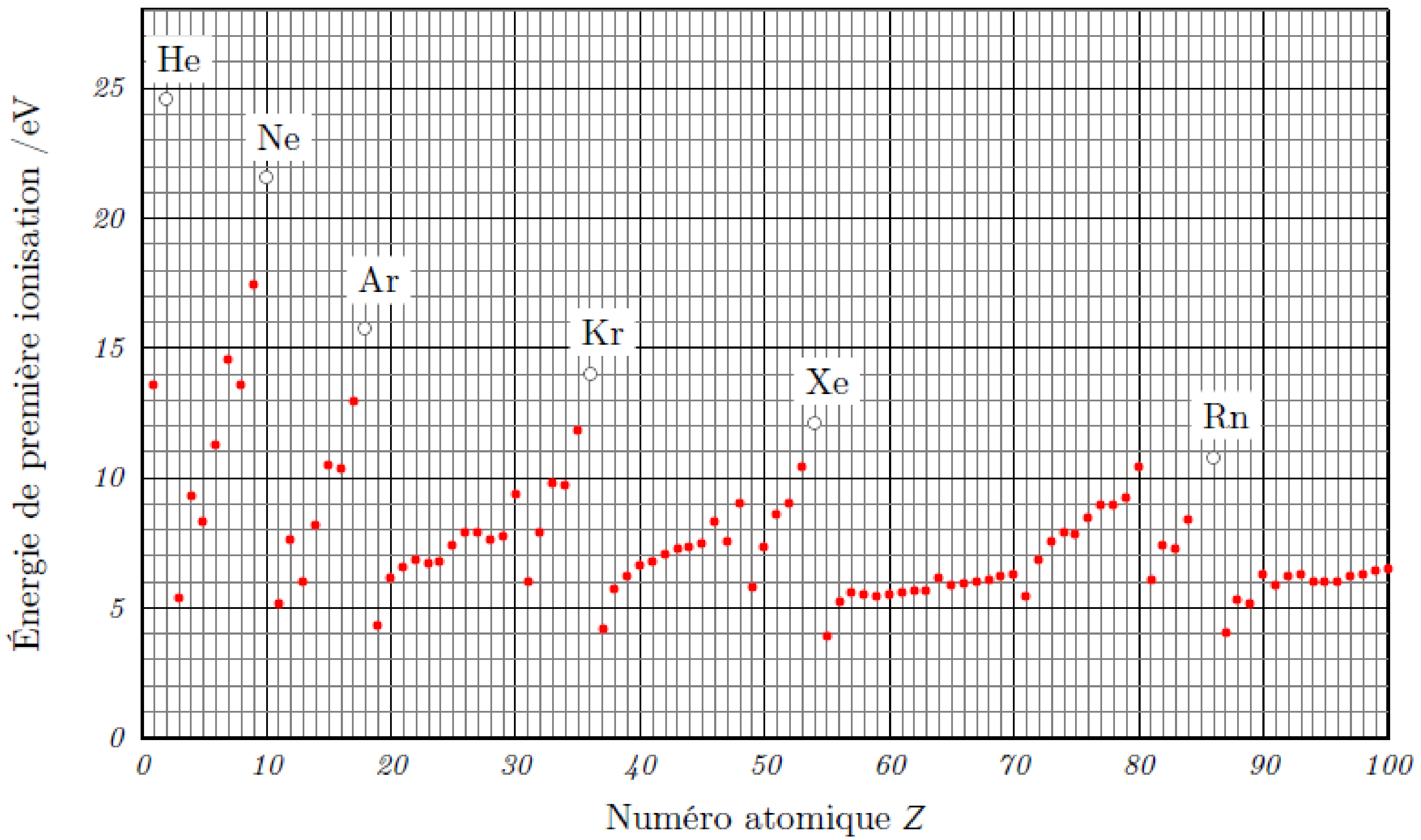
Determination of W (3)

- All terms playing a role in the calculation of W depend on E
- However → if $E \gg I$ → weak dependence (I = ionization potential = ionization threshold = minimum energy to ionize the atom)
- Only a few theoretical calculations → helium for an incident electron for instance → $\langle E_i \rangle$ = 25.9 eV, $\langle E_{ex} \rangle$ = 20.8 eV, $\langle \epsilon \rangle$ = 7.6 eV, W = 41.8 eV (high value for a gas) with 71% of collisions which are ionizing
- Generally → W is experimentally determined
- W has a weak dependence on the incident particle
- W recommended for dry air → W = 33.97 eV
- Good approximation in general for a gas → $W \approx$ 30 eV

Examples of *W* for gases (measured)

Gaz	Énergie d'excitation	Énergie d'ionisation	W_e	W_p	W_α
He	19.8	24.6	41.3	45.2	42.7
Ne	16.6	21.6	35.4	39.3	
Ar	11.6	15.8	26.4	26.6	26.3
Kr	10.0	14.0	24.4	23	
Xe	8.4	12.1	22.1	20.5	
Air (sec)			33.85	35.2	35.1
N_2	8.1	15.5	30.8	36.6	36.4
O_2	7.9	12.2	32.6		32.24
H_2	10.8	15.4	34.8		36.4
CO_2	10.0	13.7	33.0	34.4	34.2
CH_4			27.3		29.1
C_4H_{10}		10.8	23		
BF_3					35.7

Ionization threshold



Gas mixture (1)

- When we add a small quantity of particular gases to a noble gas → increasing of the number of ionizations created in the mixture
- In a general way → this effect happens for small concentration of added gas and is more important if the ionization threshold of the added gas is small by comparison to the binding energy of the first excited states of the noble gas
- In this case → the collision between an excited atom of the noble gas and an added molecule can lead to the ionization of this molecule

Gas mixture (2)

- Example: argon gas
- The Ar atom has mean ionization energy of 15.8 eV and an excited state at 11.6 eV
- We add acetylene which has a mean ionization energy of 11.2 eV
- The excited Ar atom can transfer its excitation energy to a molecule of acetylene during a collision and thus ionize the acetylene molecule
- The number of ionizations for Ar with 0.2% of acetylene increases by 25% by comparison with pure Ar

Gas mixture (3)

Mélange	W_α /eV	Rapport
Ar + C_2H_6 (3.5%)	24.4	1.08
Ar + C_2H_2 (0.4%)	20.4	1.29
Ar + CH_4 (3%)	26.0	1.01
Ar + C_3H_8 (2%)	23.5	1.12
Ar + C_6H_6 (0.1%)	22.4	1.17
Ar + C_3H_6 (1.2%)	23.8	1.11

W and modification of *W* for ≠ gas mixtures

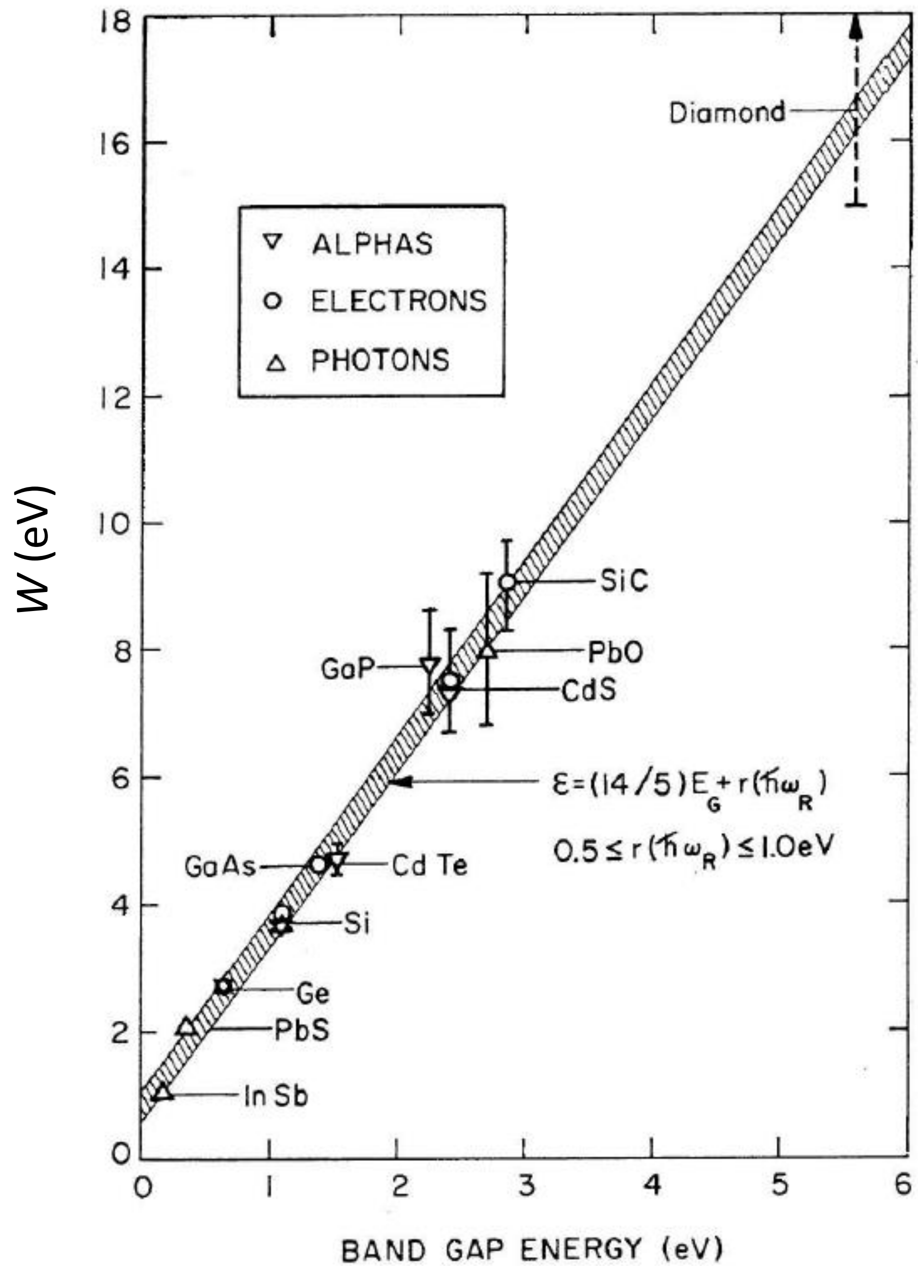
Ionization in solids (1)

- For semiconductors → ionization implies the transfer of an electron from the valence band to conduction band → formation of an electron-hole pair (equivalent to the ion-e^- pair for un gas)
- Energy band gap E_g between the two bands ≈ 1 eV < ionization threshold for a gas ($\sim$ 10 eV)
- The excitation process implies the excitation of the crystalline lattice → production of phonons → energy ≈ 0.04 eV
- About 60% of the energy implies excitation of phonons

Ionization in solids (2)

- For Si → W = 3.65 eV (for T = 300 K)
- For Ge → W = 2.97 eV (for T = 77 K)
- Ratio of 10 between the number of pairs produced in a semiconductor and in a gas
- W is larger than E_g and W/E_g is about constant for all semiconductors

Ionization in solids (3)



Fluctuations of the number of ionizations

- The number of ionizations is a random variable with a mean value of $N_i = E/W$
- Due to statistical fluctuations → limitation of the precision of the measurement of *E* from the number of observed ionizations
- The variance σ_i^2 characterize fluctuations → 2 limit cases →
  1. The number of ionizations follows the Poisson law → $\sigma_i^2 = N_i$
  2. A fixed fraction of the energy of the particle is converted into ionizations → $\sigma_i^2 = 0$
- Reality is between these two cases →

$$\sigma_i^2 = F N_i$$

with F, the Fano factor → $0 < F < 1$

Fano factor

- *F* contains all differences between reality and Poisson statistic
- *F* depends in details on the succession of events which lead to the pairs creation
- The theoretical evaluation of *F* is a very difficult problem (almost impossible) → the *F* factor is **always** obtained from experiment
- For Si → $F < 0.15$
- For a noble gas → $0.05 < F < 0.20$