Electrical phenomena in gaseous media
Physical bases

Gaseous media: conductors or insulators?

- The idea of a gaseous ionization detector implies the occurrence of electrical phenomena inside the gas…but...
- A gas in itself is an ideal insulator where each electron is well bounded to its atom. How can it become a conductor?
- A gas, as any other material, is surrounded of ionizing sources that create a small number of free electrons inside it
- A gas has a very peculiar property: in presence of a sufficiently strong electric field its electrical resistivity can change of many orders of magnitude in a sub-nanoseconds time
- Speaking of resistivity as an intrinsic gas property would be therefore completely improper

Explaining the electrical conduction inside the gases (1)

- An electron drifting in the gas under the action of an electric field $\boldsymbol{E}$ has a probability $p = dl/\lambda$ of colliding with a gas molecule/atom. Here dl and λ
- are the recurred distance and the mean free path 1/nσ = λ respective
- The electron, after a free flight l, can Ionize an atom in the next collision if the condition $\boldsymbol{E}el$ > E_i is fulfilled. $\boldsymbol{E}el$ > E_i. The minimum required distance is therefore $l_{min} = E_i/\boldsymbol{E}e = V_i/\boldsymbol{E}$, E_i and V_i being the atom ionization energy and potential respectively
- The correspnding probability is $\int_{l_{min/\lambda}}^{\infty} e^{-\frac{l}{\lambda}} \frac{dl}{\lambda} = e^{-V_i/\lambda\boldsymbol{E}}$ and the number of ionizations per unit length is therefore $\alpha = \frac{1}{\lambda} e^{-V_i/\lambda\boldsymbol{E}}$
- Number of ionizations in Δl is $< n >= \frac{\Delta l}{\lambda} e^{-V_i/\lambda\boldsymbol{E}} = \alpha\, \Delta l$

Explaining the electrical conduction inside the gases (2)

- The probability of a free electron, drifting under the action of the electric field F, to produce another free electron in a trajectory element dl is
  - $dp = \alpha dl$ where α is the first Townsend coefficient
  - This model due to Townsend is the simplest model explaining the free electron multiplication inside the gas
- If there are n electrons drifting, their increase in dl is $dn = \alpha n \, dl$ →
- $n = n_0 e^{\alpha l}$ → avalanche **exponential** growth Given the great electron mobility inside the gas (drift velocity order millimeters/ns) and the achievable values of α, this explains how fast is the transition *insulator→conductor*

Avalanche saturation

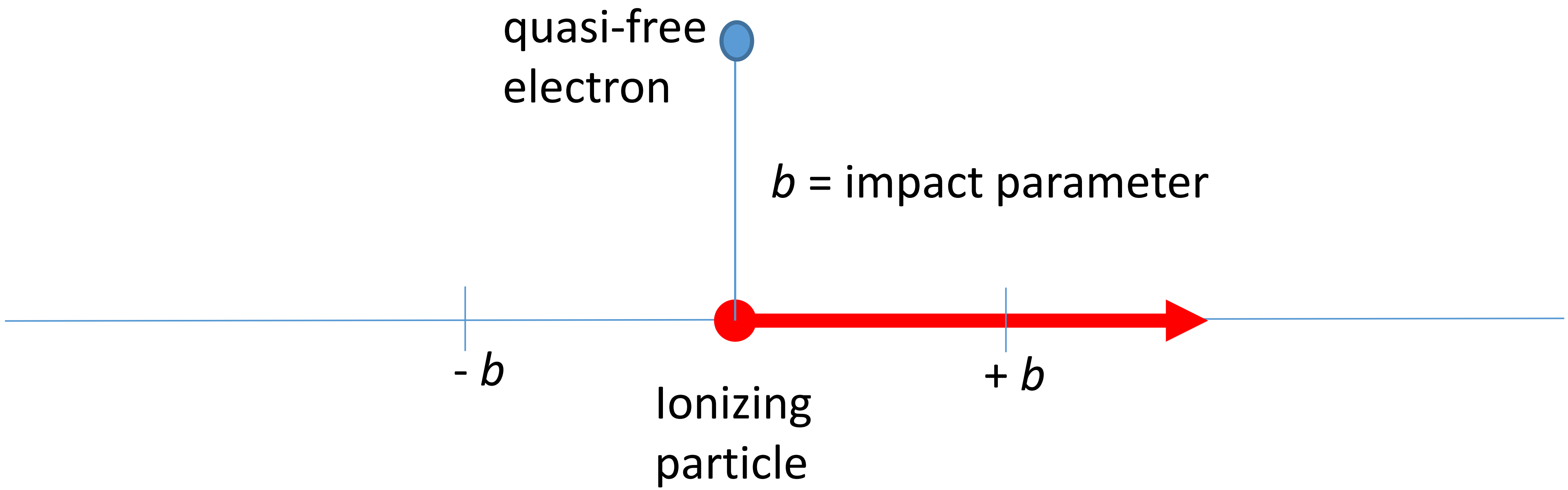
- The avalanche exponential growth, like ani exponential process, must find a saturation point
- The saturation in this case is produced by the space-charge field which reduces the intensity of the applied
- Saturation means that the number of free electrons in the avalanche remains constant
- Howere the induced signal in a ionization detector continue to grow untill the electron drift motion continues

Gas ionization by external agents

- The environment is populated by ionizing particles coming from radioactivity (MeV energy) the surronding material as well as by cosmic radiation (mostly GeV energy μ) →these particles continuously produce free electrons and ions inside a gas
- A metal sharp spike negatively charged can also inject free electrons in the gas
- In a collision of a ionizing particle with an atom an electron can be extracted and, if a sufficient kinetic energy is ganed in the collision, it can be itself a ionizing particle that can produce new free electrons
- We can therefore distinguish a *primary* and a *secondary* ionization
- The total number of free electrons produced in the gas is the sum of the primary ionizations, each one weighed for the secondary ionizations

Simplified classical model of the particle-electron interaction

- The electrostatic field of the particle produces a force ***F*** on the electron
- The electron momentum due to the interaction *is* $\boldsymbol{p}_e = \boldsymbol{F}\,\Delta t$
- $\Delta t = 2b/v$
- $E_e = \boldsymbol{p}^2/2m_e = (2b^2/m_e)\,\boldsymbol{F}^2/v^2$



The Bethe equation

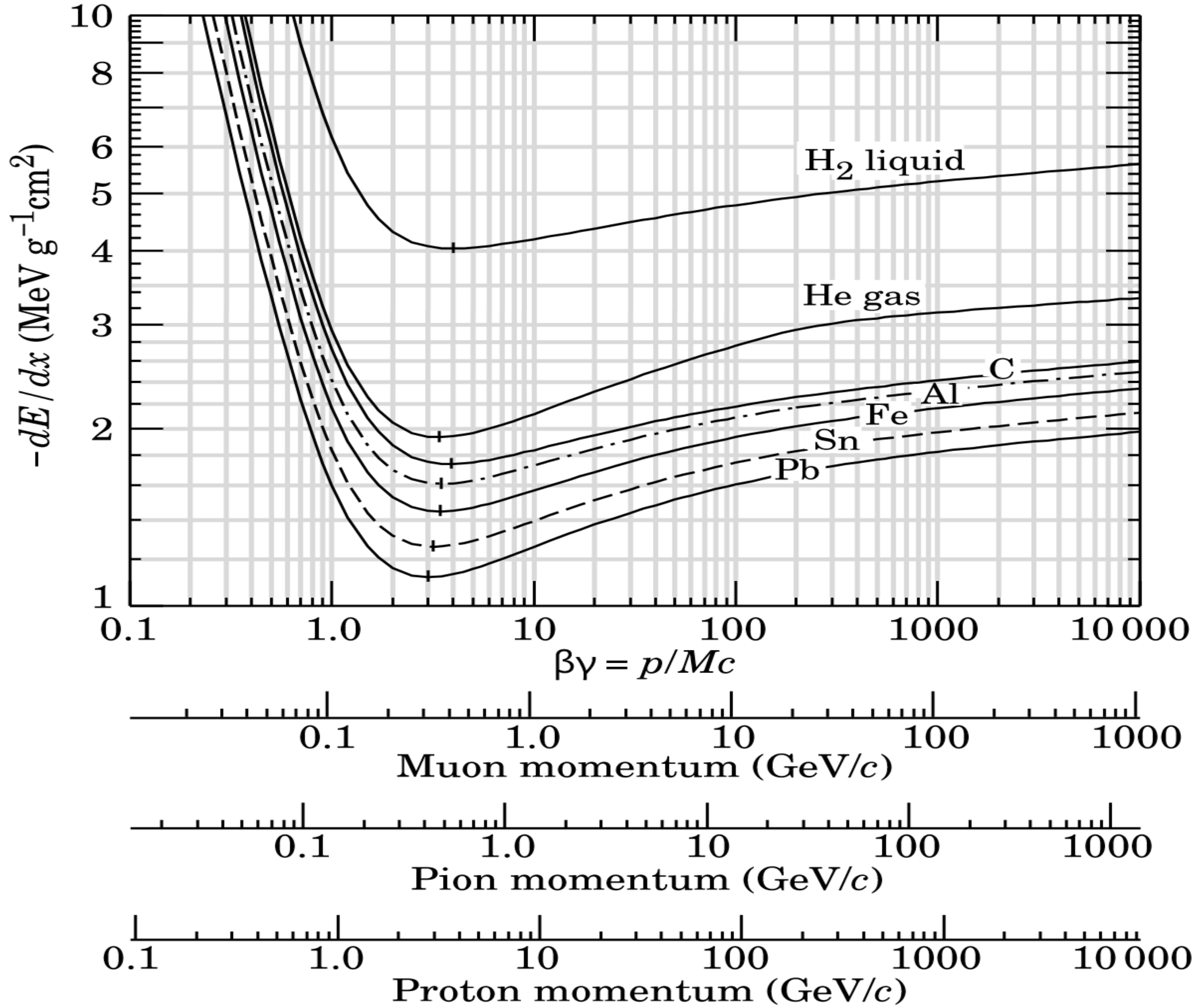
- It is a relativistic equation that can be applied to heavy charged particles (not electrons)
- Its main features however can be obtained by a simple semi-classical calculation. Here *I* is the mean excitation energy

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

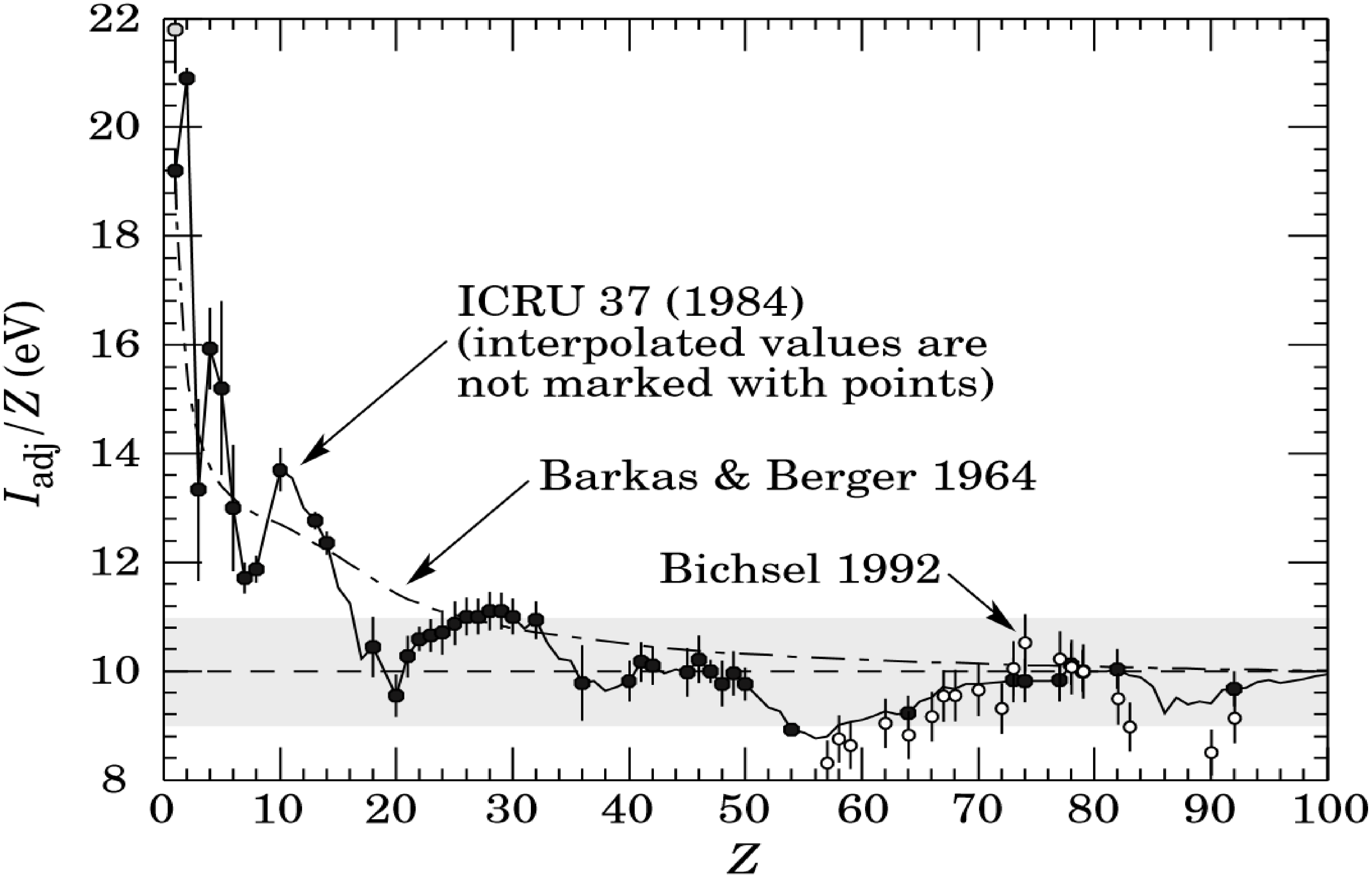
$$T_{\max} = \frac{2m_e c^2\, \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

- The most important points concern:
  - The linear dependence of the material atomic number
  - The quadratic dependence on the particle charge
  - The inverse quadratic dependence on the particle velocity
  - The dependence on I^2
  - The presence of a minimum ionization

Stopping power of different materials around the minimum ionization point



Average ionization potential divided by Z



Energy distribution of the electrons scattered by the ionizing particle and fluctuations in energy loss

The electrons scattered by the particle in the trajectory interval *dx* can get very different kinetic energies *T*. The distribution is given by

$$\frac{d^2N}{dT\,dx} = \frac{1}{2}\,K z^2 \frac{Z}{A}\,\frac{1}{\beta^2}\,\frac{F(T)}{T^2}$$

F(T) being close to 1

In this approximation the kinetic energy distribution is close to $1/T^2$ (strange distribution which deceases much more slowly than the gaussian for increasing T!) showing that it can get very high *T* values even if with small probability

Thin targets

- The scattered electron is itself a ionizing particle crossing the material that for large T values can produce many electron- ion pairs
- For thin layers of material a high energy secondary electron can exit, thus leaving in the material only part of its energy
- For thin targets therefore T_{max} Is replaced by T_{cut} in the Bethe equation
- In the gaseous detectors the gas target is usually thin

Total ionization fluctuations

- The primary ionization follows the *Poisson* statistics
- The collision probability in an trajectory element dl is

$$dp = dl/l_0 \quad \text{with} \quad l_0 = \frac{1}{n\sigma} = average\ free\ path$$

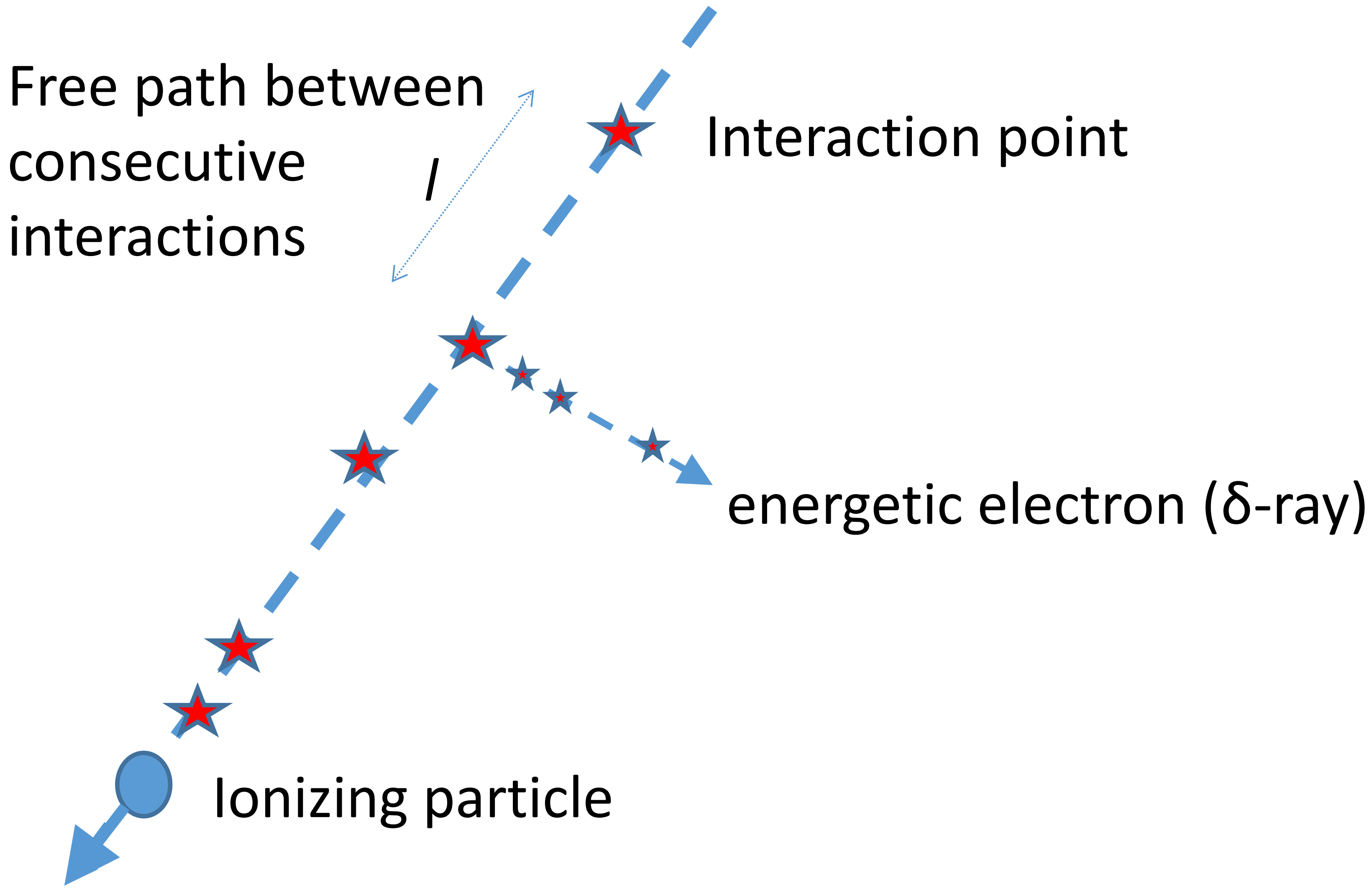
$$n = number\ of\ molecules\ per\ unit\ volume$$

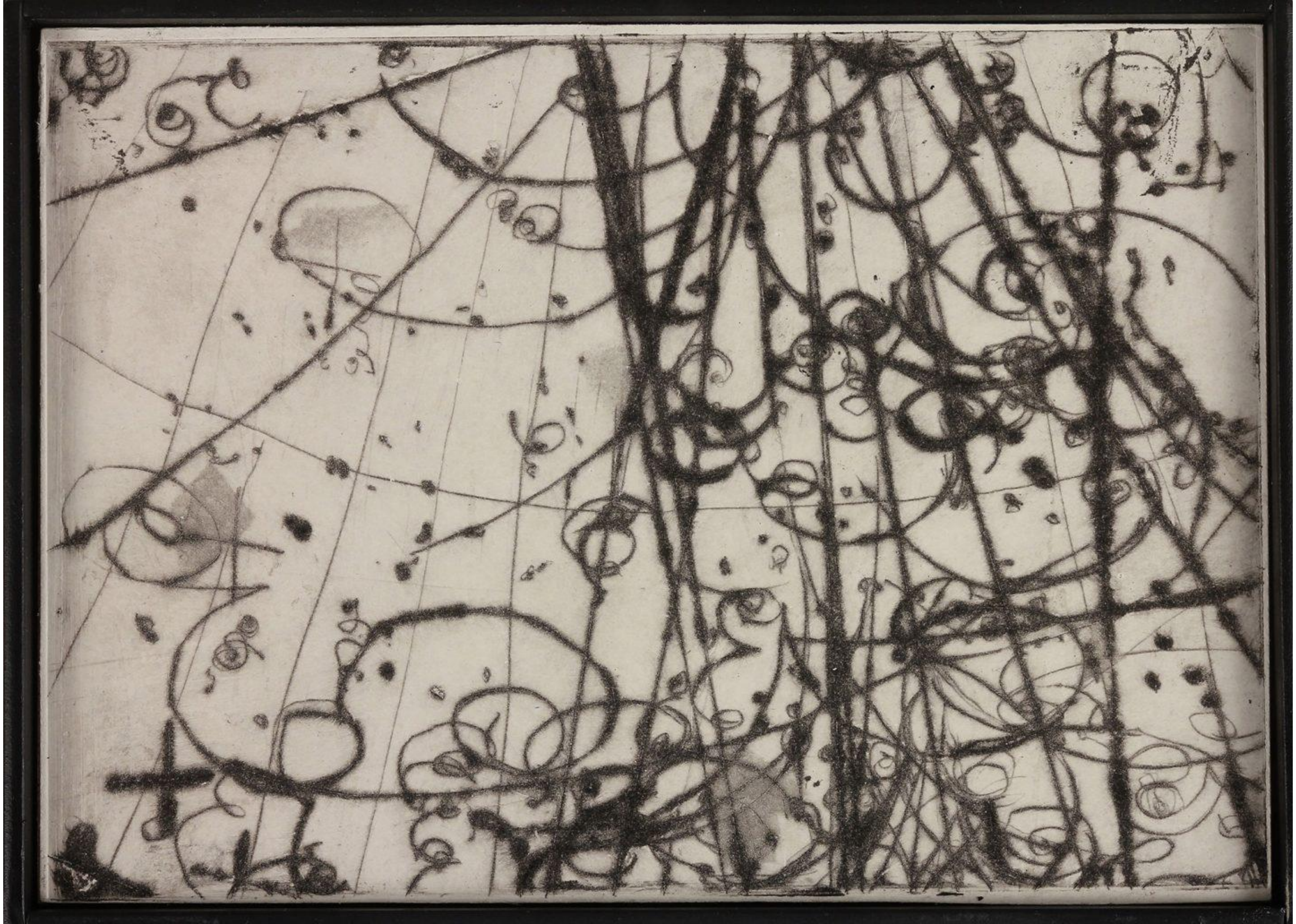
$$\sigma = total\ cross\ section$$

$$probability\ of\ n\ pair\ in\ L\ = e^{-L/l_0} \frac{(\frac{L}{l_0})^k}{k!}$$

- The secondary ionizatio follows the *Landau* statistics

number of electron-ion pairs proportional the the kinetic energy T distributed like $1/T^2$


Free path between
consecutive
interactions
l
Interaction point
energetic electron (δ-ray)
Ionizing particle

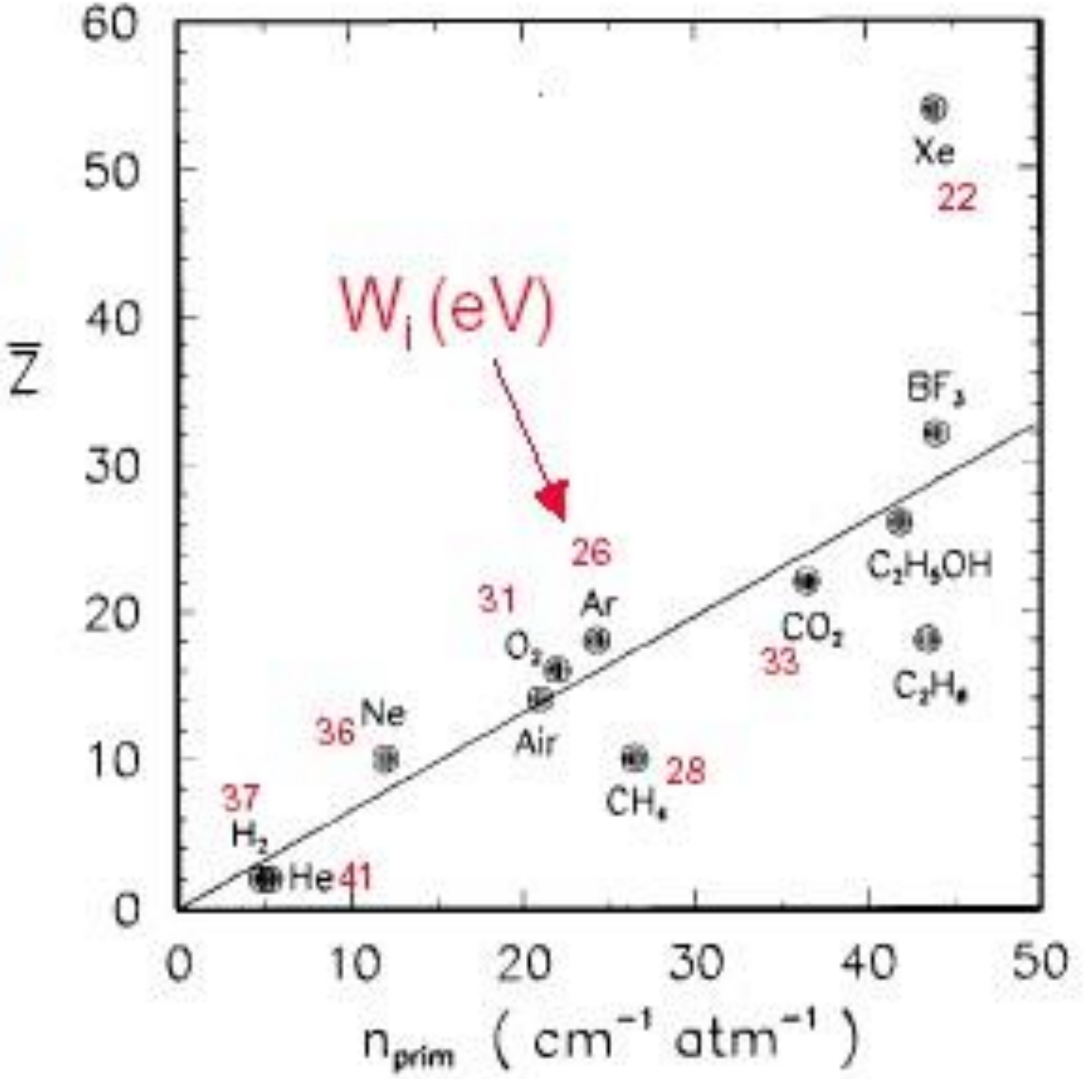


Number of collisions/cm in various gases

gas	1cm/l □# collisioni)	γ
H_2	5.32±0.06	4.0
He	5.02±0.06	4.0
Ne	12.4±0.13	4.0
Ar	27.8±0.3	4.0
Xe	44	4.0
N_2	19.3	4.9
O_2	22.2±2.3	4.3
Aria	18.5±1.3	3.5

Number of primary electron/ion pairs in frequently used (detector) gases.

(Lohse and Witzeling, Instrumentation In High Energy Physics, World Scientific, 1992)



Gas	Z	A	E_{ex} eV	E_i eV	I_0 eV	W_i eV	dE/dx MeV/g cm^{-2}	dE/dx KeV/cm	n_p i.p/cm	n_T i.p/cm
Ar	18	39.9	11.6	15.7	15.8	26	1.47	2.44	29.4	94
Kr	36	83.8	10.0	13.9	14.0	24	1.32	4.60	22	192
Xe	54	131.3	8.4	12.1	12.1	22	1.23	6.76	44	307
CO_2	22	44	5.2	13.7	13.7	33	1.62	3.01	34	91
CH_4	10	16		15.2	13.1	28	2.21	1.48	16	53
C_4H_{10}	34	58		10.6	10.8	23	1.86	4.50	46	195

Dove: E_{ex} = energia minima di eccitazione; E_i = energia minima di ionizzazione;
I_0 =I/Z = potenziale efficace medio di ionizzazione per elettrone atomico;
W_i = perdita di energia media per produrre una coppia ione-elettrone; dE/dx = perdita di energia per particelle al minimo (MIP); n_p = numero di coppie primarie;
n_T = numero totale di coppie.

Nel caso di composti e miscugli Z, A ed I sono valori medi.

Drifting Electron elastic and inelastic collisions

- Peculiarity if the noble gases: large value of the minimum excitation energy E_{ex} and relatively short interval $\Delta = E_i - E_{ex}$ between and ionization energies E
- Ar: $= 11.6\ \ \Delta = 4.1\ eV$; Kr: $E_{ex} = 10.0\ \ \Delta = 3.9\ eV$
  Xe: $E_{ex} = 8.4\ \ \Delta = 3.7\ eV$
- A drifting electron colliding cannot tranfer an energy $E < E_{ex}$. For momentum transfer $\Delta p < \sqrt{2mE_{ex}}$ the collision must be elastic and, the atom mass being $\mathrm{M} \gg \mathrm{m}$ there is no energy transfer: the electron changes direction keeping all its kinetical energy
- The situation is different for very complex molecules like for example i-C4H10; in this case, due to the very low energy of the roto-vibrational levels very small energies can be transferred. The electron motion is similar to a motion inside a viscous liquid

Quenching mechanisms

- The same parameters can explain the discharge quenching mechanism which is crucial for controlling the avalanche growth
- An Ar atom for example can only absorb and re-emit photons of energy Egamma>11.6 eV which can ionize other kind of atoms with lower Eion in the gas. This photo-ionization would produce a further avalanche
- On the contrary, complex molecules like i-C_4H_{10} can absorb high energy UV photons and re-emit their energy in form of the very low energy photons due to the roto-vibrational modes.
- This is the base of the quenching mechanism

The avalanche exponential growth (2)

- The total charge delivered in the gas is given by

$$Q=en \int e\ \alpha x dx = Ie\ \alpha g/\alpha g$$

(with the integral extended between *0* and *g)*

- The ratio of the prompt to total charge

$$q/Q= 1/\alpha g$$

is $<<1$ αg being moderately smaller than 20 (the limit of the avalanche to streamer transition)

- This is due to the fact that most free electrons are produced very near to the anode plate

The avalanche exponential growth (2)

- This simple model of avalanche exponential growth is unrealistic for two reasons
- It is based just on average values and do not contain the fluctuations of primary ionization
- Even more important in the RPC case it do not contain the avalanche saturation due to the space charge effects

Intrinsic RPC efficiency

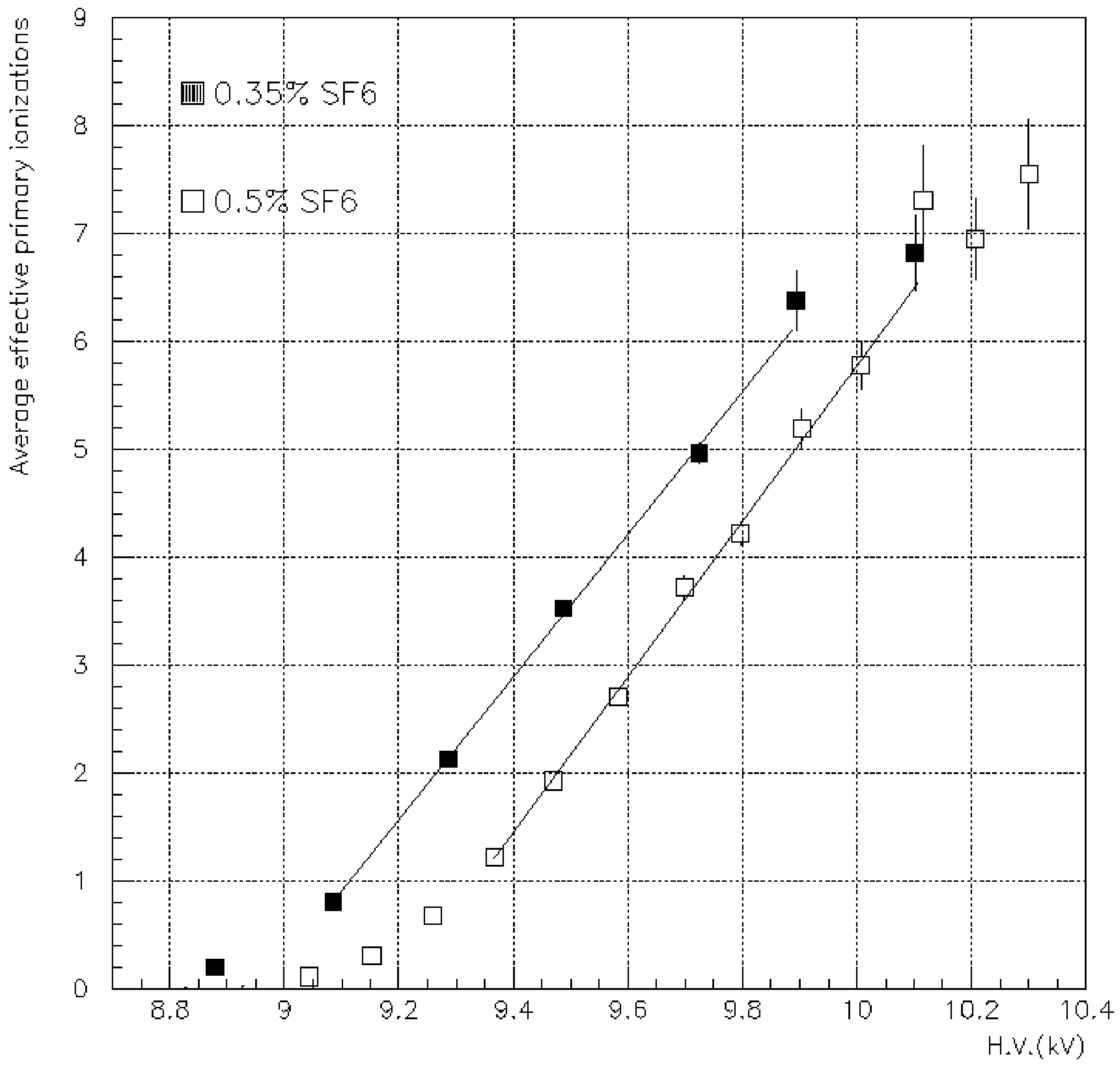
- The RPC achievable efficiency is limited, as for any real detector, by blind areas due to structural elements like spacers and edge frame
- If the effect of the blind areas is discounted the residual inefficiency is intrinsic to the detector
- If $<N>$is the average number of effective primary clusters contributing to the efficiency

$$1-\varepsilon= e-<N><N>=ln(1-\varepsilon)-1$$

- The value of $<N>$is not easy to evaluate also because primary clusters produced near the anode plate are completely ineffective

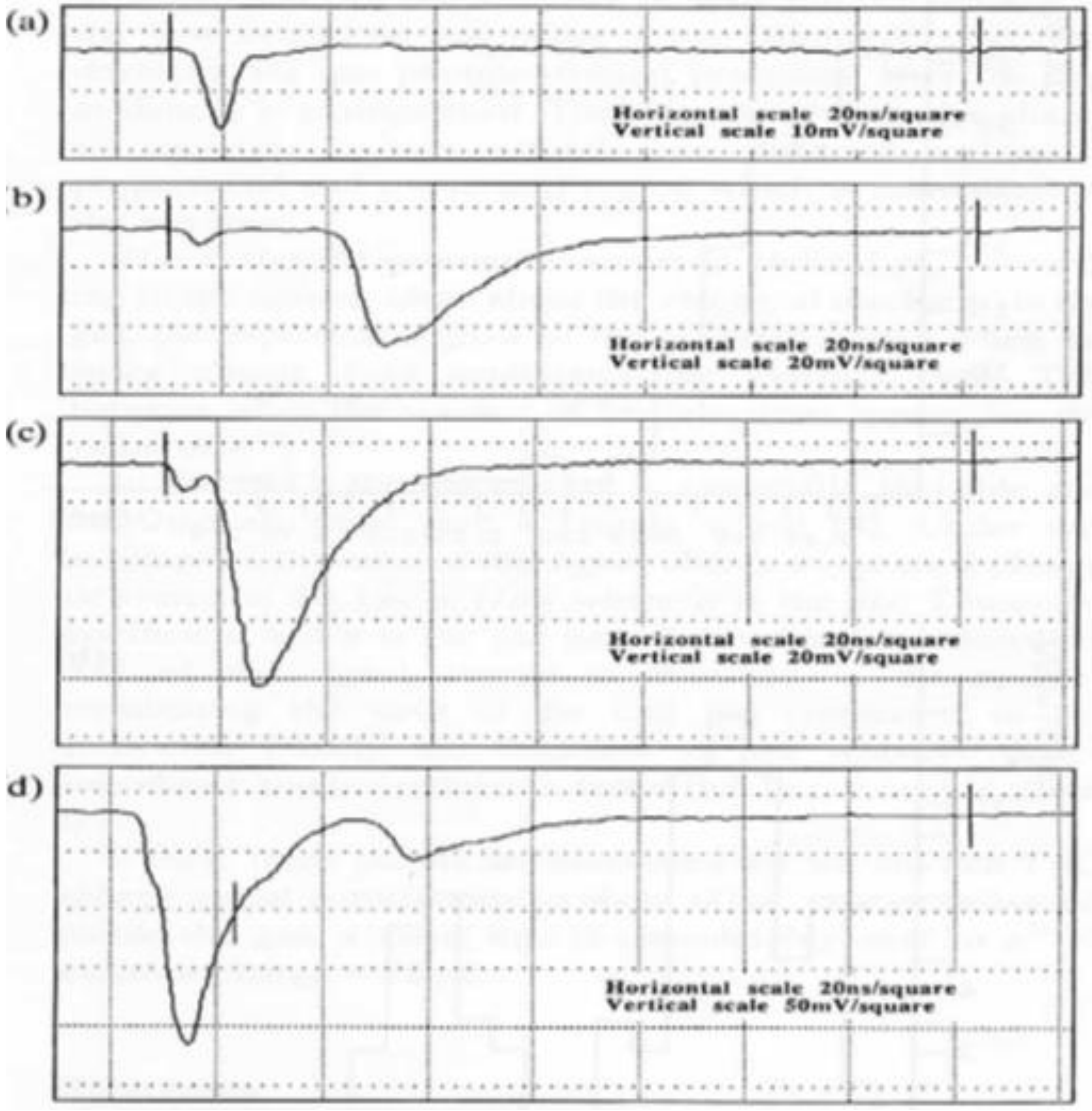
Average number of primary clusters contributing to the efficiency

- ➢ Streamer mode operation ???
- ➢ Anyway depending on the sensitivity of the front end electronics



The avalanche to streamer transition in RPCs

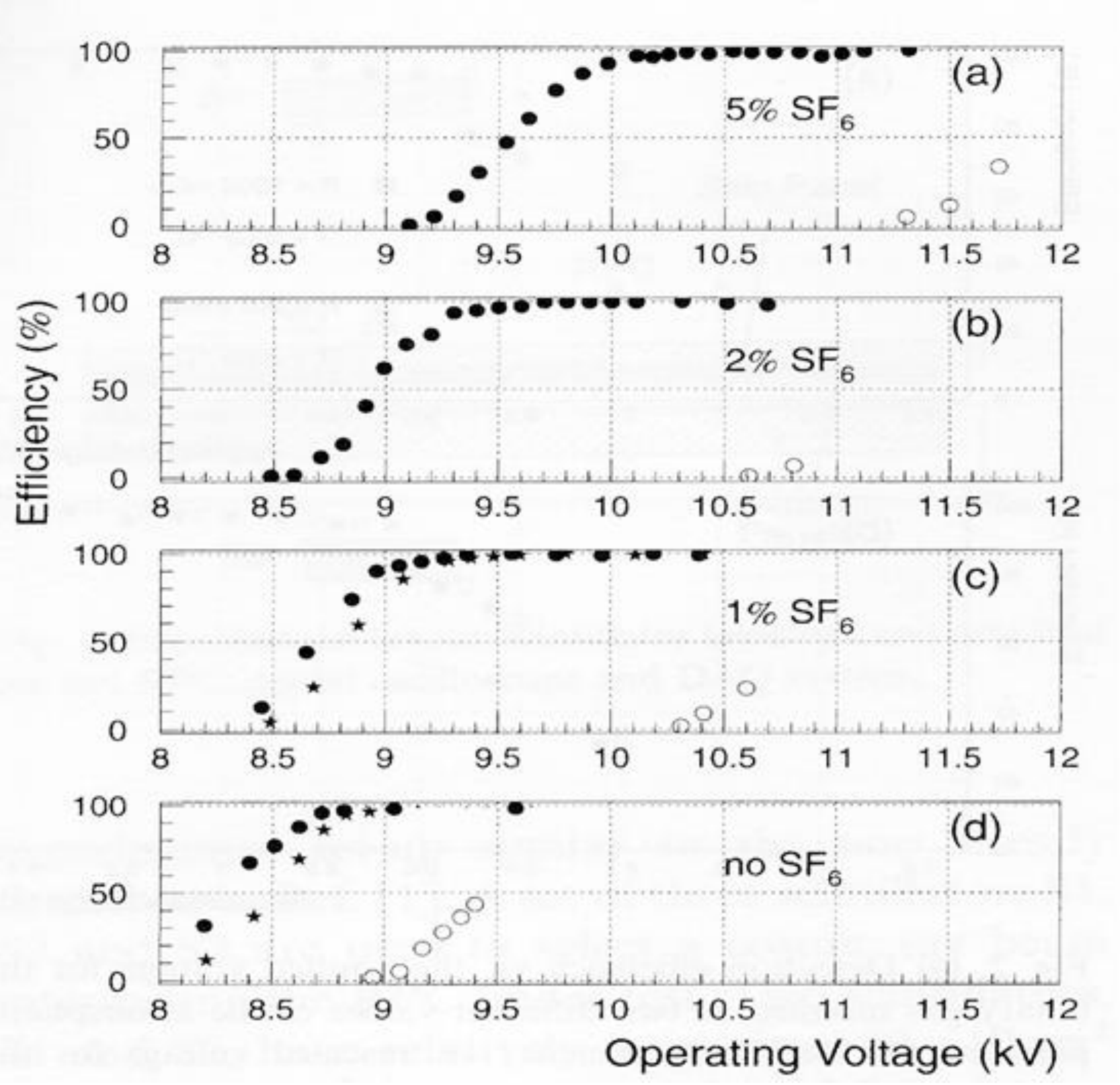
Fig. 2. Signal waveforms at different opearting voltages. The avalanche signal (a, 9.4 kV) has a typical duration of 4–5 ns FWHM. A streamer signal follows the avalanche with a delay of 38 ns (b, 9.6 kV). At higher voltages (c, 10.2 kV) the avalanche to streamer delay becomes gradually shorter and finally (d, 11.4 kV) the avalanche and streamer signals merge into a single pulse. Multistreamer signals are also observed.



Streamer suppression with SF6

● EFFICIENCY (threshold = 30 mV)
★ EFFICIENCY (threshold = 100 mV)
○ STREAMER FRACTION

Fig. 4. Detection efficiency and streamer probability vs. operating voltage for (a) 5%, (b) 2%, (c) 1% SF_6 concentrations and (d) no SF_6.



Back up

Gaseous detectors brief history

- A gaseous detector is characterized by:
  - a gaseous target made of a proper gas mixture
  - a strong electric field acting on the gas
- The field is strong enough to accelerate the small number of free ionization electrons left by the incoming particle and to produce of an avalanche of size detectable by the front end electronics
- The first type of gaseous detectors which found application to the particle physics is the wire detector/chamber based on the field produced by a positive charged wire
- The family of the wire chambers, derived from the G&M counter developed in the decade of 1920, have found very relevant applications to particle physics since a long time

The Geiger-Muller counter

- The first idea of a gaseous radiation detector was the G&M counter
- This is a metallic cylindrical tube with a well isolated .metal wire in the tube axis. The tube is filled with a noble gas to which a very small amount of organic component (alcohol or hydrocarbon) is added. The wire is kept at constant *positive voltage* of about +1 kV with respect to the tube (grounded)
- The electrostatic field is

$$E = \lambda/2\pi\varepsilon_0 r = \frac{V}{r ln(r_2/r_1)}$$

The field decreasing as $1/r$ is ***"critical"*** only for r of the order of the wire diameter where the gas multiplication processes can happen

- The family of the wire chambers, derived from the G&M counter developed in the decade of 1920, have found very relevant applications to particle physics up to now

The Keuffel counter

- In 1949 Keuffel proposed a new type of gaseous detector, based on the uniform field generated by a plane capacitor, which was very attractive for his potential time resolution
- This detector was so critical and unstable that could never find applications
- It triggered however (indirectly) the development of a new family of planar pulsed detectors: the optical spark chamber, with narrow and wide gap, and the pulsed streamer chamber, which were (together with the bubble chambers) the main instrument of the particle physics up to the years 70

The Resistive Plate Chamber RPC

- The idea of a continuously sensitive *planar* gaseous detector, not needing a trigger signal, continued to be a “dream” to be pursued
- For timing applications Yu Pestov proposed a DC coupled planar detector under high pressure, with one glass electrode, which showed a 30 ps time resolution. This detector could never find real applictions
- The Resistive Plate Chambers, RPC, developed in 1979 and published in 1981, were proposed as planar detectors suitable for large area applications with 1 ns time resolution

The optical spark chamber

Detectors derived from the G&M counter

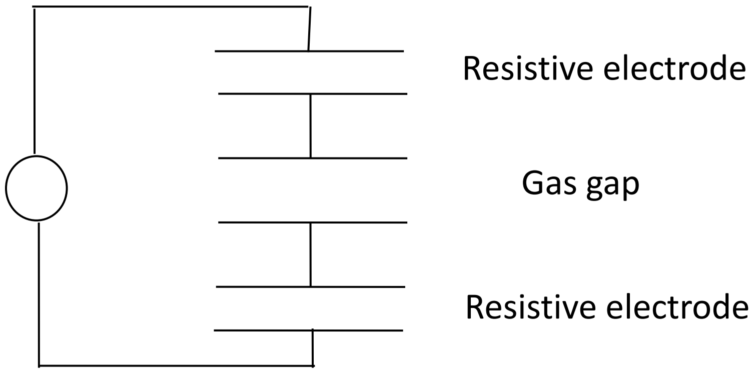
- The signal in the G&M counters
- Limited Geiger tubes → Limited streamer tubes
- Multi-wire proportional chambers

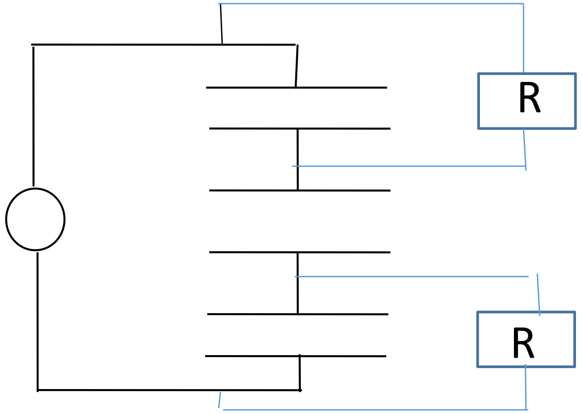
Detectors derived from the optical spark chamber

- Wide gap spark chamber
- Pulsed streamer chamber

The RPC basic idea

- The RPC "elementary cell" is schematically represented as in fig, where the central capacitor C represents the gas gap and the other two capacitors C* the resistive plates with the relative resistors R* in parallel. Indicating by ΔS the cell area: $C = \varepsilon_0\, \Delta S/g \quad C^* = \varepsilon_0\, \varepsilon_r\, \Delta S/d \quad R^* = \rho\, d/\Delta S$





The RPC basic idea (2)

- The characteristic discharge time of the electrode capacitors is

  τ = $R^{*}C^{*}$ with $C^{*} = \varepsilon_0\, \varepsilon_r\, \Delta S/d \quad R^{*} = \rho\, d/\Delta S$

  τ = $R^{*}C^{*}$= $\varepsilon_0\, \varepsilon_r\, \rho$

- The electrostatic laws are valid only for t << τ

  This is in most cases a very short time. Eg take a good insulator with ε_r = 3 and ρ = 10^14 Ohm*cm → τ = 27 s !

- In steady conditions and in absence of ionization the generator voltage is totally applied to the gas gap. The field is zero inside the resistive electyrodes

Gaseous media: conductors or insulators?

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- A gas has a very peculiar property: in presence of a sufficiently strong electric field its electrical resistivity can change of many orders of magnitude in a sub-nanoseconds time
- This means also that speaking of resistivity as an intrinsic property of a gas would be completely improper

Lay out (1)

- Conductor and insulators
- Gases as ideal insulators
- Nevertheless important conduction phenomena in gases. Why? The gas is usually surrounded by ionization sources
- Injecting a free electron inside an insulator. Electron mobility
- A free electron injected inside the gas flights in vacuum between two consecutive…Maximum mobility
- Gas under electric field and multiplication phenomena
- The Townsend model of a discharge. First Townsend coefficient

Lay out (2)

- Free electron sources
- A negatively charged metal spike inside the gas
- A ionizing particle…In this case a gas can be used as the target of a ionization detector –> gaseous ionization detectors
- Energy loss of a charged particle crossing a gaseous medium
- Thin target and reduced energy loss
- Primary and secondary ionization
- Statistics of the two kinds of ionization
- Examples of different gases
- Ionization energy and energy spent for creating a free electron
- Delayed ionization and Penning effect

Lay out (3)

- Possibility to create a DC coupled plane capacitor gaseous detector. The optical spark chamber as an ancestor
- Detectors characterized by a positively charged metal wire and skepticism about a plane capacitor
- Drift region in the gas and multiplication region
- Coincidence of the two regions in a plane capacitor
- –> consequence of very different yield for different primay clusters

Lay out (4)

- Ectrical discharge between high resistivity electrodes
- Discharge localization
- Correct names for different stages of the discharge: avalanche, streamer and spark (non uniform spark intensity in multi-traks)
- Gas related Features