Gas-based detectors

Ionisation
Electron transport

Gaseous detectors

- Some examples:
  - Geiger counters
  - Multi-wire proportional chambers (MWPC)
  - Drift chambers (DC)
  - Time projection chambers (TPC)
  - Ring imaging Čerenkov chamber (RICH)
  - Microstrip gas counters (MSGC)
  - Gas electron multiplier (GEM)
  - Micromegas
  - Gossip
  - Microdot detector

[Four Curies: Pierre, Marie, Irène and Pierre's father, around 1904 at the BIPM]

1896: Ionisation by radiation

- Early in the study of radioactivity, ionisation by radiation was recognised:

” Becquerel discovered in 1896 the special radiating properties of uranium and its compounds. Uranium emits very weak rays which leave an impression on photographic plates. These rays pass through black paper and metals; they make air electrically conductive. “

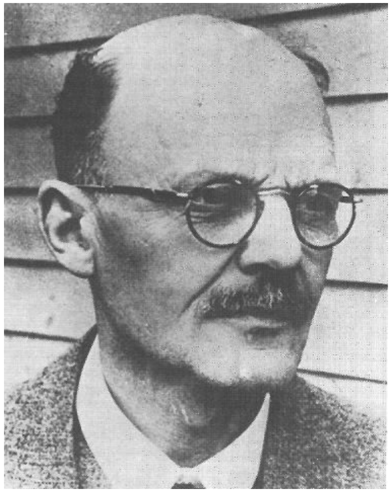
[Pierre Curie, Nobel Lecture, June 6th 1905]

“A sphere of charged uranium, which discharges spontaneously in the air under the influence of its own radiation, retains its charge in an absolute vacuum. The exchanges of electrical charges that take place between charged bodies under the influence of the new rays, are the result of a special conductivity imparted to the surrounding gases, a conductivity that persists for several moments after the radiation has ceased to act.”

[Antoine Henri Becquerel, Nobel Lecture, December 11th 1903]

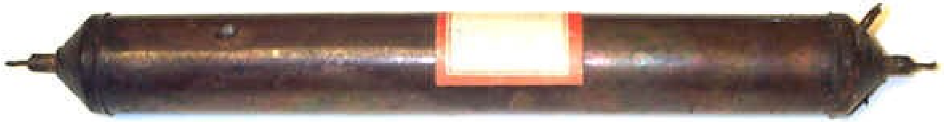
1908: Geiger counter

- Detects radiation by discharge.
- Can count α and β particles (at low rates).
- No tracking capability.
- First models in 1908 by Hans Geiger, further developed from 1928 with Walther Müller.



Hans Geiger
(1882-1945)

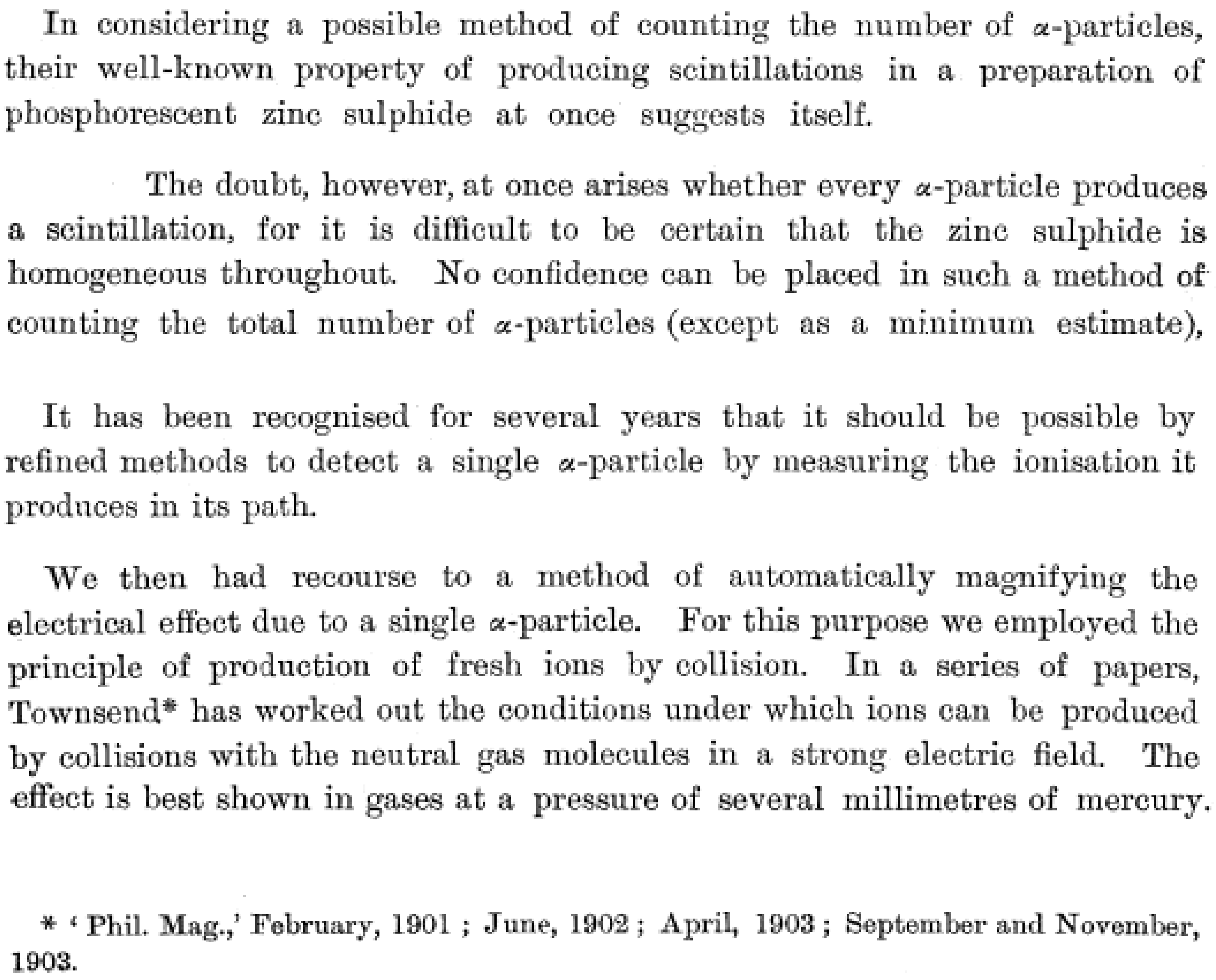
?



A Geiger-Muller counter built in 1939 and used in the 1947-1950 for cosmic ray studies in balloons and on board B29 aircraft by Robert Millikan et al.

Made of copper, 30 cm long

Motivation for the Geiger counter



In considering a possible method of counting the number of α-particles, their well-known property of producing scintillations in a preparation of phosphorescent zinc sulphide at once suggests itself.

The doubt, however, at once arises whether every α-particle produces a scintillation, for it is difficult to be certain that the zinc sulphide is homogeneous throughout. No confidence can be placed in such a method of counting the total number of α-particles (except as a minimum estimate),

It has been recognised for several years that it should be possible by refined methods to detect a single α-particle by measuring the ionisation it produces in its path.

We then had recourse to a method of automatically magnifying the electrical effect due to a single α-particle. For this purpose we employed the principle of production of fresh ions by collision. In a series of papers, Townsend* has worked out the conditions under which ions can be produced by collisions with the neutral gas molecules in a strong electric field. The effect is best shown in gases at a pressure of several millimetres of mercury.

---

* 'Phil. Mag.,' February, 1901 ; June, 1902 ; April, 1903 ; September and November, 1903.

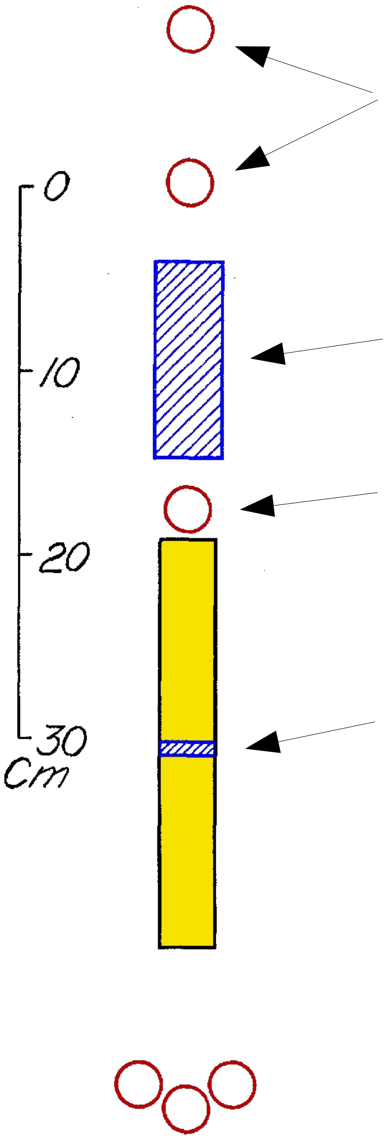
[E. Rutherford and H. Geiger, *An Electrical Method of Counting the Number of α-Particles from Radio-Active Substances,* Proc. R. Soc. Lond. A **81** (1908) 141-161]

Efficiency losses of visual detection

Ionisation signal usable but small

Use multiplication at low pressure as discovered in 1901 by JS Townsend

1937: first muon event



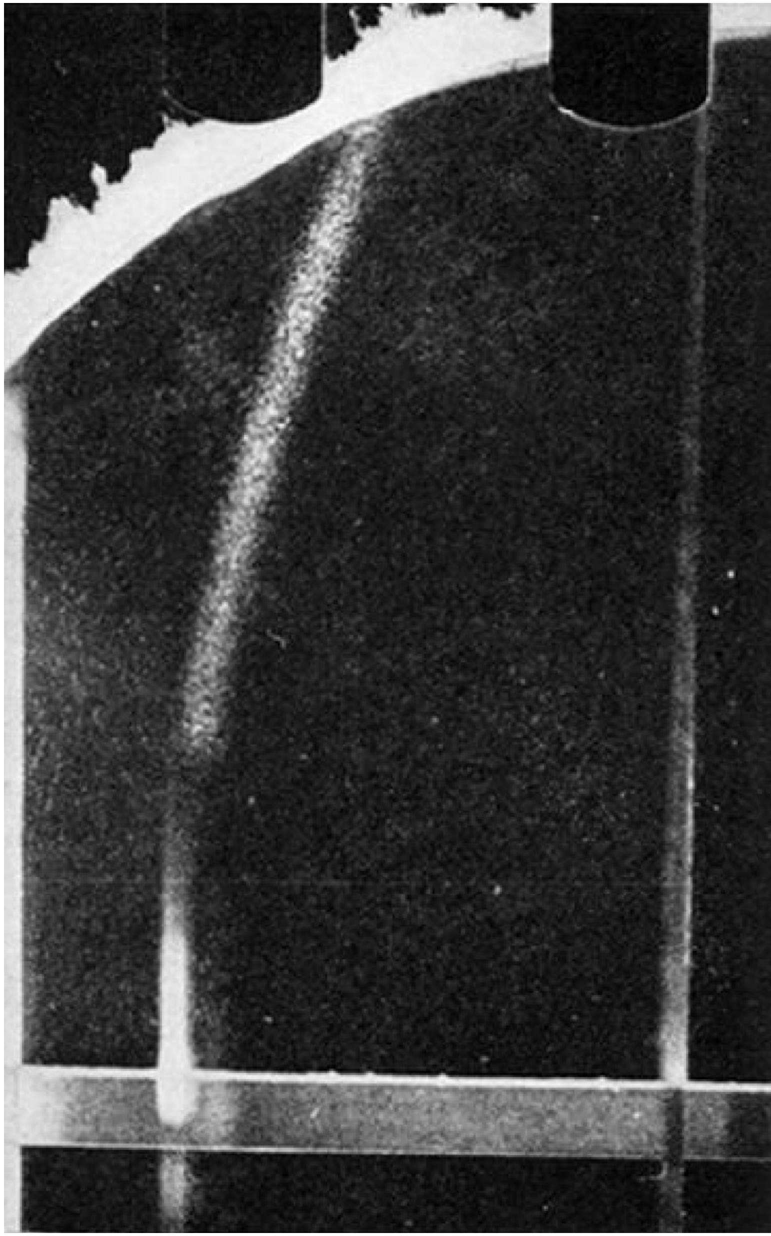
Trigger counters

Lead absorber

Trigger counter

Cloud chamber, filter,
0.35 T magnetic field

Veto counter



[J. C. Street and E. C. Stevenson, Phys. Rev 52 (1937) 1003]

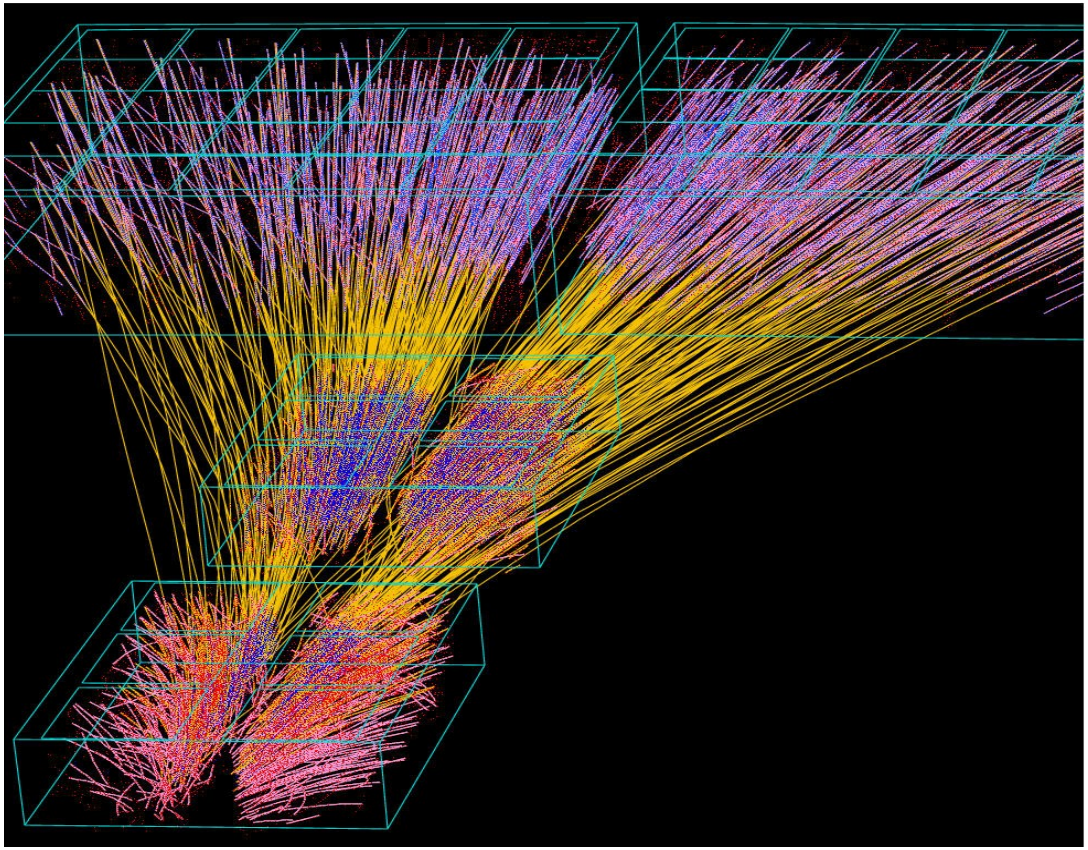
TPC

- Typically very large
- Almost empty inside
- Excellent for dealing with large numbers of tracks

- 1976: David Nygren
  (for PEP4)

Alice

Star

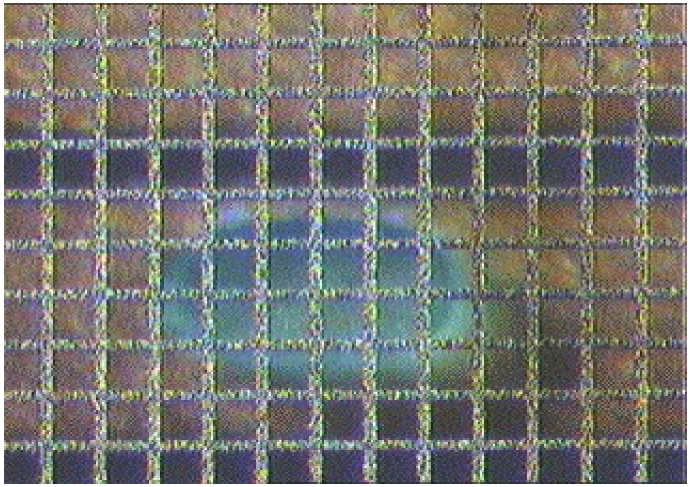


NA49

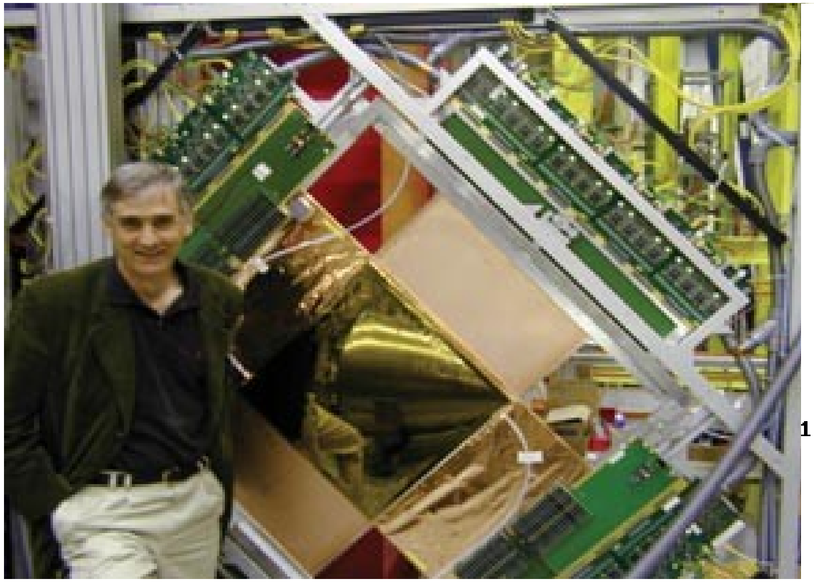
David Nygren

Micromegas

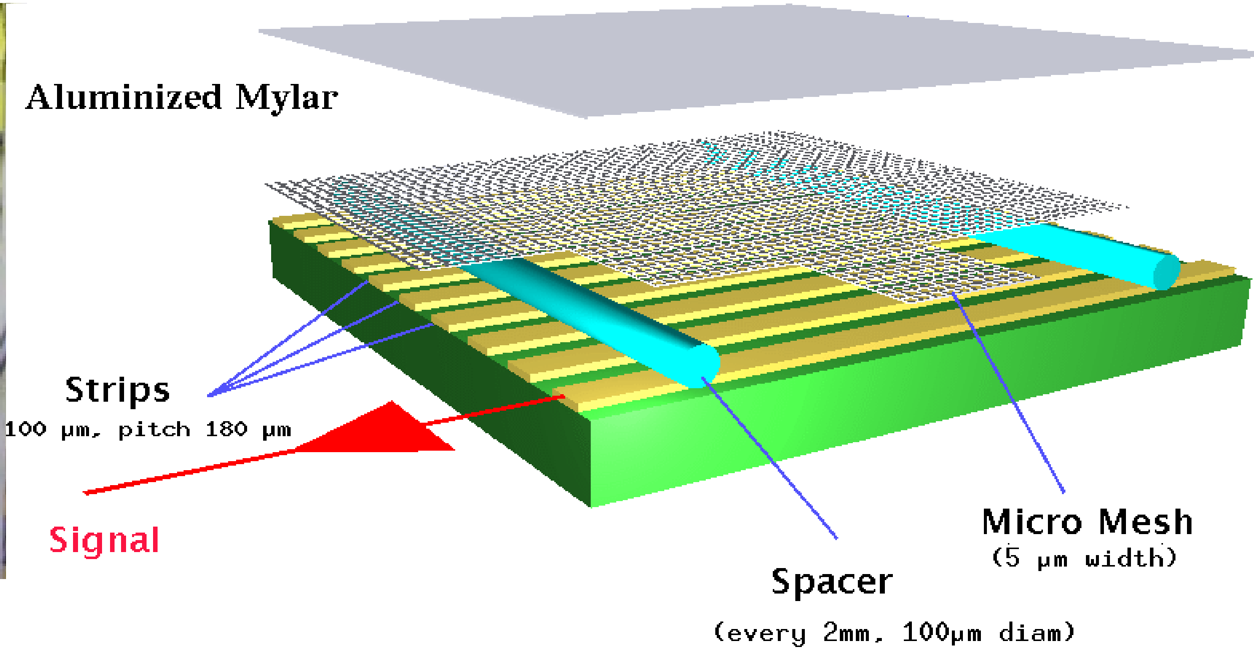
- Fast, rate tolerant tracking device
- 1994: Yannis Giomataris and Georges Charpak



A mesh – holes of 30 µm

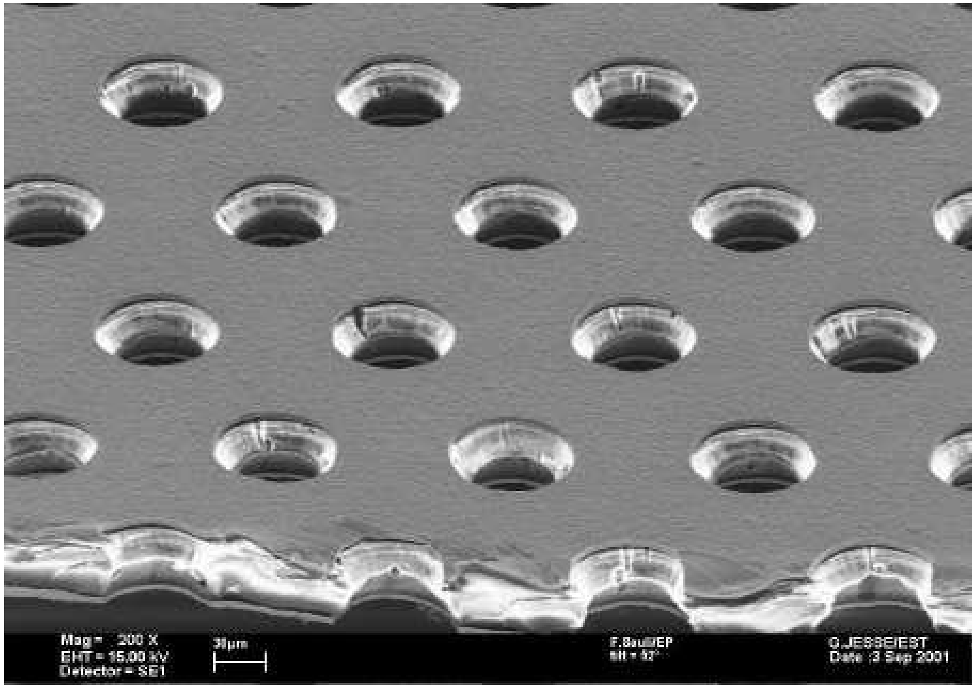


Yannis Giomataris

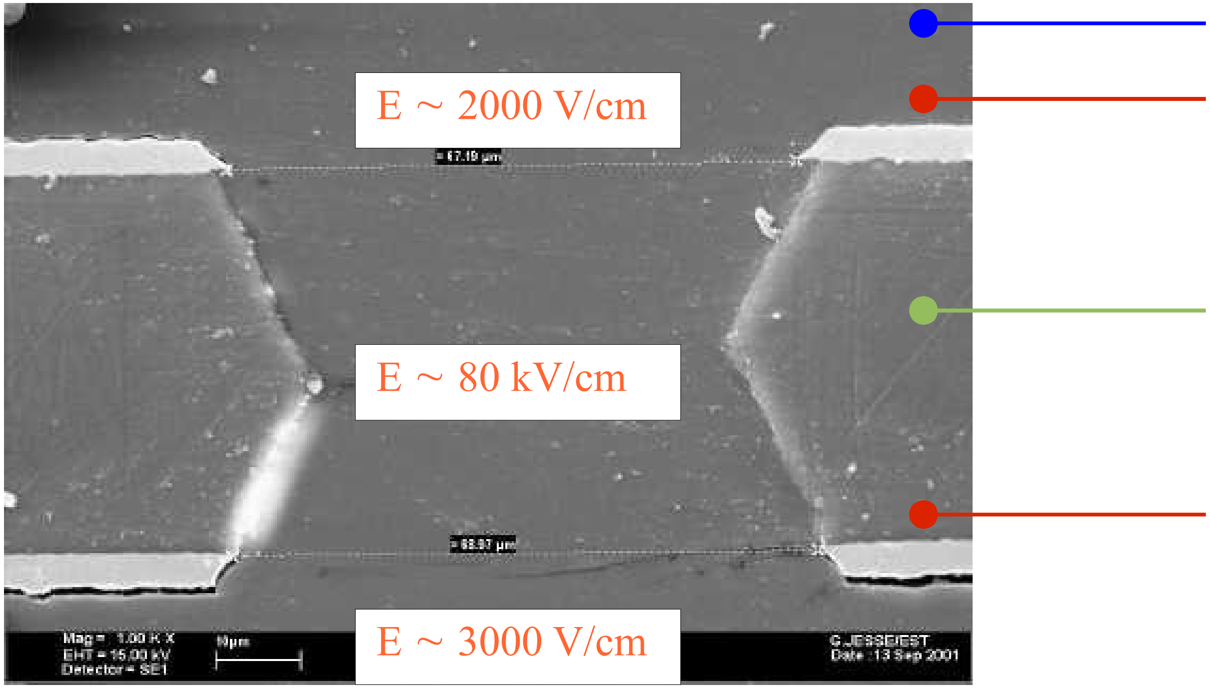


GEMs

- Originally a “pre-amplifier”, now a standalone detector.
- 1996: Fabio Sauli



A few electrons enter here



E ~ 2000 V/cm

E ~ 80 kV/cm

E ~ 3000 V/cm

Gas

Metal

Dielectric

Metal

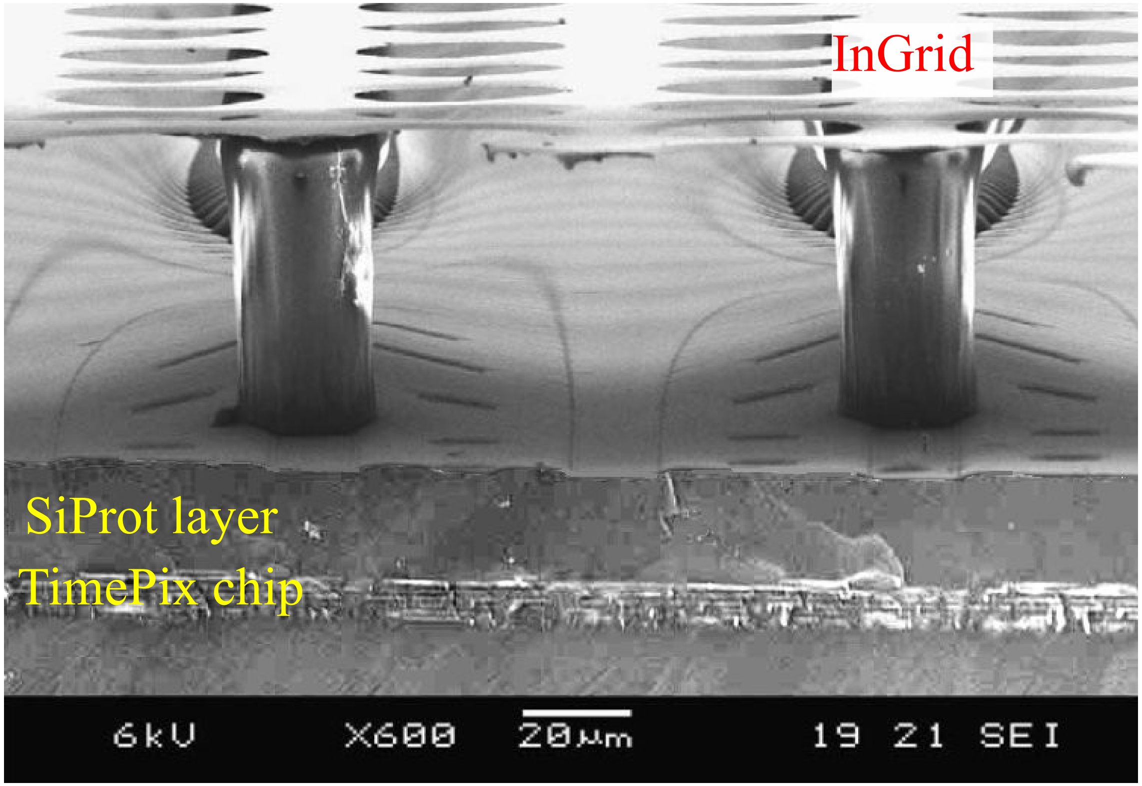
Many electrons exit here

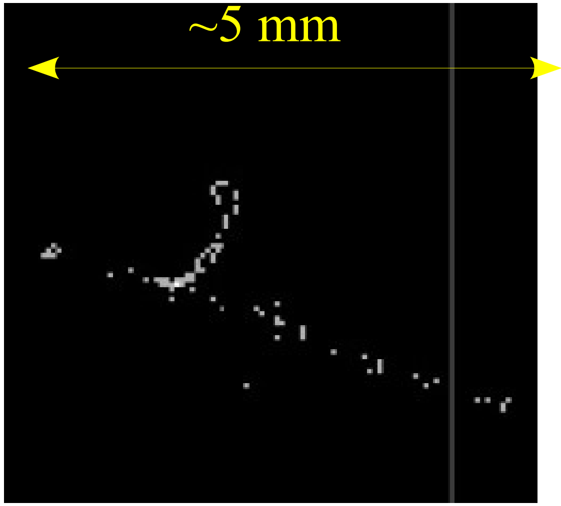
Fabio Sauli

Gossip

- The “electronic bubble chamber”.

Harry van der Graaf (r)





δ-electrons made visible in He/iC_4H_{10}, using a modified MediPix, ~2004.

How do they work ?

- Perhaps surprisingly, they all work according to much the same principles:
  - a charged particle passing through the gas ionises some of the gas molecules;
  - the electric field in the gas volume transports the ionisation electrons and, in some areas, also provokes multiplication;
  - the charge movements (of electrons and ions) lead to induced currents in electrodes, and these currents are recorded.

Trends in tracking

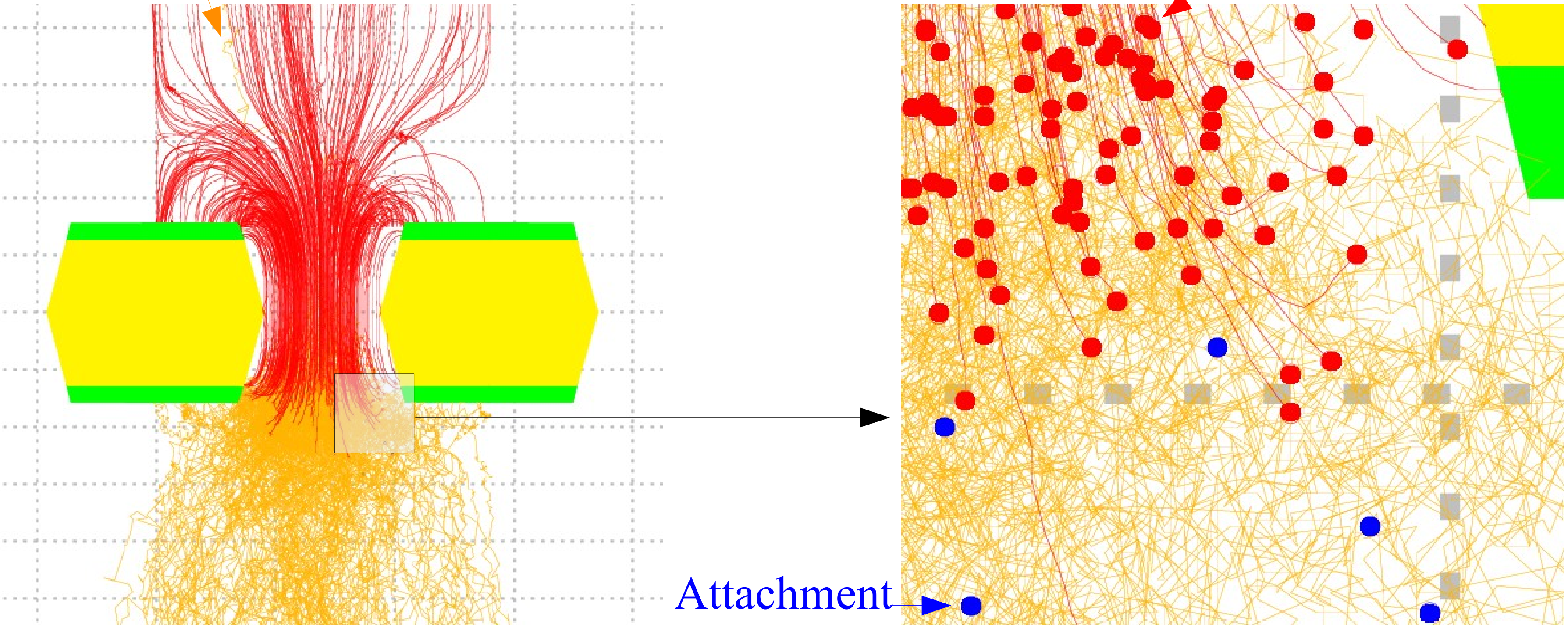
- Intrinsic resolution:

Geiger counter:	~1 cm	tube is hit or not
MWPC:	~1 mm	detect which wire is hit
drift chambers:	150-250 μm	measure drift time
LHC experiments:	50-200 μm	gas, electronics ...
micropattern detectors:	20- 50 μm	small scale electrodes

- Need to understand gases at a smaller and smaller scale.

A closer look

- Micropattern devices have characteristic dimensions that are comparable with the mean free path.



[Plot by Gabriele Croci and Matteo Alfonsi]

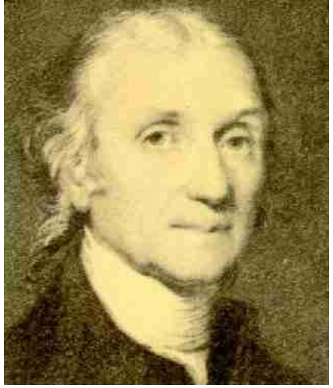
The sensitive medium: a gas

- Which gas would be suitable ?
  - easily ionisable;
  - neither flammable, nor explosive, nor toxic;
  - affordable;
  - no sparks in strong electric fields;
  - not attaching: doesn't swallow electrons.

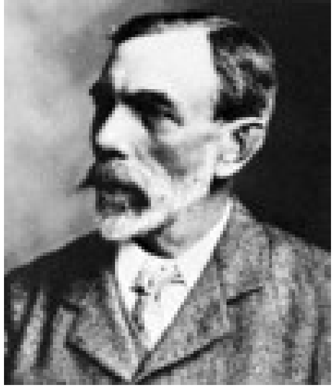
- Typically, we will use a noble gas as basis, with an admixture of some organic gas for stability.

- Today, we concentrate on argon, pure and mixed with CO_2 but there are many alternatives.

Argon

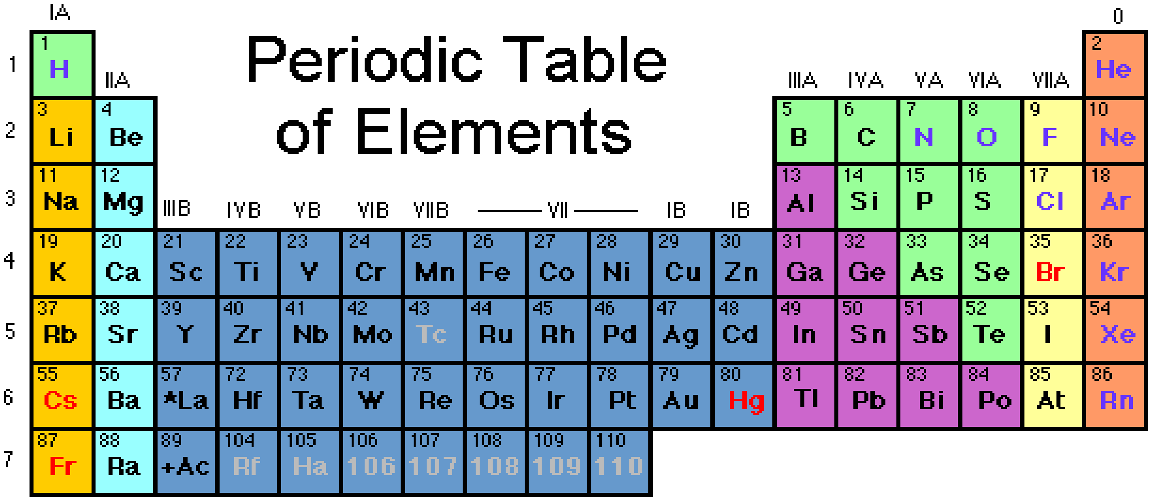

Henry Cavendish
(1731-1810)


JohnWilliam Strutt,
3rd Baron Rayleigh of
Terling Place
(1842-1919)


Sir William Ramsey
(1852-1916)

- Ocurrence:
  - Abundant in the atmosphere !
- Other qualities:
  - Chemically exceedingly inert, hence not toxic
  - Cheap: 0.001 €/l (CERN stores)

Gas	Percent volume
nitrogen	78.080000
oxygen	20.950000
argon	0.930000
water	up to 4 %
carbon dioxide	0.036000
neon	0.001800
helium	0.000500
methane	0.000170
hydrogen	0.000050
nitrous oxide	0.000030
ozone	0.000004


Periodic Table of Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110								

CO_2

- Positive electron affinity, but clusters do attach;
- cheap;
- non-flammable, non-toxic ...
- not ageing.

Organic gases, haloalkanes ...

- Commonly used:
  - CH_4, C_2H_6, C_3H_8, iC_4H_{10}, ...
  - DME,
  - CF_4, $C_2F_4H_2$, SF_6 ...
- Qualities:
  - photon absorption.
- Problems:
  - some are flammable, toxic, bad for the environment ...
    - dissociation, polymerisation (ageing);
  - attachment.

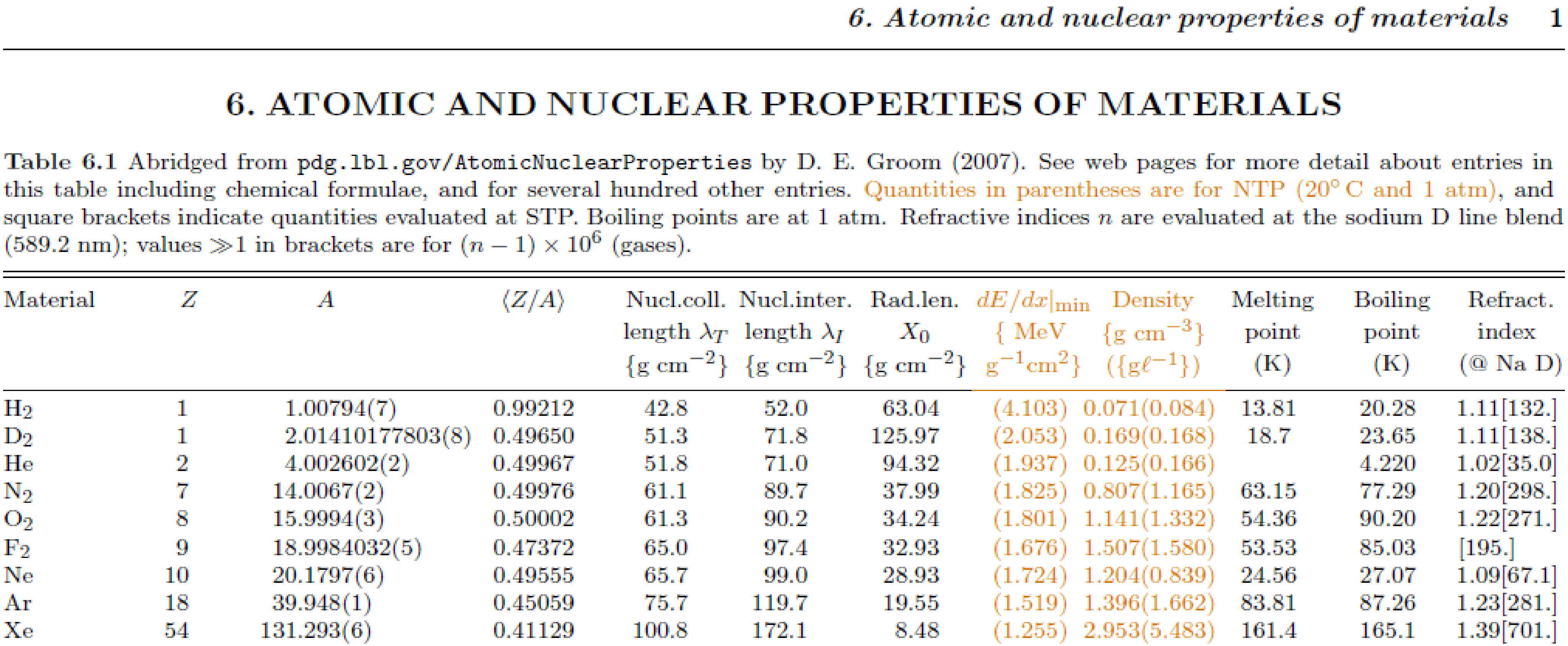
Phase 1: Ionisation by charged particles

- Ionisation of the gas:
  - how many electrons are produced ?
  - how far are they from the track ?

- How to model the ionisation process:
  - dE/dx tables ?
  - virtual photons ?

Using d*E*/d*x* tables

- Start from the energy loss tables, e.g. from the PDG:



6. Atomic and nuclear properties of materials 1

6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Table 6.1 Abridged from `pdg.lbl.gov/AtomicNuclearProperties` by D. E. Groom (2007). See web pages for more detail about entries in this table including chemical formulae, and for several hundred other entries. Quantities in parentheses are for NTP (20° C and 1 atm), and square brackets indicate quantities evaluated at STP. Boiling points are at 1 atm. Refractive indices n are evaluated at the sodium D line blend (589.2 nm); values $\gg$1 in brackets are for $(n-1)\times 10^6$ (gases).

Material	Z	A	$\langle Z/A \rangle$	Nucl.coll. length λ_T $\{\text{g cm}^{-2}\}$	Nucl.inter. length λ_I $\{\text{g cm}^{-2}\}$	Rad.len. X_0 $\{\text{g cm}^{-2}\}$	$dE/dx\|_{\text{min}}$ $\{\text{MeV g}^{-1}\text{cm}^2\}$	Density $\{\text{g cm}^{-3}\}$ $(\{\text{g}\ell^{-1}\})$	Melting point (K)	Boiling point (K)	Refract. index (@ Na D)
H_2	1	1.00794(7)	0.99212	42.8	52.0	63.04	(4.103)	0.071(0.084)	13.81	20.28	1.11[132.]
D_2	1	2.01410177803(8)	0.49650	51.3	71.8	125.97	(2.053)	0.169(0.168)	18.7	23.65	1.11[138.]
He	2	4.002602(2)	0.49967	51.8	71.0	94.32	(1.937)	0.125(0.166)		4.220	1.02[35.0]
N_2	7	14.0067(2)	0.49976	61.1	89.7	37.99	(1.825)	0.807(1.165)	63.15	77.29	1.20[298.]
O_2	8	15.9994(3)	0.50002	61.3	90.2	34.24	(1.801)	1.141(1.332)	54.36	90.20	1.22[271.]
F_2	9	18.9984032(5)	0.47372	65.0	97.4	32.93	(1.676)	1.507(1.580)	53.53	85.03	[195.]
Ne	10	20.1797(6)	0.49555	65.7	99.0	28.93	(1.724)	1.204(0.839)	24.56	27.07	1.09[67.1]
Ar	18	39.948(1)	0.45059	75.7	119.7	19.55	(1.519)	1.396(1.662)	83.81	87.26	1.23[281.]
Xe	54	131.293(6)	0.41129	100.8	172.1	8.48	(1.255)	2.953(5.483)	161.4	165.1	1.39[701.]

- A minimum-ionising particle loses

$$1.519\,\text{MeV cm}^2/\text{g}\times 1.662\times 10^{-3}\,\text{g}/\text{cm}^3 = 2.5\,\text{keV}/\text{cm}$$

Electron binding energies

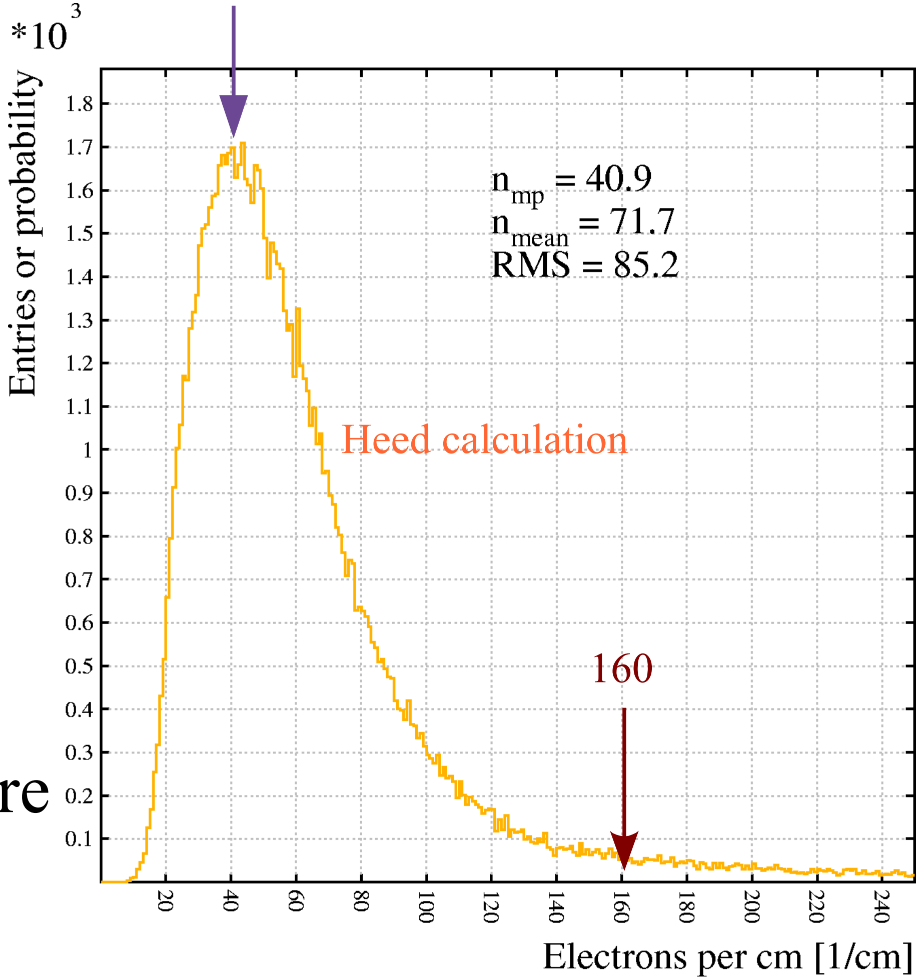
- Next, we need the binding energies, which we can get from e.g. `http://www.webelements.com`

Shell	Orbital	Binding energy
K	1s	3205.9 eV
L I	2s	326.3 eV
L II	2p 1/2	250.6 eV
L III	2p 3/2	248.4 eV
M I	3s	29.3 eV
M II	3p 1/2	15.9 eV
M III	3p 3/2	15.76 eV

- One might expect $2.5\,\mathrm{keV/cm} \;\; / \;\; 15.8\,\mathrm{eV/e^-} \approx 160\,\mathrm{e^-/cm}$

Electrons produced per cm in pure Ar

- Heed, a photo-absorption and ionisation model, finds for a minimum ionising $\mu^{\pm}$:
  - Peak: $n_e = 41/\text{cm}$
  - "Mean": $n_e = 72/\text{cm}$
  - The mean is ill-defined due to rare but large deposits.
- Recall:
  - dE/dx: $n_e = 160/\text{cm}$
  - Apparently, ionising takes more than the binding energy.



Лев Давидович Ландау
(1908-1968)

Energy loss fluctuations

- Given a single-collision energy loss distribution *w*(ϵ), the distribution *f*(ϵ) of the energy loss ϵ after many collisions is *schematically* given by the Laplace transform:

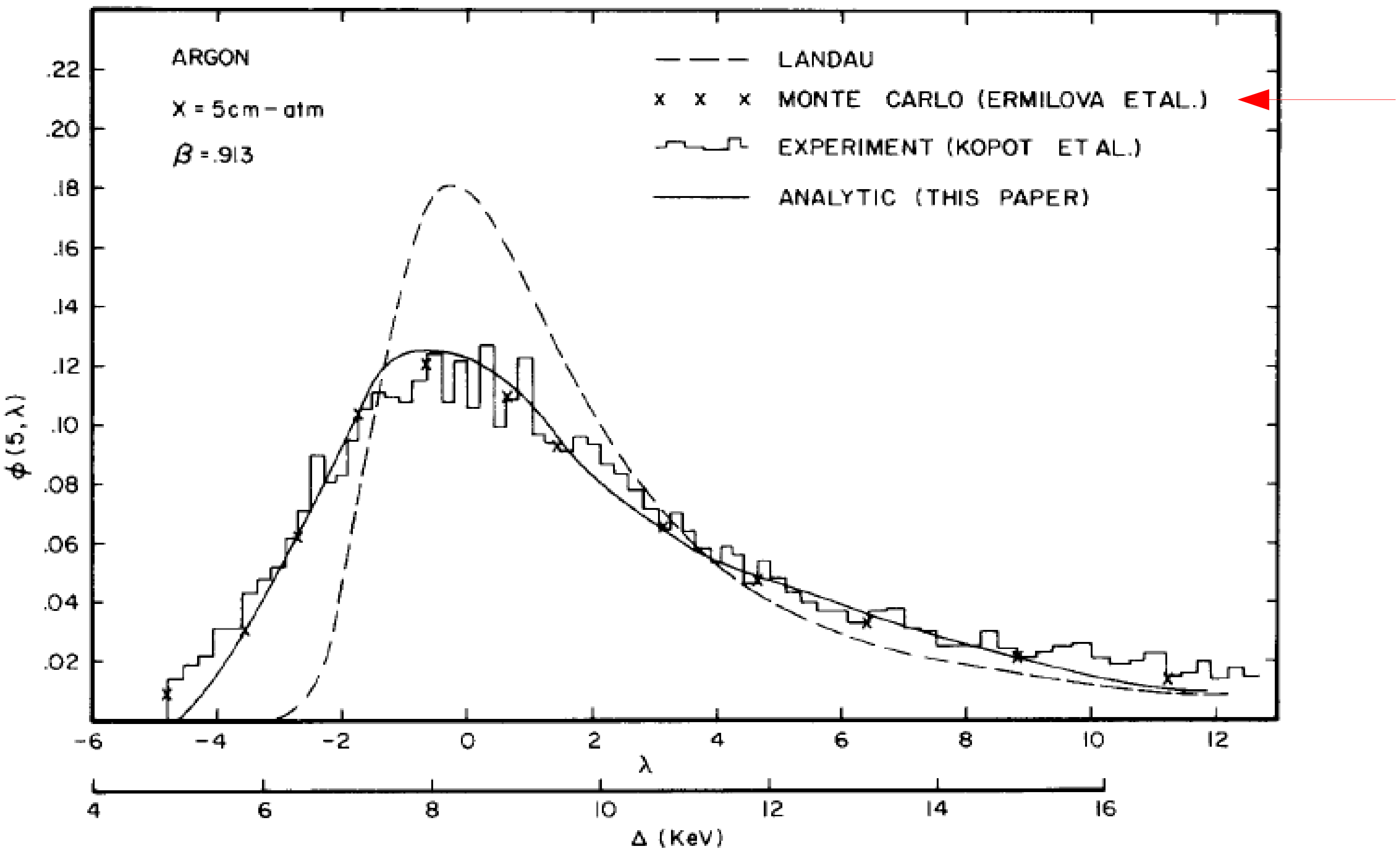
$$L\,f(x,s)=e^{-x\int_0^\infty (1-e^{-s\epsilon})\,w(\epsilon)\,d\epsilon}$$

- Ландау showed (1944), assuming in particular:
  - thick layers: numerous small energy losses;
  - Rutherford-inspired energy loss distribution $w(\epsilon) \sim 1/\epsilon^2$;
  - neglect of the atomic structure:

$$L\,f(s)\approx s^s$$

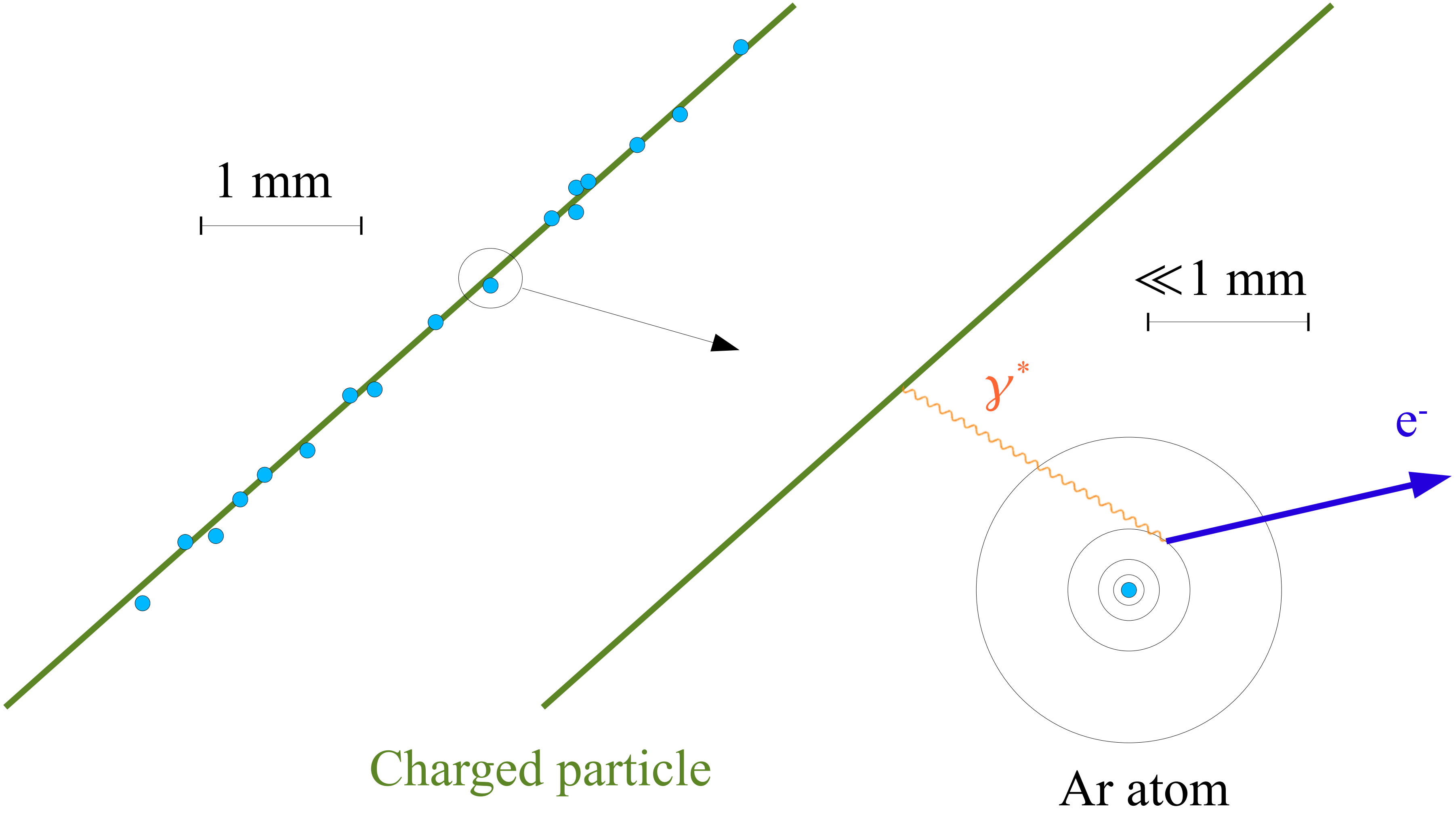
Is the Landau distribution appropriate ?

- 2 GeV protons on an (only !) 5 cm thick Ar gas layer:



[Diagram: Richard Talman, NIM A **159** (1979) 189-211]

Virtual photon exchange model



Basics of the PAI model


Wade Allison


John Cobb

- Key ingredient: photo-absorption cross section $\sigma_\gamma(E)$

$$\begin{aligned}\frac{\beta^2\pi}{\alpha}\frac{\mathrm{d}\sigma}{\mathrm{d}E} = {} & \frac{\sigma_\gamma(E)}{E}\log\left(\frac{1}{\sqrt{(1-\beta^2\epsilon_1)^2+\beta^4\epsilon_2^2}}\right)+ \\ & \frac{1}{N\hbar c}\left(\beta^2-\frac{\epsilon_1}{|\epsilon|^2}\right)\theta+ \\ & \frac{\sigma_\gamma(E)}{E}\log\left(\frac{2m_e c^2\beta^2}{E}\right)+ \\ & \frac{1}{E^2}\int_0^E \sigma_\gamma(E_1)\,dE_1\end{aligned}$$

Cross section to transfer energy E

Relativistic rise

Čerenkov radiation

Resonance region

Rutherford scattering

With:

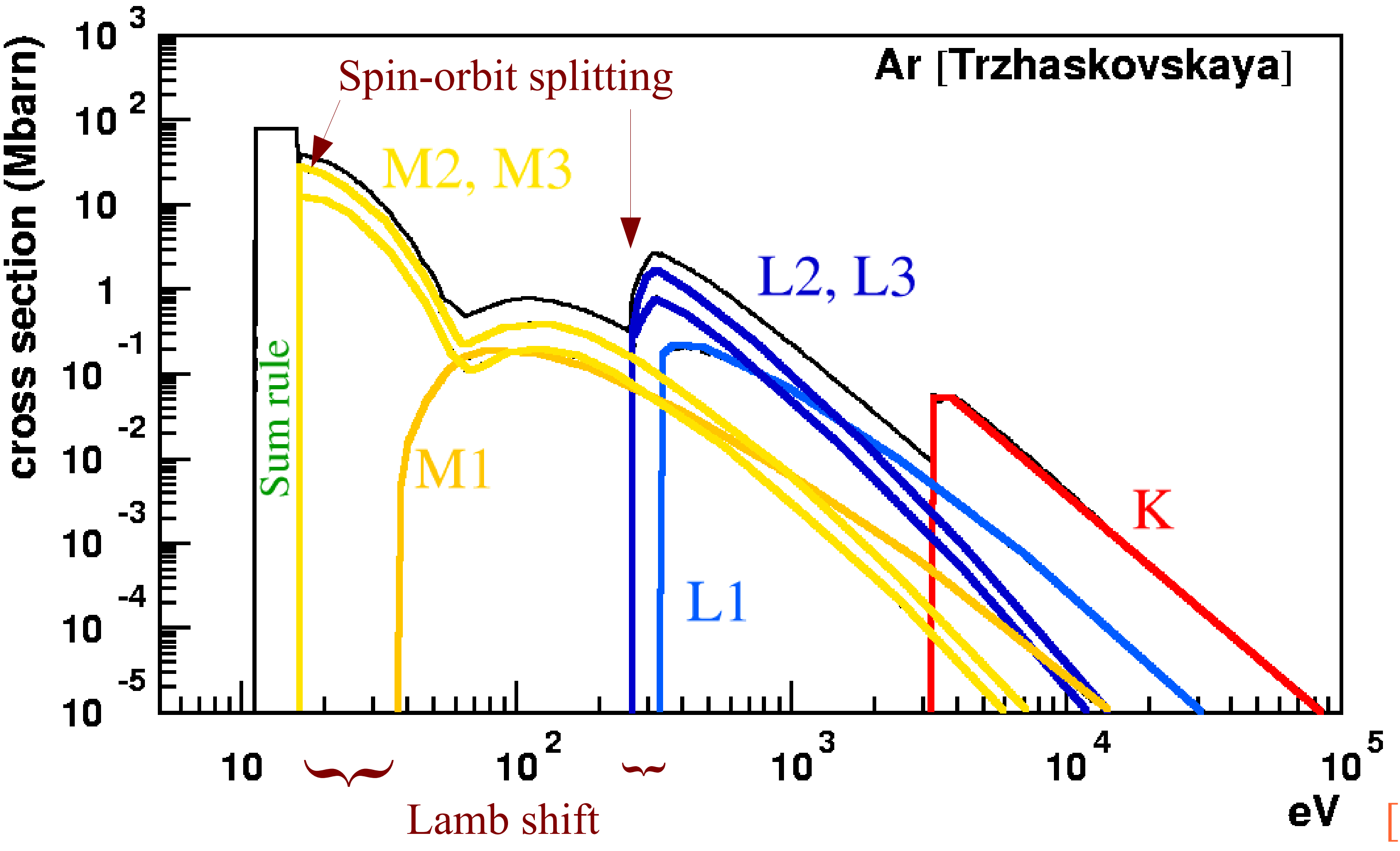
$$\epsilon_2(E)=\frac{N_e\hbar c}{EZ}\sigma_\gamma(E)$$

$$\epsilon_1(E)=1+\frac{2}{\pi}\mathrm{P}\int_0^\infty\frac{x\epsilon_2(x)}{x^2-E^2}\mathrm{d}x$$

$$\theta=\arg(1-\epsilon_1\beta^2+i\epsilon_2\beta^2)=\frac{\pi}{2}-\arctan\frac{1-\epsilon_1\beta^2}{\epsilon_2\beta^2}$$

Photo-absorption in argon

- Argon has 3 shells, hence 3 groups of lines:



[Plot from Igor Smirnov]

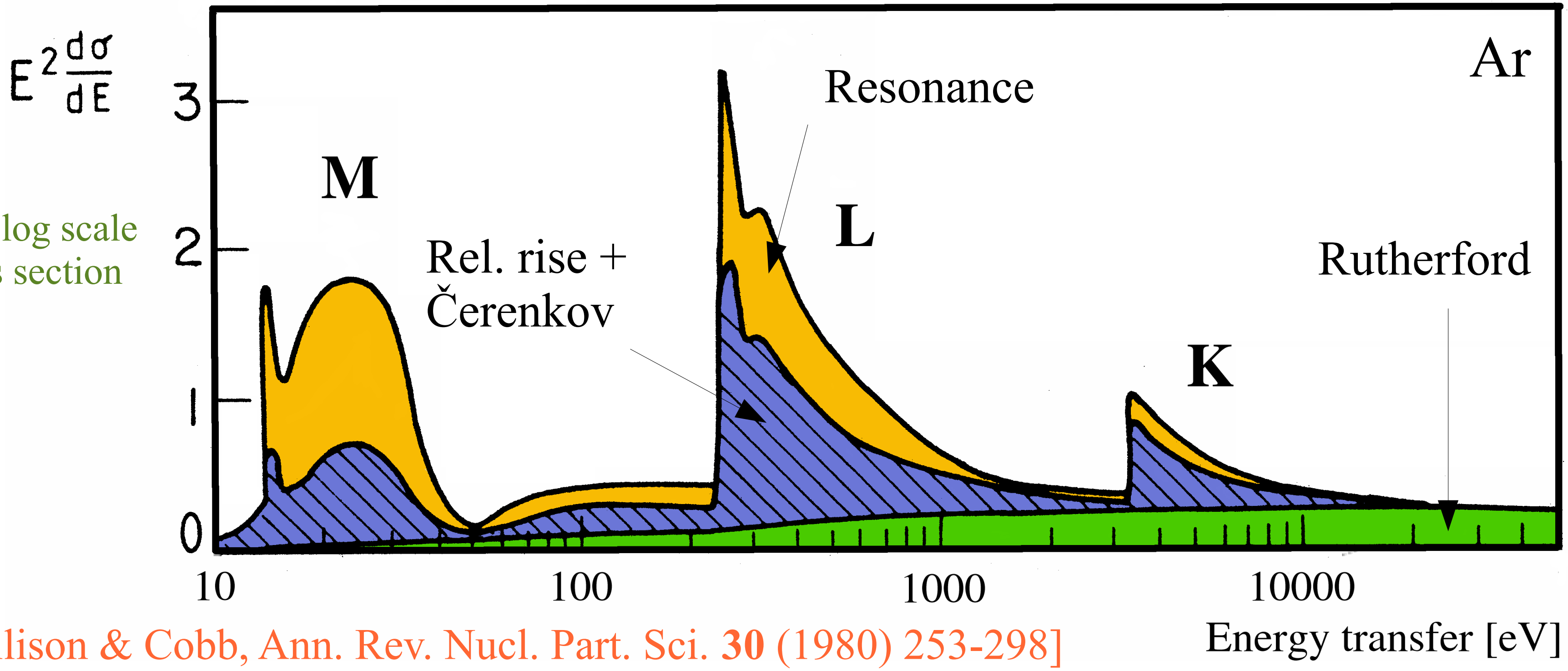
K = 1s

L1 = 2s
L2 = 2p 1/2
L3 = 2p 3/2

M1 = 3s
M2 = 3p 1/2
M3 = 3p 3/2

Importance of the PAI model terms

- All electron orbitals (shells) participate:
  - outer shells: frequent interactions, few electrons;
  - inner shells: few interactions, many electrons.
- All terms in the formula are important.



Scaling with E^2:
equal areas on log scale
weighing cross section

[Adapted from Allison & Cobb, Ann. Rev. Nucl. Part. Sci. **30** (1980) 253-298]

Heed

Igor Smirnov

- PAI model or absorption of real photons:

  Atom + π^- ➞ Ion^{+*} + π^- + e$^-$ (photo-electric effect,
  Atom + γ ➞ Ion^{+*} + e$^-$ real or virtual photon)

- Decay of excited states:

  Ion^{+*} ➞ Ion^{++} + e$^-$ (Auger)
  Ion^{+*} ➞ Ion^{+} + γ (fluorescence)
  Ion^{+*} ➞ Ion^{+*} (Coster-Kronig)

- Processing of electrons:
  - below ionisation energy → transport
  - photo- and Auger-electrons (“δ-electrons”):

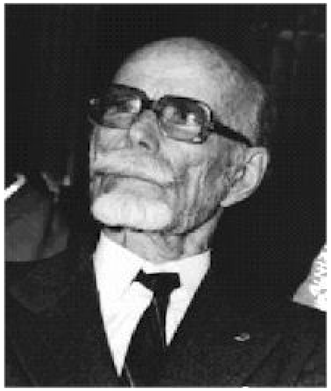
  e$^-$ + Atom ➞ Ion^{+} + 2 e$^-$ (absorption of high-energy electrons)

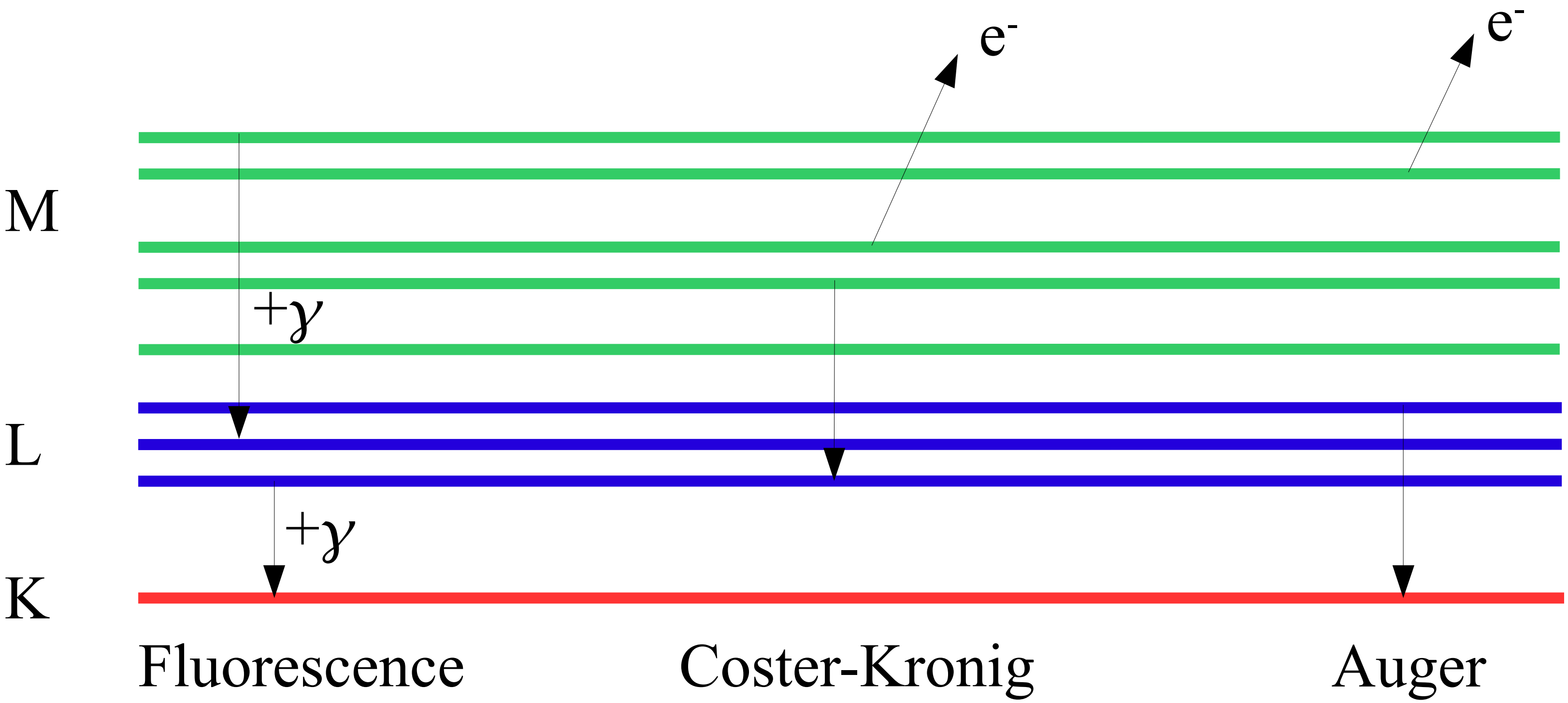
De-excitation


Ralph de Laer Kronig
(1904-1995)


Dirk Coster
(1889-1950)


Lise Meitner
(1878-1968)


Pierre Victor Auger
(1899-1993)



References:

D. Coster and R. de L. Kronig, Physica **2** (1935) 13-24.

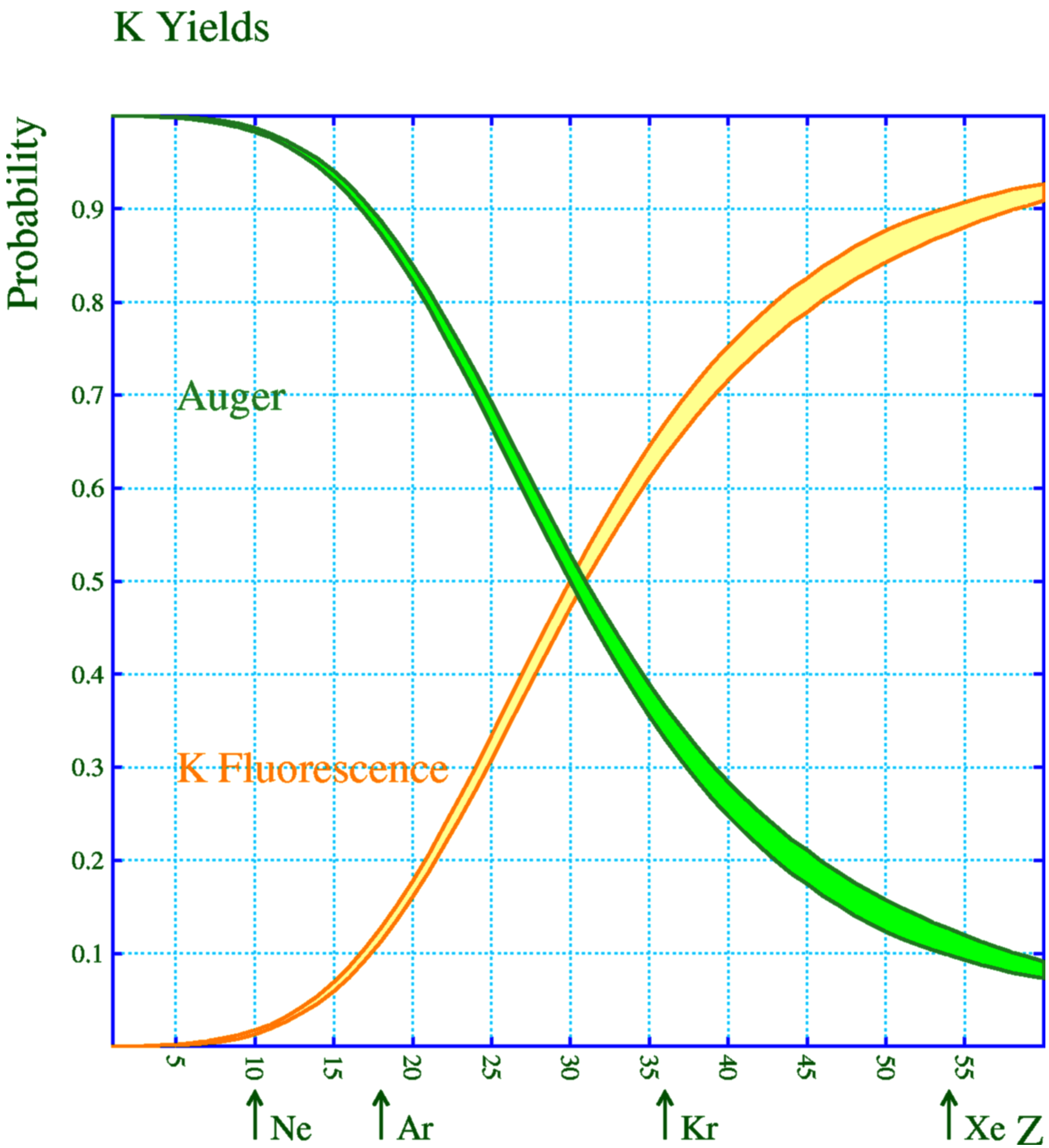
Lise Meitner, *Über die β-Strahl-Spektra und ihren Zusammenhang mit der γ-Strahlung*, Z. Phys. **11** (1922) 35-54.

L. Meitner, *Das β-Strahlenspektrum von UX_1 und seine Deutung*, Z. Phys. **17** (1923) 54-66.

P. Auger, J. Phys. Radium **6** (1925) 205.

K Yields

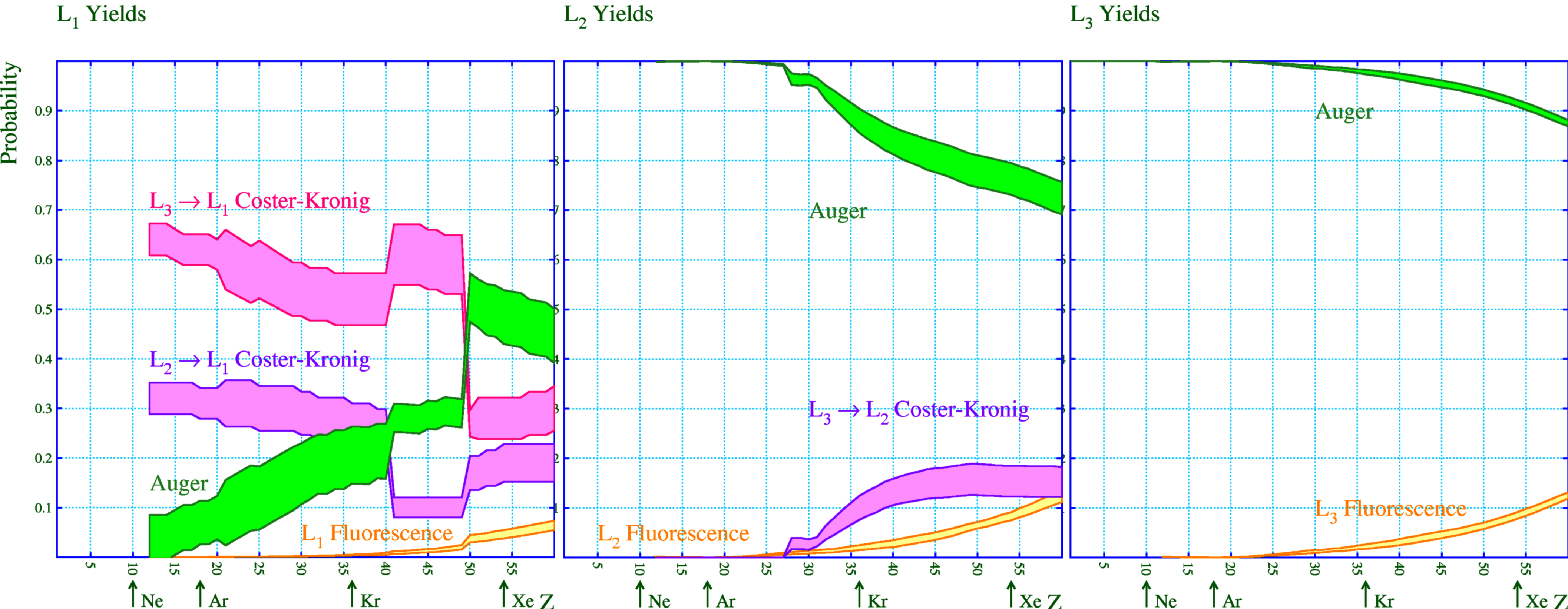
- Light atoms de-excite by Auger e^- emission, heavy atoms via fluorescence.
- Precision of the fluorescence yields:
  - Ar: ~5 %
  - Xe: ~1 %



[Source: US Nuclear Data Program, http://ie.lbl.gov/]

L Yields

- L_1 (rare): Coster-Kronig followed by Auger e^-.
- L_2 and L_3 (dominant): Auger e^- or fluorescence.
- Uncertainties: ± 15-20 % for Coster-Kronig and ± 20-30 % for fluorescence and Auger e^-.

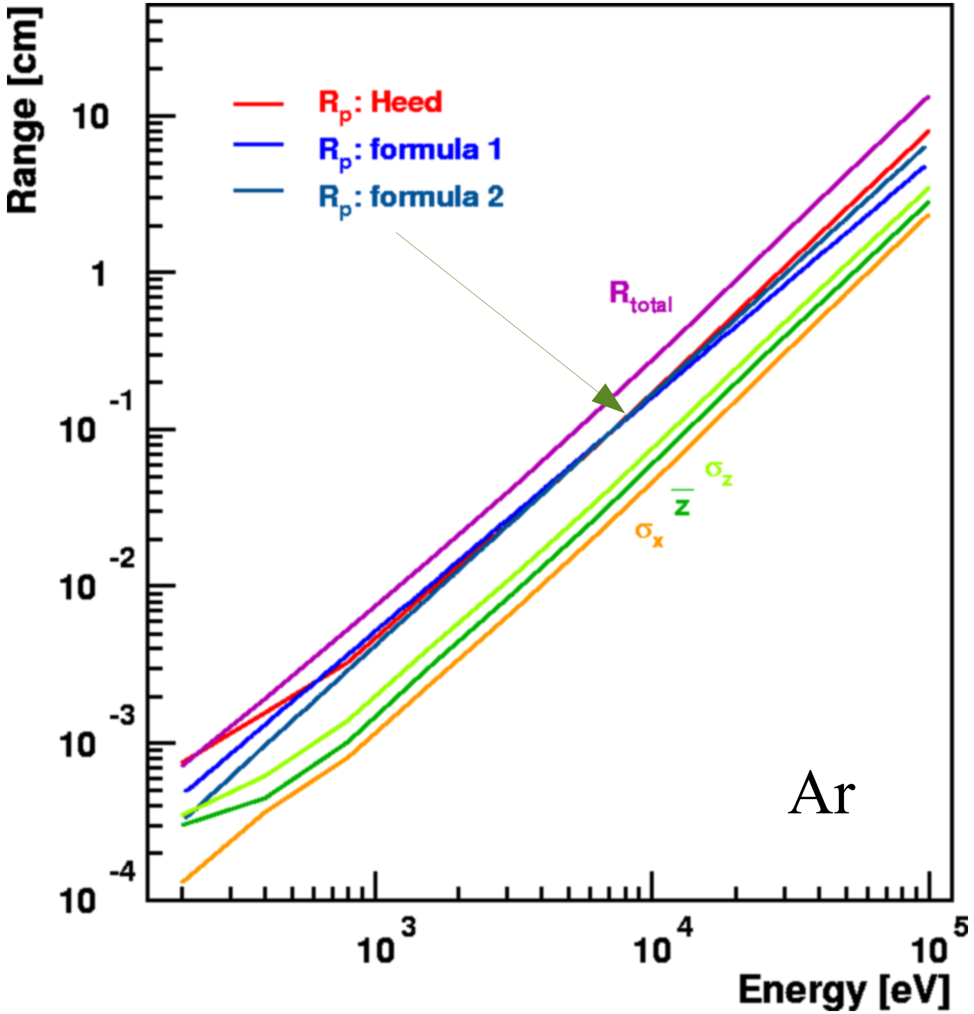


Absorbing photo- & Auger-electrons

- Both typically have enough energy to ionise:
  - $E_{\mathrm{pe}} = E_{\gamma} - E_{\mathrm{shell}}$,
  - $E_{\mathrm{Auger}} = E_{\mathrm{knock\text{-}out}} - E_{\mathrm{filling}} - E_{\mathrm{emitted}}$
- The energy is dissipated by scattering, excitation and ionisation of the outer shells, producing electrons serving for detection → transport. This consumes ~20-30 eV per electron produced – much more than the ionisation energy.
- In the process, δ-electrons are scattered extensively, leaving an erratic trace of ionisation electrons.

Range of photo- and Auger-electrons

- Electrons scatter in a gas.
- Measures of the range:
  - R_{total}: total path length
  - R_p: practical range
  - $\bar{z}$: cog in direction of initial motion
  - σ_z: RMS in direction of initial motion
  - σ_x: RMS transverse to initial motion



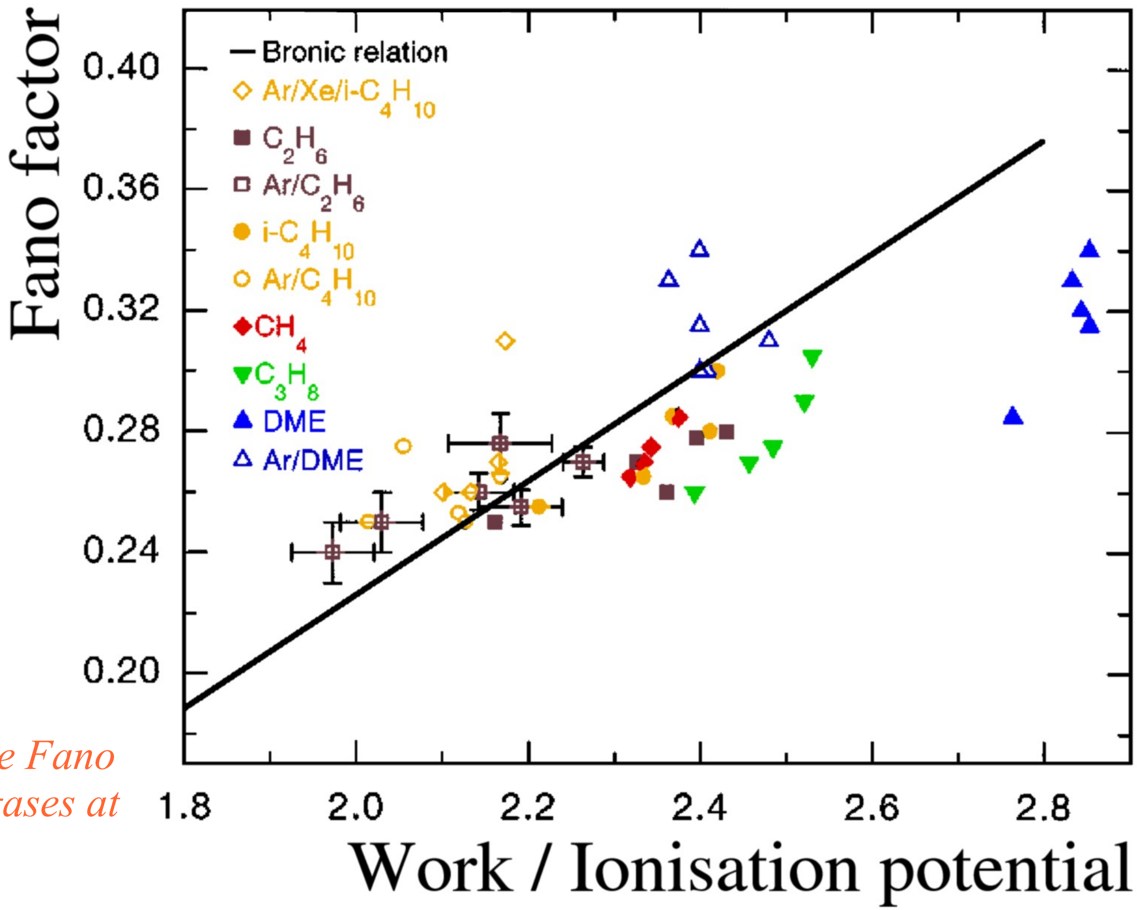
Practical range: distance at which the tangent through the inflection point of the descending portion of the depth- absorbed dose curve meets the extrapolation of the Bremsstrahlung background (ICRU report 35, 1984)

Energy per electron

- Data and calculations exist, but the spread (≈10 %) is larger than the measurement errors (1-4 %).

Gas	*w* [eV]	*F*
He	41.3-43.3	0.21
Ne	35.4	0.13
Ar	26.3-26.4	0.16
Kr	24.4	0.17-0.19
Xe	21.9-22.1	0.13-0.17
CO_2	33.0-37.2	0.33
CH_4	34.3	0.265-0.285
C_2H_6	11.5	0.250-0.280
iC_4H_{10}	10.6	0.255-0.300

[Plot from: A. Pansky, A. Breskin and R. Chechik, *The Fano factor and the mean energy per ion-pair in counting gases at low X-ray energies,* J. Appl. Phys. **82** (1997) 871.]



Summary: charged particle + gas

- Charged particles ionise gas molecule through electromagnetic interactions.

- Outer shells interactions are most frequent, but with little energy exchange. The converse goes for inner shells. At the end of the day, they all matter.

- Energy transfer comparable with the atomic binding energy: i.e. typically between eV and keV.

Phase 2: Transport of electrons

- We have typically ~ 40 electrons/cm in the gas to reconstruct the charged particle's trajectory with.
  - As long as they stand still, they are invisible, and they will eventually recombine with an ion;
  - we make them move by means of an electric field;
  - moving charges induce currents which we can try and measure.

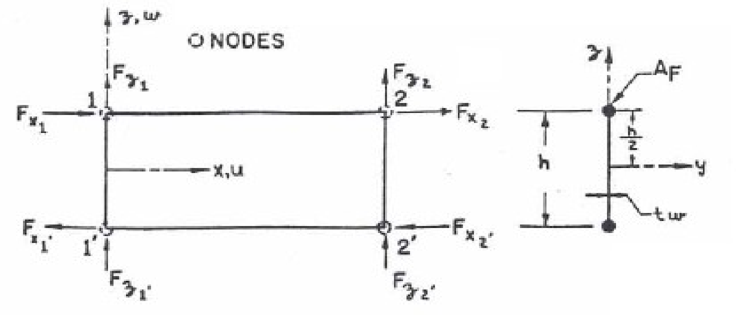
Field calculation techniques

- Analytic calculations:
  - almost all 2d structures made of wires, planes !
  - fast and precise, if applicable.
- Finite elements:
  - 2d and 3d structures, with or without dielectrics;
  - several major intrinsic shortcomings.
- Boundary element methods or Integral equations:
  - equally comprehensive with fewer intrinsic flaws;
  - technically more challenging and emerging.
- Finite differences:
  - still used for iterative, time-dependent calculations.

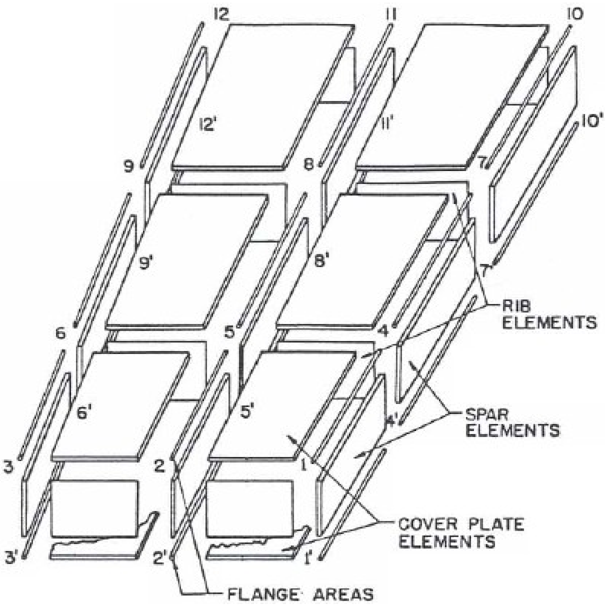
Ιωα′ννης Αργυ′ρης
(1913-2004)

Aircraft wings – finite elements

- “*Stiffness and Deflection Analysis of Complex Structures*”, a study in the use of the finite element technique (then called “direct stiffness method”) for aircraft wing design.



$$[K] = \frac{6EI}{Lh^2(1+4n)} \begin{array}{c} \begin{array}{cccccc} u_1 & v_1 & w_1 & u_2 & v_2 & w_2 \end{array} \\ \begin{bmatrix} (4/3)\,(1+n) & & & & & \\ 0 & 0 & & & & \\ -(h/L) & 0 & h^2/L^2 & & & \\ (2/3)\,(1-2n) & 0 & -(h/L) & (4/3)\,(1+n) & & \\ 0 & 0 & 0 & 0 & 0 & \\ h/L & 0 & -(h^2/L^2) & h/L & 0 & h^2/L^2 \end{bmatrix} \end{array}$$



[M.J. Turner, R.W. Clough, H.C. Martin and L.J. Topp, *Stiffness and Deflection Analysis of Complex Structures*, J. Aero. Sc. **23** (1956), 805-824. MJT & LJT with Boeing.]

The price to pay for finite elements

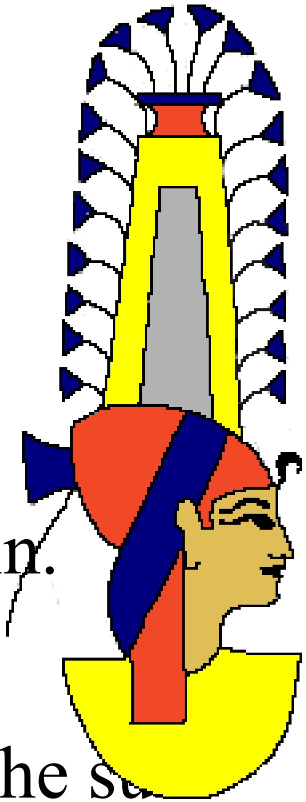
- Finite element programs are flexible but they focus on the wrong thing: they solve V well, but we do not really need it:
    - quadratic shape functions do a fair job at approximating $V \approx \log(r)$ potentials;
    - potentials are continuous.
- E is what we use to transport charges, but:
    - gradients of quadratic shape functions are linear and not suitable to approximate $E \approx 1/r$, left alone $E \approx 1/r^2$ fields;
    - electric fields are discontinuous at element boundaries;
    - a local accuracy of ~50 % in high-field areas is not unusual.

Continuity: the *E* field

- The *E* field look like the roofs of Nice: locally linear, and discontinuous.

Photo from: `http://www.06nice.com/somvol/fotaer/gfoaer.htm`

Boundary element methods



- Contrary to the finite element method, the elements are on the boundaries, not inside the problem domain. Charges are computed for the boundary elements.
- The fields in the problem domain are calculated as the su of Maxwell-compliant field functions, not polynomials, extending over the entire problem domain. There are therefore no discontinuities.
- In contrast, the method poses substantial numerical challenges: non-sparse matrices and inherent singularities.