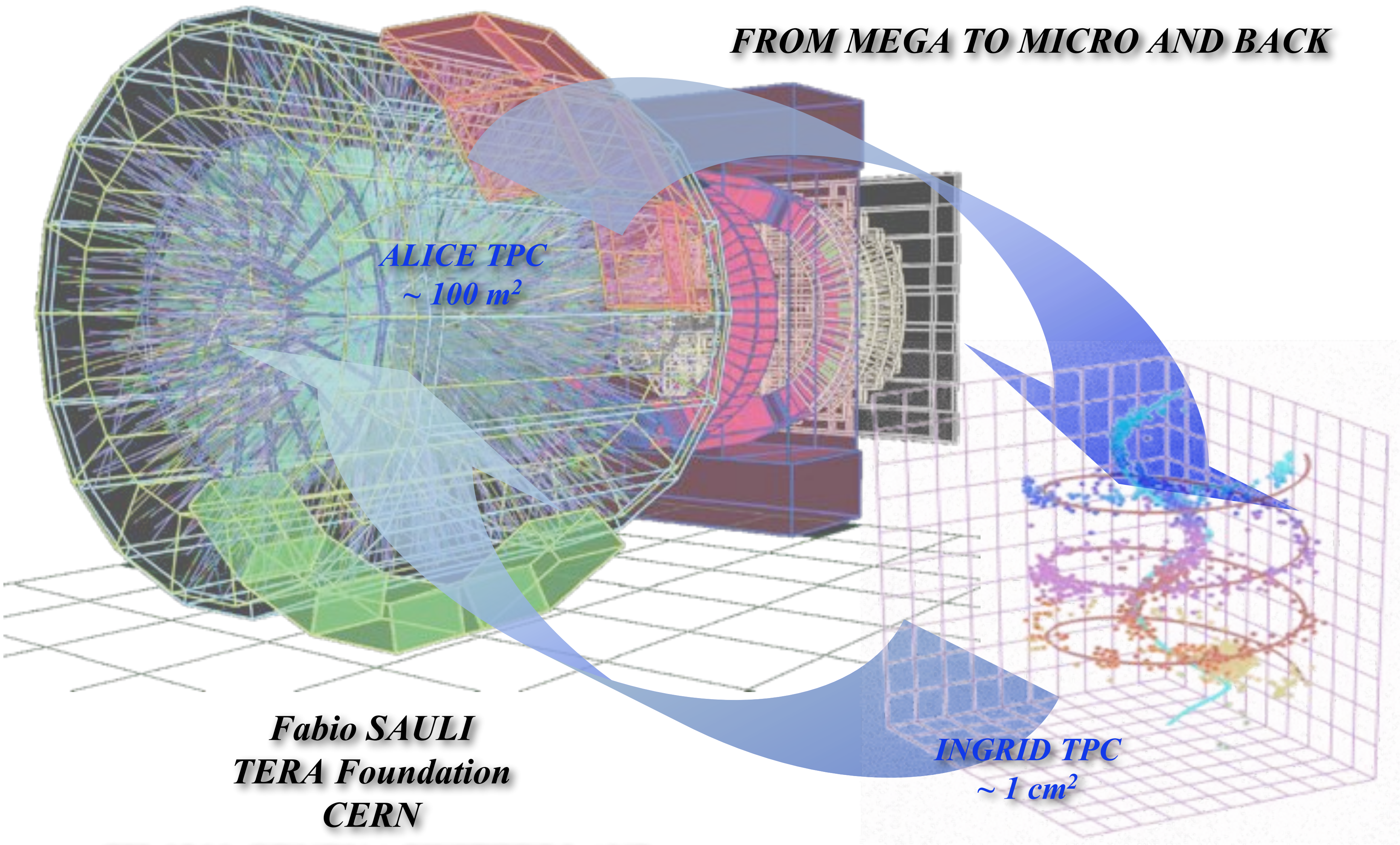
MICRO-PATTERN GAS DETECTORS

FROM MEGA TO MICRO AND BACK



Fabio SAULI
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MICRO-PATTERN GAS DETECTORS

PART ONE: BASIC PRINCIPLES

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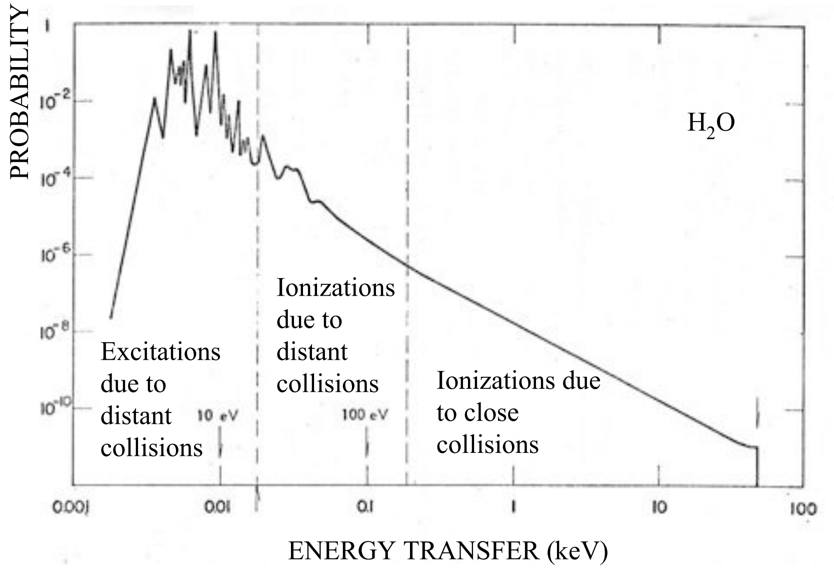
PRIMARY INTERACTIONS



ELECTROMAGNETIC (COULOMB) INTERACTIONS:
Elastic collisions, Excitations, Ionizations

PHYSICAL PROPERTIES OF GASES AT STP:

Differential energy loss, primary and total ionization for minimum ionizing, z=1 particles

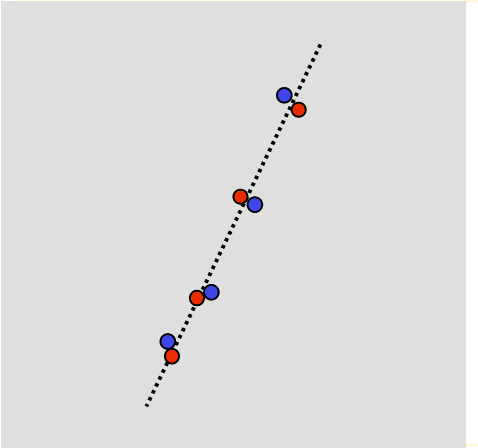
Gas	Density, mg cm^{-3}	E_x eV	E_I eV	W_I eV	$dE/dx\|_{min}$ keV cm^{-1}	N_P cm^{-1}	N_T cm^{-1}
Ne	0.839	16.7	21.6	30	1.45	13	50
Ar	1.66	11.6	15.7	25	2.53	25	106
Xe	5.495	8.4	12.1	22	6.87	41	312
CH_4	0.667	8.8	12.6	30	1.61	37	54
C_2H_6	1.26	8.2	11.5	26	2.91	48	112
iC_4H_{10}	2.49	6.5	10.6	26	5.67	90	220
CO_2	1.84	7.0	13.8	34	3.35	35	100
CF_4	3.78	10.0	16.0	54	6.38	63	120

E_x, E_i : first excitation and ionization potentials
w_i: average energy per ion pair
N_P , N_T : primary and total ion pairs/cm²

The Review of Particle Physics C. Amsler et al.,Physics Letters B667 (2008) 1

http://pdg.lbl.gov/

PRIMARY IONIZATION



$$P_k^n = \frac{n^k}{k!} e^{-n}$$ n: average k: actual number

Minimum ionizing particles in Argon STP:

dE/dx: 2.4 keV/cm n_P: 25 ion pairs/cm

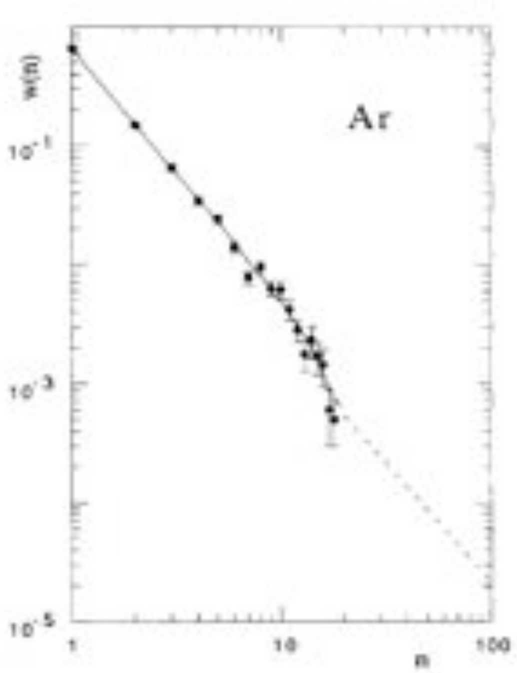
Detection efficiency:

$$\varepsilon = 1 - P_0^n = 1 - e^{-n}$$

Argon NTP:

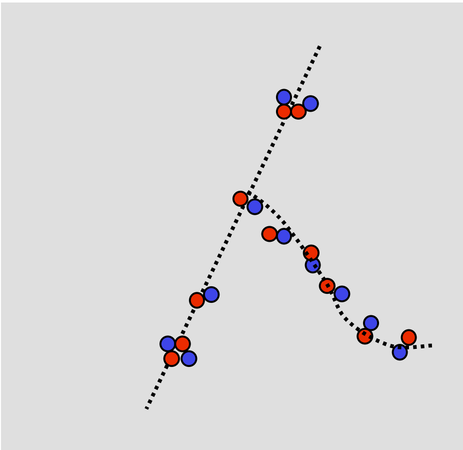
s (mm)	ε (%)
1	91.8
2	99.3

CLUSTER SIZE PROBABILITY :



H. Fischle et al, Nucl. Instr. and Meth. A301 (1991) 202

TOTAL IONIZATION:
Clusters and delta electrons



Total number of ion pairs:

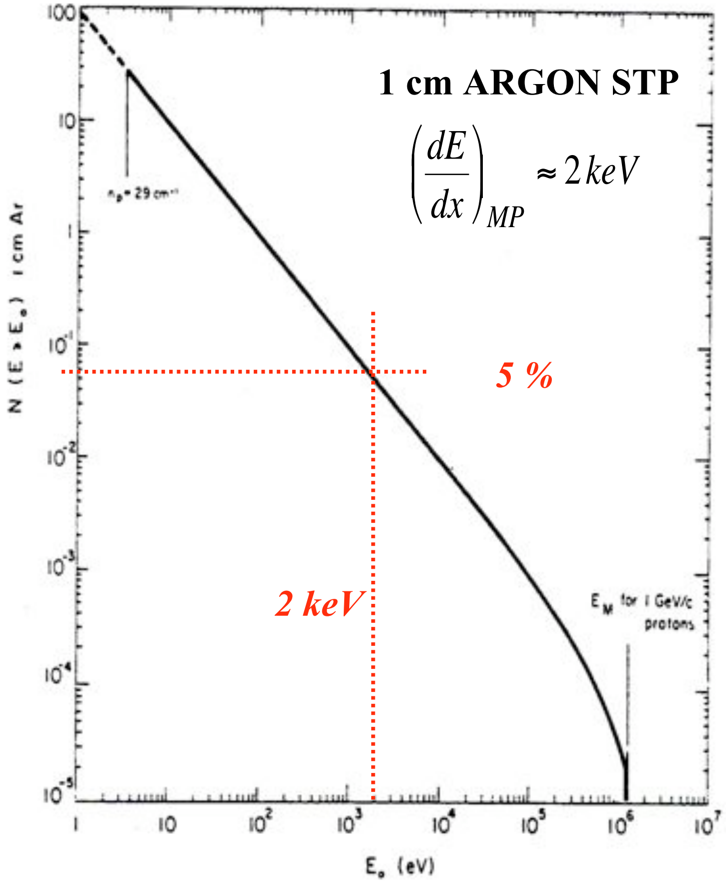
$$n_T = \frac{\Delta E}{w_i}$$

For minimum ionizing particles in Argon:

ΔE = 2.4 keV/cm
w_i = 26 eV
$n_T \approx$ 90 ip/cm

$$\frac{n_T}{n_P} \approx 3$$

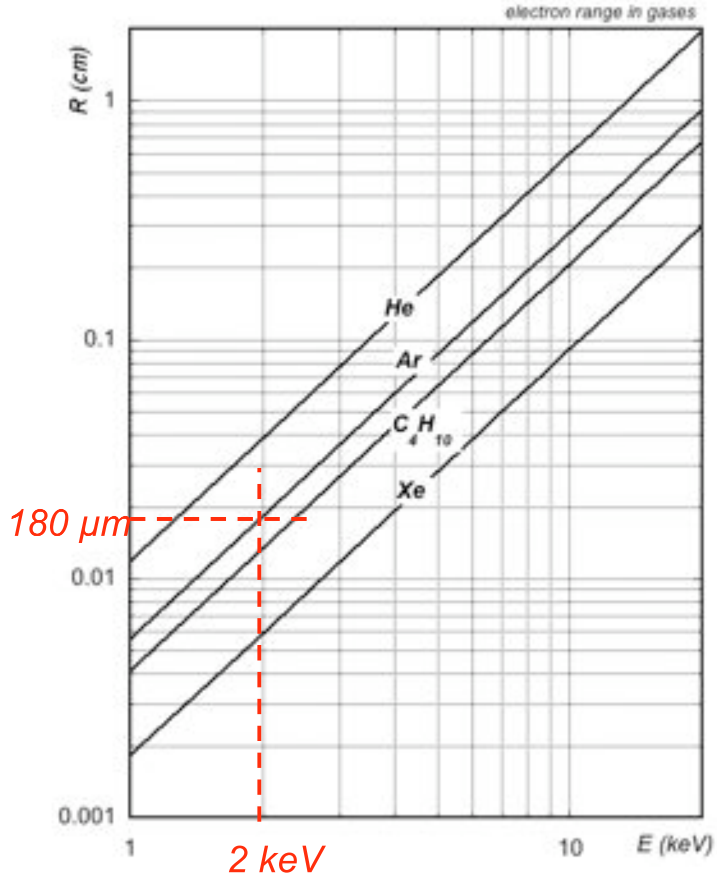
ELECTRONS ENERGY DISTRIBUTION:



$$N(E \geq E_0) \cong \frac{W}{E_0} \qquad W = K\frac{Z}{A}\rho x$$

K= 0.154 MeV cm^2/g
ρ: density (g/cm^3) x: material thickness (cm)

ELECTRON RANGE IN GASES AT STP:



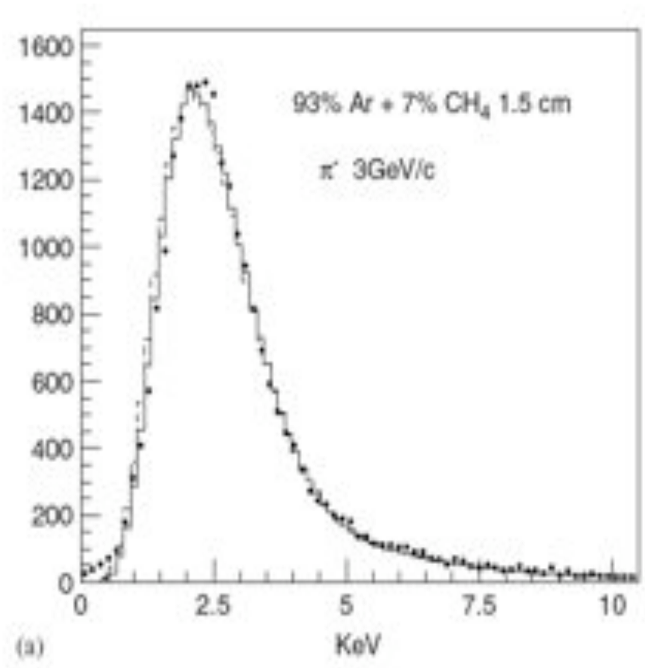
$$R \approx \frac{1}{\rho} 10\, E^{1.7}$$

R : range in cm
E : electron energy in keV
ρ : density in µg cm^{-3}

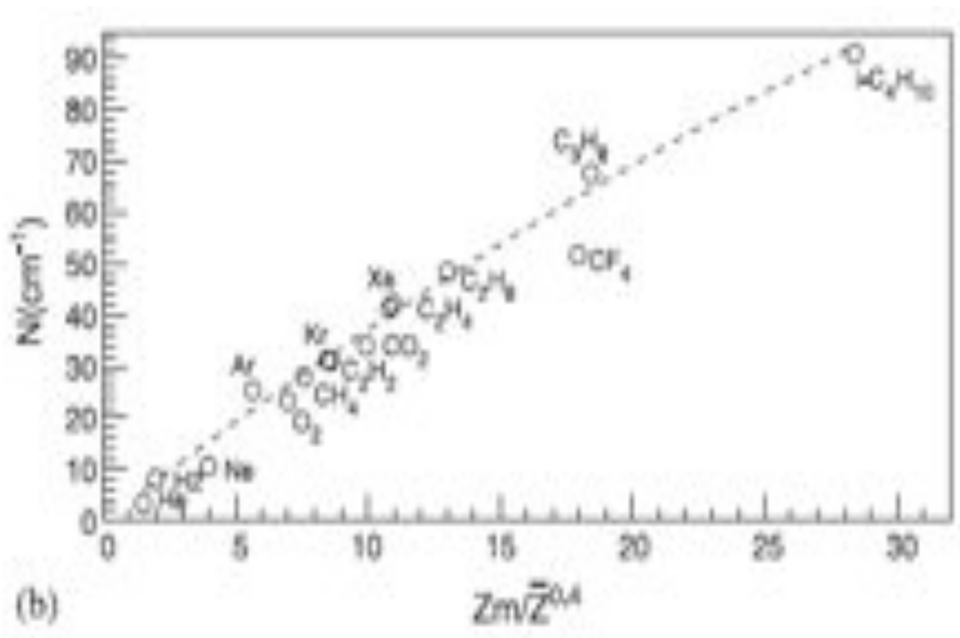
http://physics.nist.gov/PhysRefData/Star/Text/contents.html

MONTECALO CALCULATION OF IONIZATION ENERGY LOSS OF IONIZING PARTICLES

ENERGY LOSS: (dots: experiment)



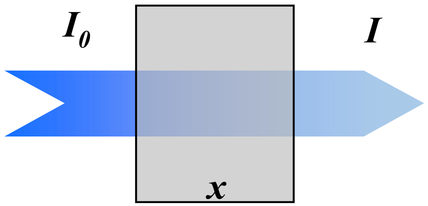
PRIMARY CLUSTERS PER cm (STP):



I. B. Smirnov, Nucl. Instr. and Meth. A554(2005)474

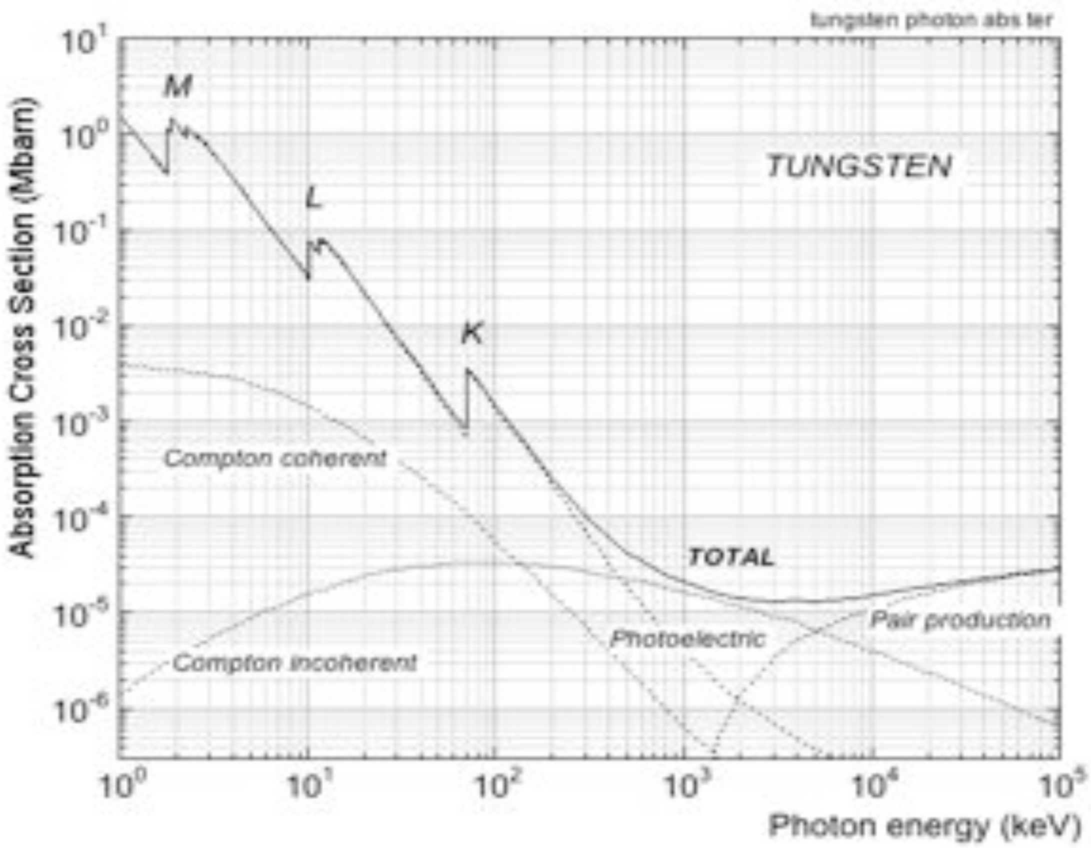
http://consult.cern.ch/writeup/heed/

PHOTON ABSORPTION



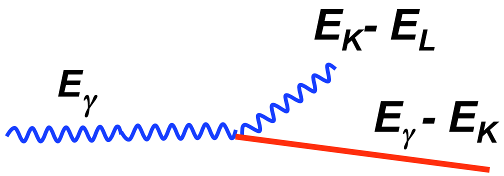
$$I = I_0 \, e^{-\frac{x}{\lambda}} \qquad \lambda = \frac{1}{N\sigma}$$

x : material thickness (cm)
λ : linear absorption length (cm)
σ : cross section (cm^2)
N : molecules/cm^3

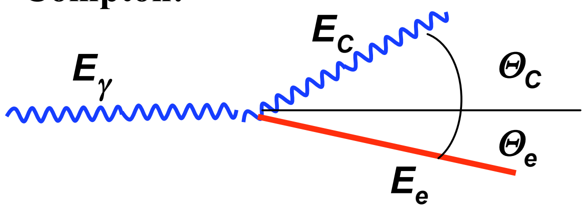


A. Thompson et al, X-RAY DATA BOOKLET (2001)

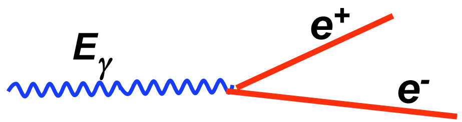
Potoelectric:



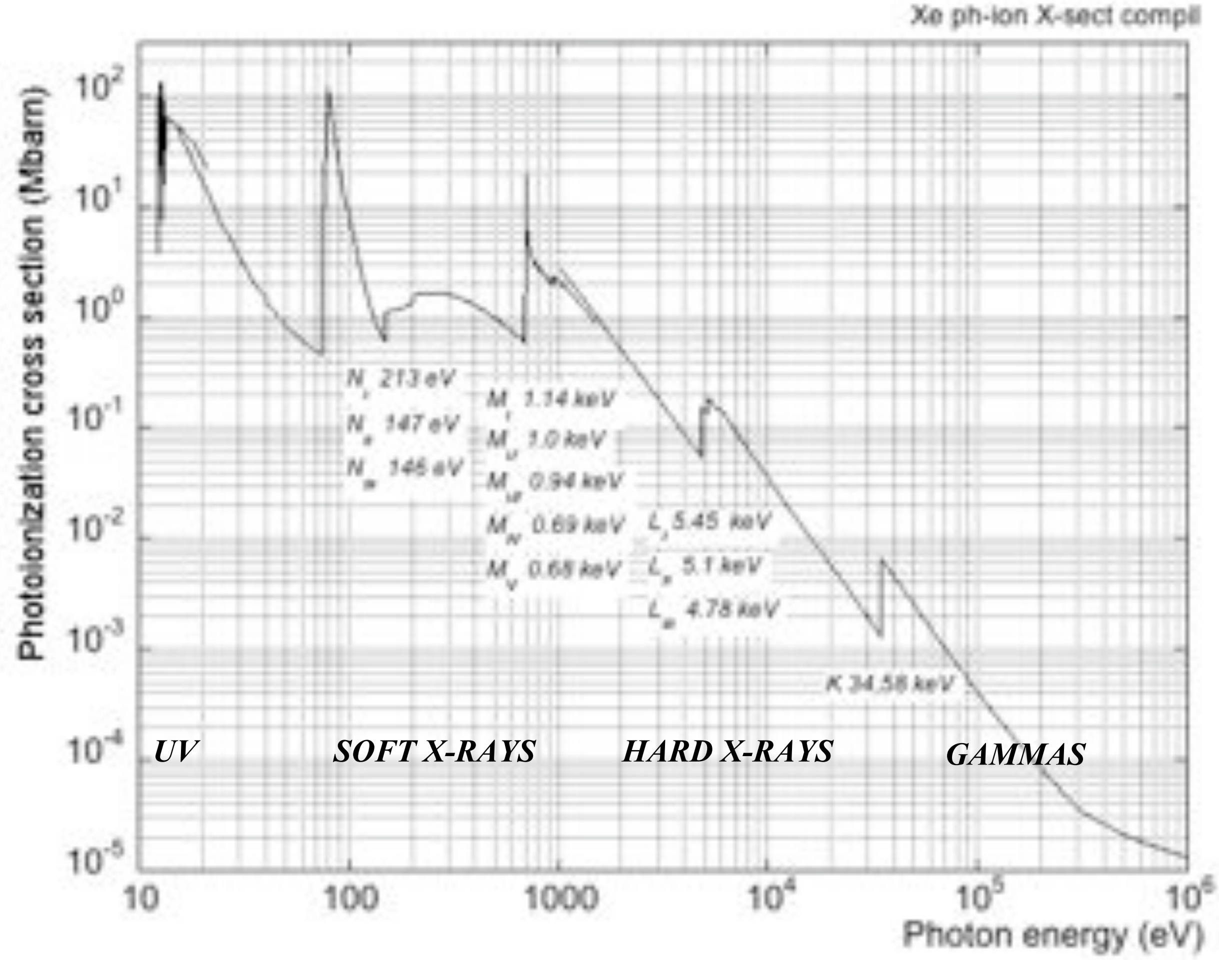
Compton:



Pair Production:



PHOTOIONIZATION CROSS SECTION FOR XENON:

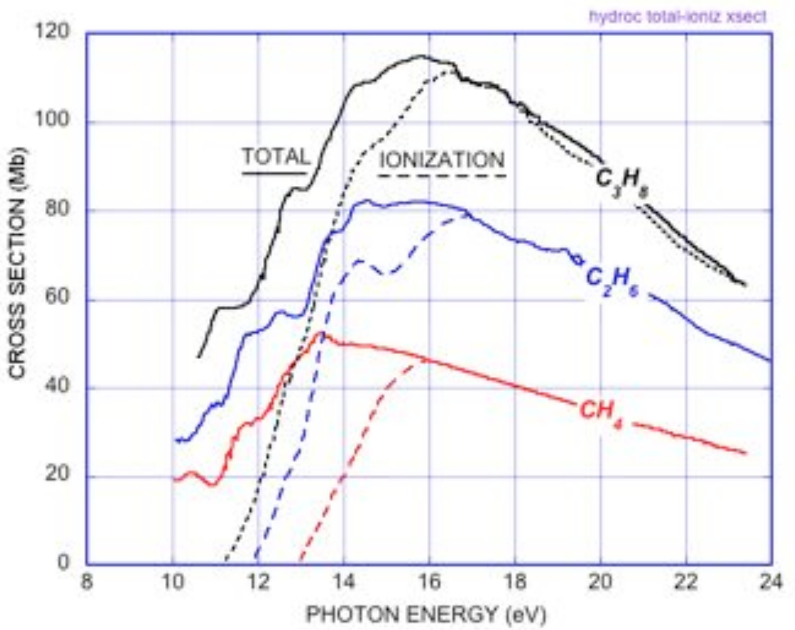


http://xdb.lbl.gov/

http://henke.lbl.gov/optical_constants/

http://physics.nist.gov/PhysRefData/FFast/html/form.html

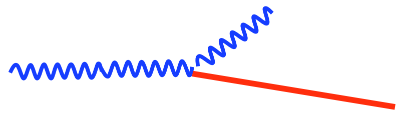
TOTAL AND PHOTOIONIZATION CROSS SECTIONS:

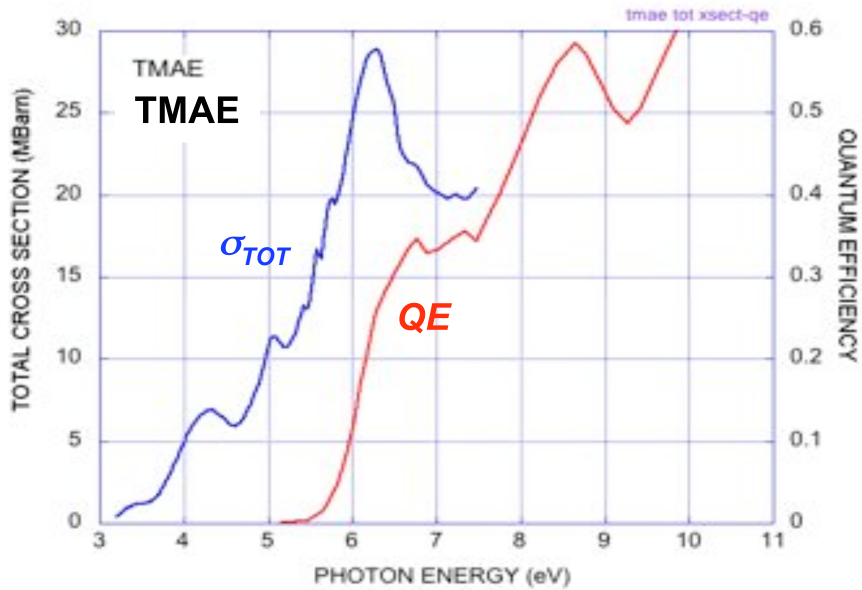


	E_I (eV)
C_6H_6	9.3
TEA	7.45
TMAE	5.6

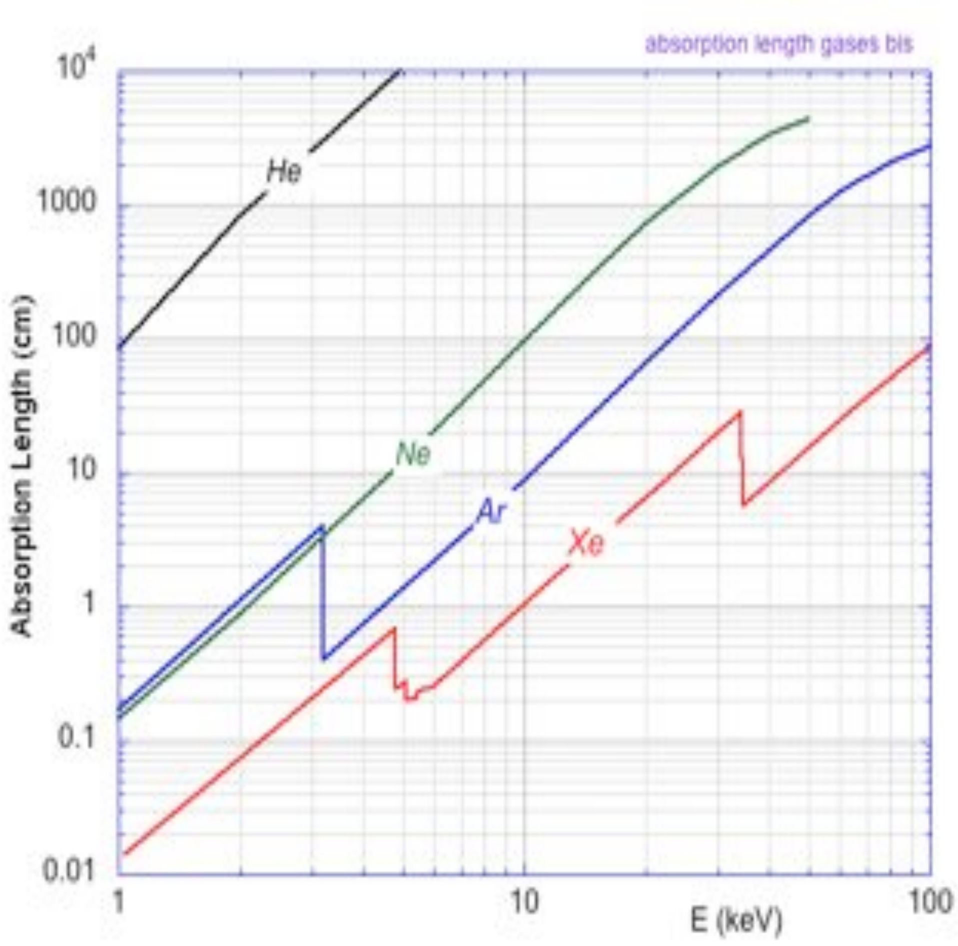
TEA: Triethylamine $(C_2H_5)_3N$
TMAE: Tetrakis-dimethylamino ethylene $[(CH_3)_2N]_2C$

PHOTOELECTRIC EFFECT:





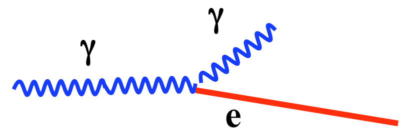
ABSORPTION LENGTH IN GASES AT NTP



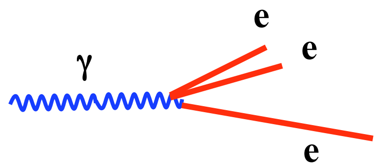
For gases at STP (0°C, 1 Atm): N=2.687 10^{19} cm^{-3}

$$\lambda(cm) = \frac{1}{26.87\,\sigma(MBarns)}$$

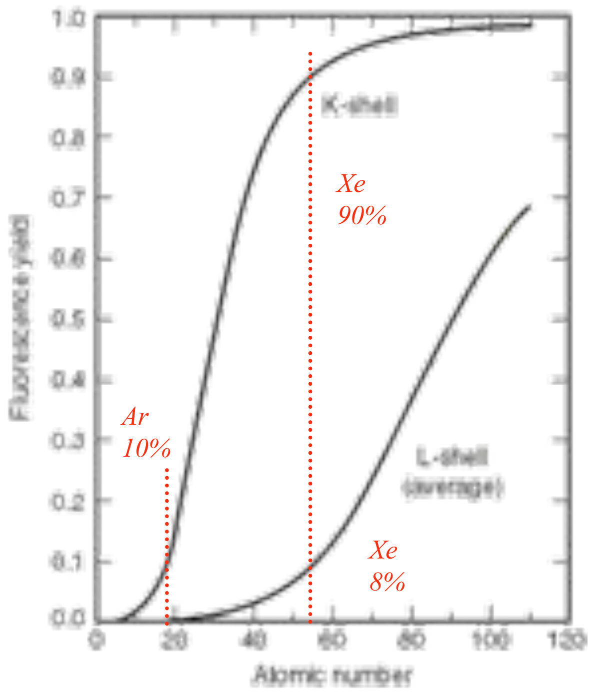
FLUORESCENCE:



NON-RADIATIVE (AUGER):

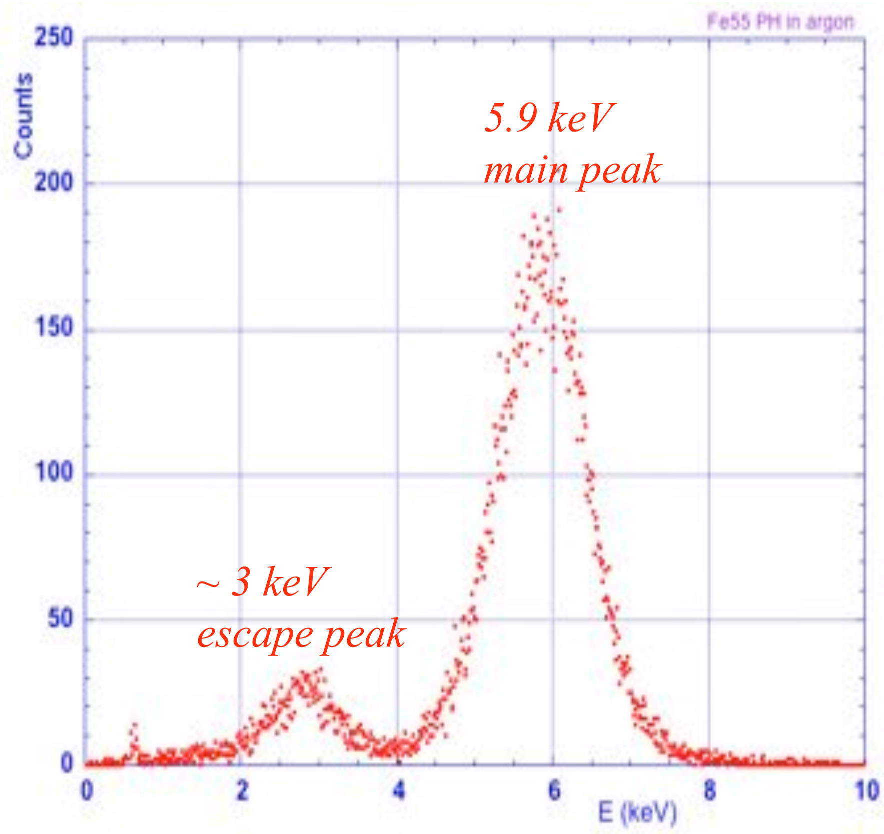


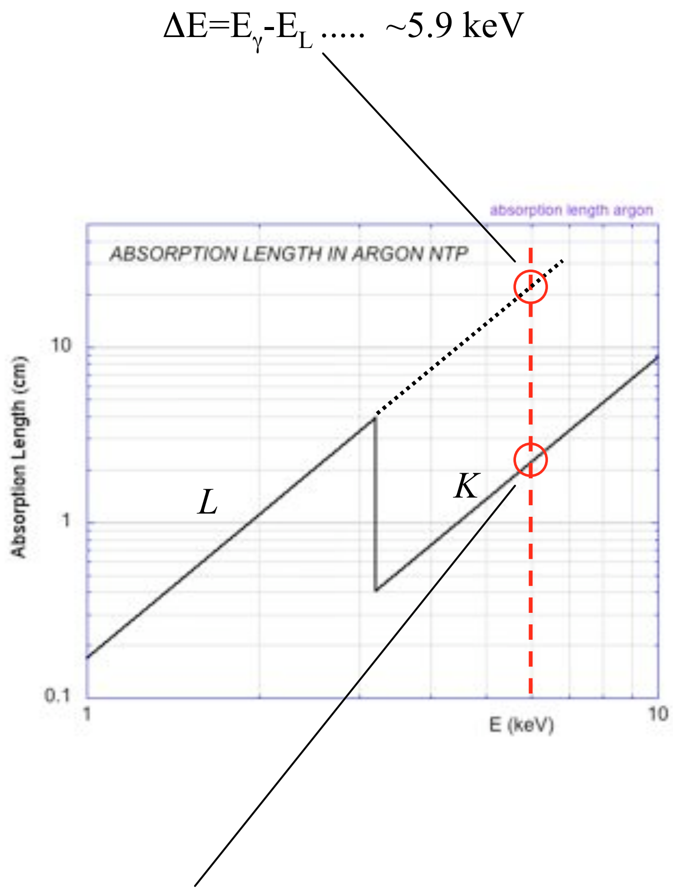
FLUORESCENCE YIELD $= \dfrac{N_{FL}}{N_{FL} + N_{NR}}$



M. O. Krause, J. Phys. Chem. Ref. Data 8 (1979) 307

X-RAY ABSORPTION SPECTRUM
^{55}Fe X-Rays (5.9 keV) in Argon:

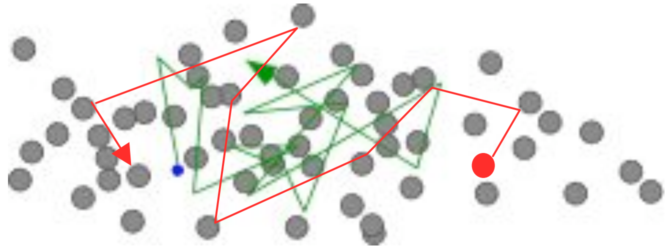


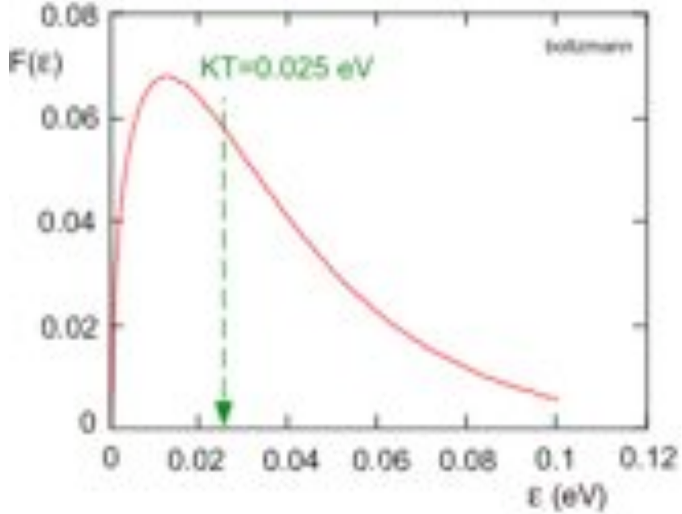


Auger: E~5.9 keV
Fluorescence: reconverted E~5.9 keV
escaped E~3.2 KeV

E = 0

THERMAL DIFFUSION (Ions and electrons):

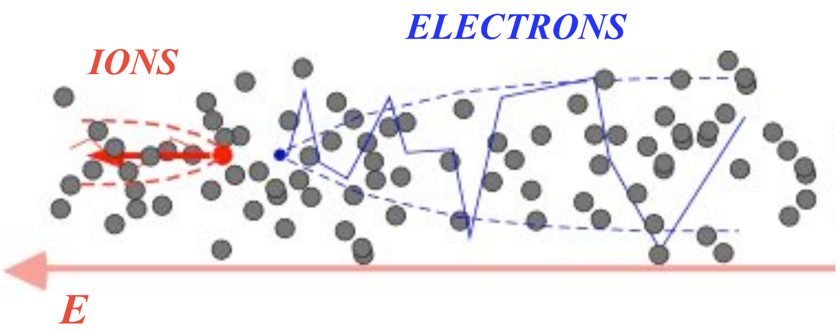


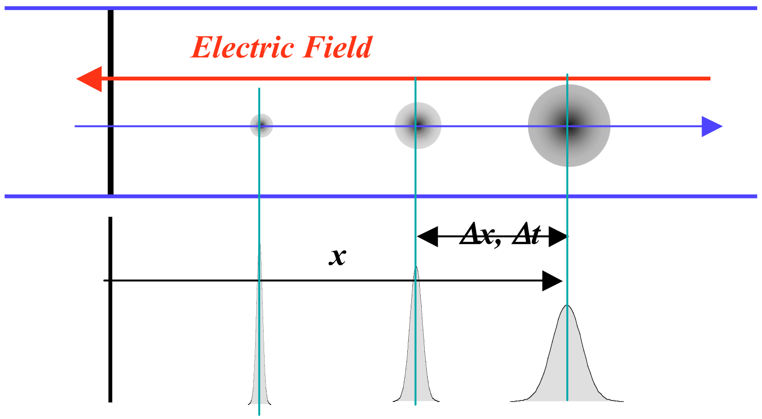


Maxwell energy distribution: $F(\varepsilon) = C\sqrt{\varepsilon}\, e^{-\frac{\varepsilon}{KT}}$

E > 0

CHARGE TRANSPORT AND DIFFUSION





Drift velocity: $w = \frac{\Delta x}{\Delta t}$

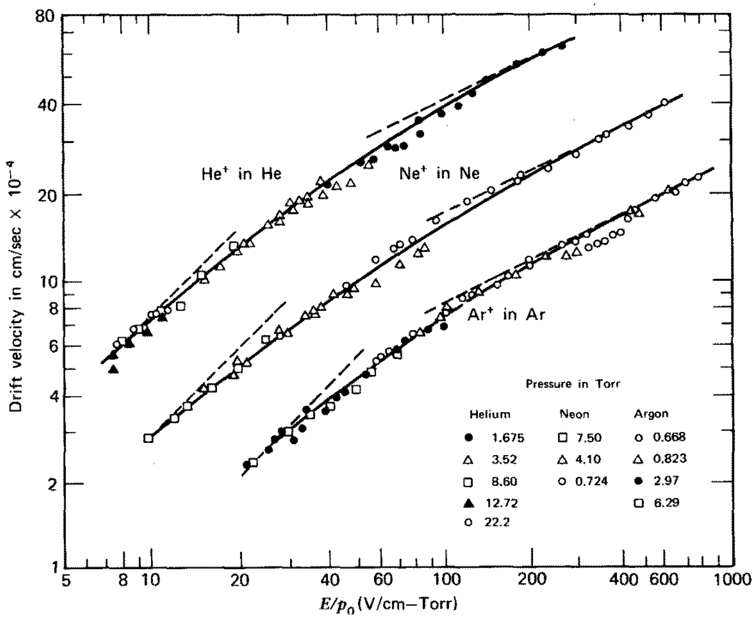
Diffusion: $\sigma = \sqrt{2Dt} = \sqrt{2D\frac{x}{w}}$

IONS DRIFT VELOCITY

Mobility: $\mu^{+} = w^{+}/E$

GAS	ION	$\mu^{+}(cm^2s^{-1}V^{-1})$
He	He^{+}	10.2
Ar	Ar^{+}	1.7
CH_4	CH_4^{+}	2.26
CO_2	CO_2^{+}	1.09

$$\mu(P,T) = \frac{T}{T_0}\frac{P_0}{P}\mu(P_0,T_0)$$

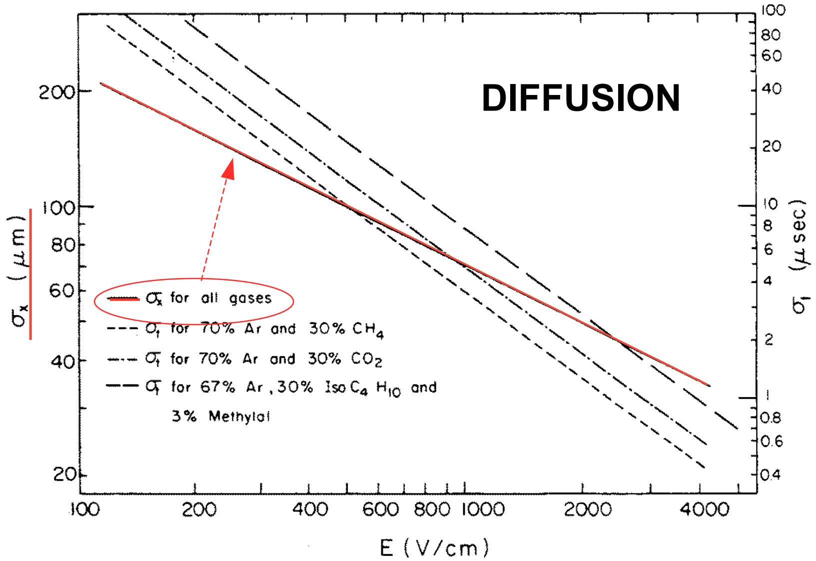


IONS DIFFUSION

$$\sigma_x = \sqrt{2Dt}$$

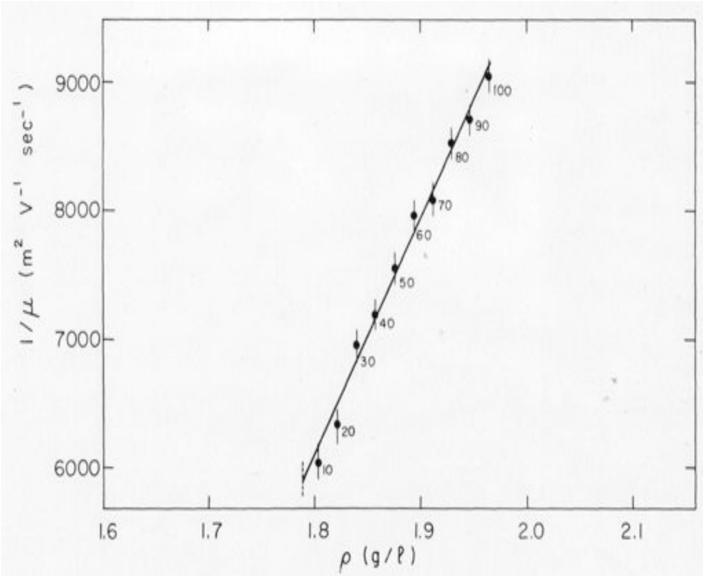
Einstein's law:

$$\frac{D}{\mu} = \frac{KT}{e} \qquad \sigma_x = \sqrt{\frac{2KT}{e}\frac{x}{E}}$$



E. McDaniel and E. Mason,
The Mobility and Diffusion of Ions in Gases (Wiley 1973)

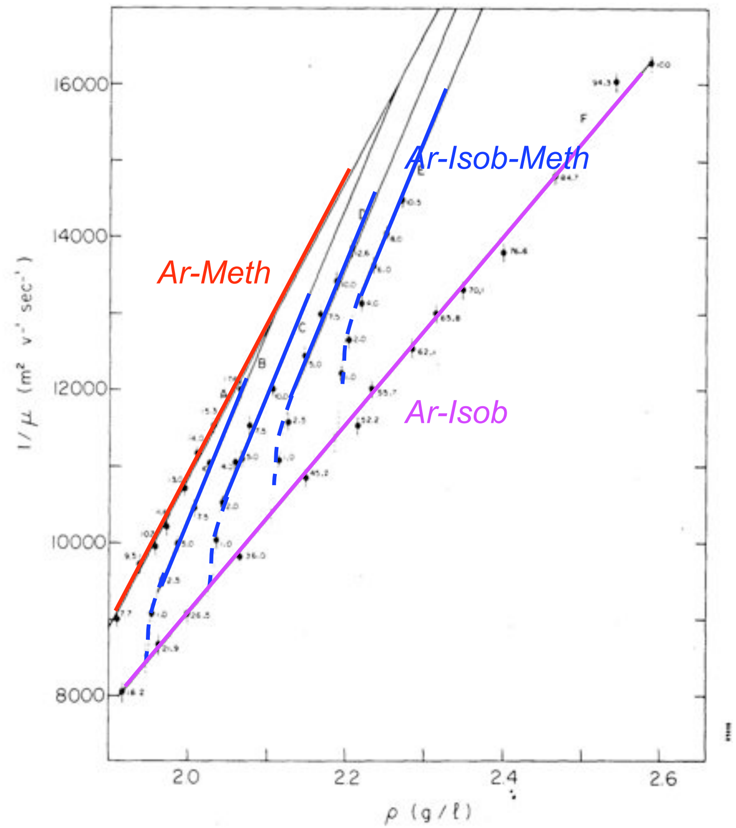
GAS MIXTURES:



BLANC'S LAW

$$\frac{1}{\mu(I^+, M_1 M_2 ... M_i)} = \sum_i \frac{P(M_i)}{\mu(I^+, M_i)}$$

$\mu(I^+, M_i)$ **: mobility of ion I^+ in gas M_{ii}**



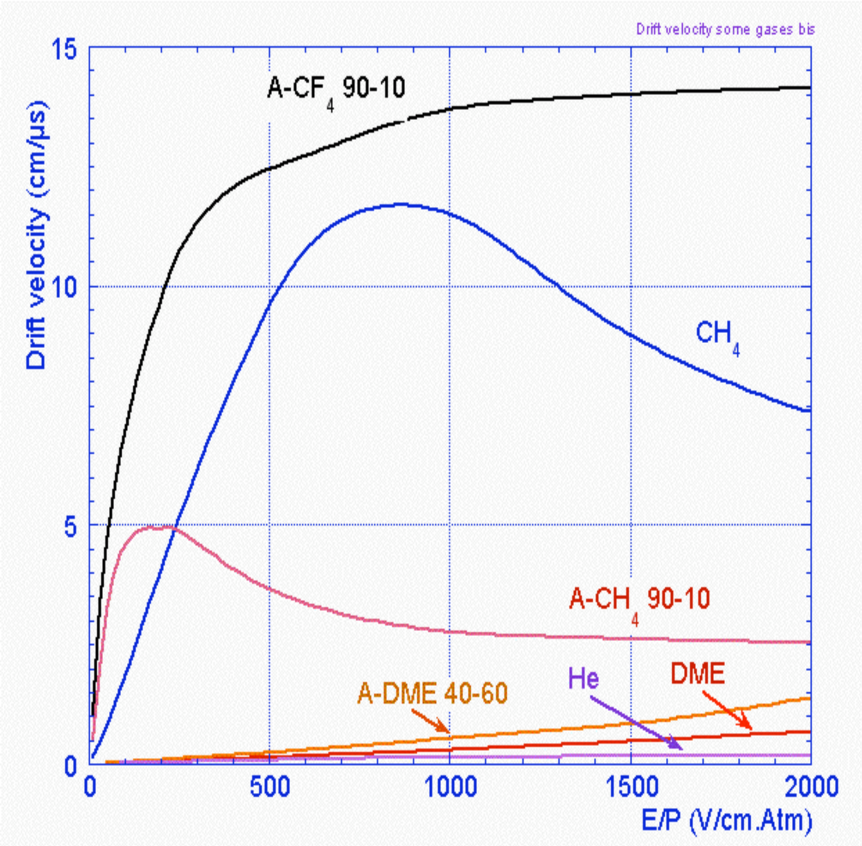
WHICH IONS ARE DRIFTING?

Collisional charge transfer process:

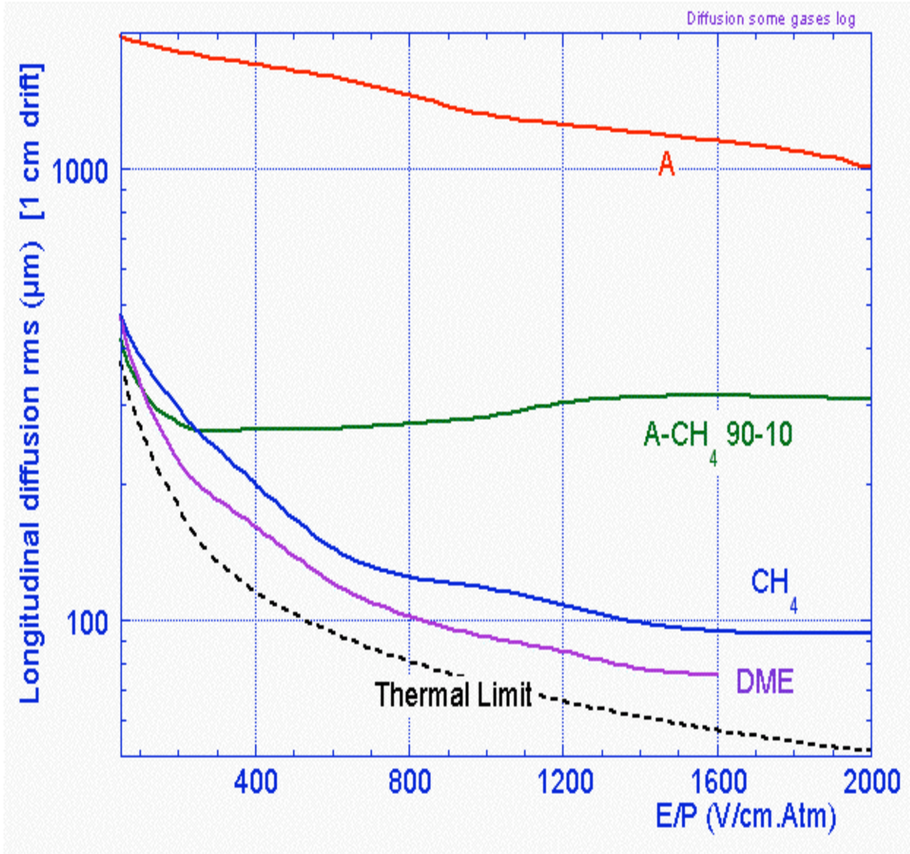
$$A^+ \, B \rightarrow A \, B^+ \quad if \quad E_i(B) \leq E_i(A)$$

G. Shultz, G. Charpak and F. Sauli
Rev.Phys. Appl. 12(1977)67

DRIFT VELOCITY:

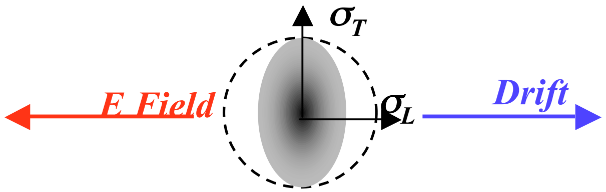


DIFFUSION:



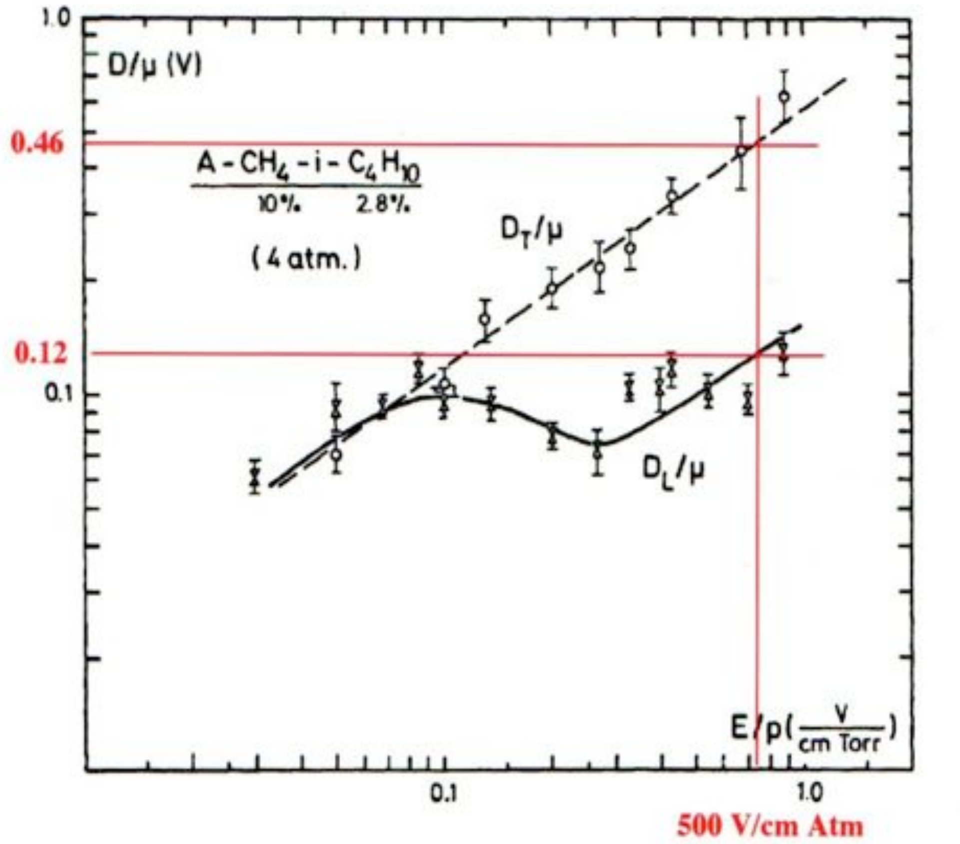
A. Peisert and F. Sauli, drift and Diffusion of Electrons in Gases: a compilation CERN 84-08 (1984)

LONGITUDINAL AND TRANSVERSE DIFFUSION



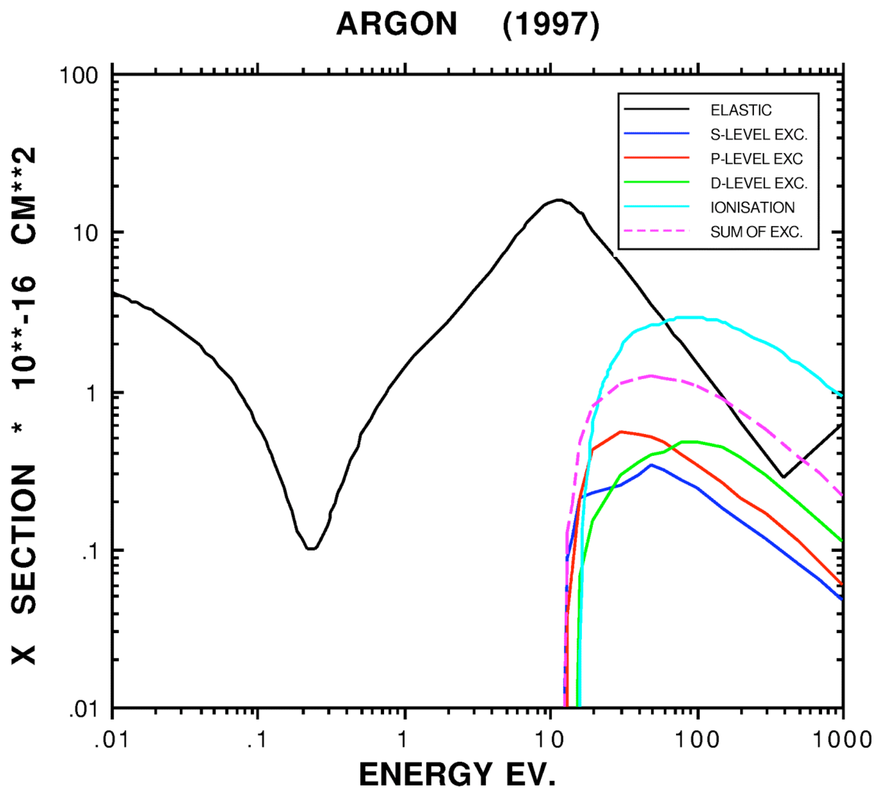
$\frac{D_T}{D_L} \approx 4$ **@ 500 V/cm**

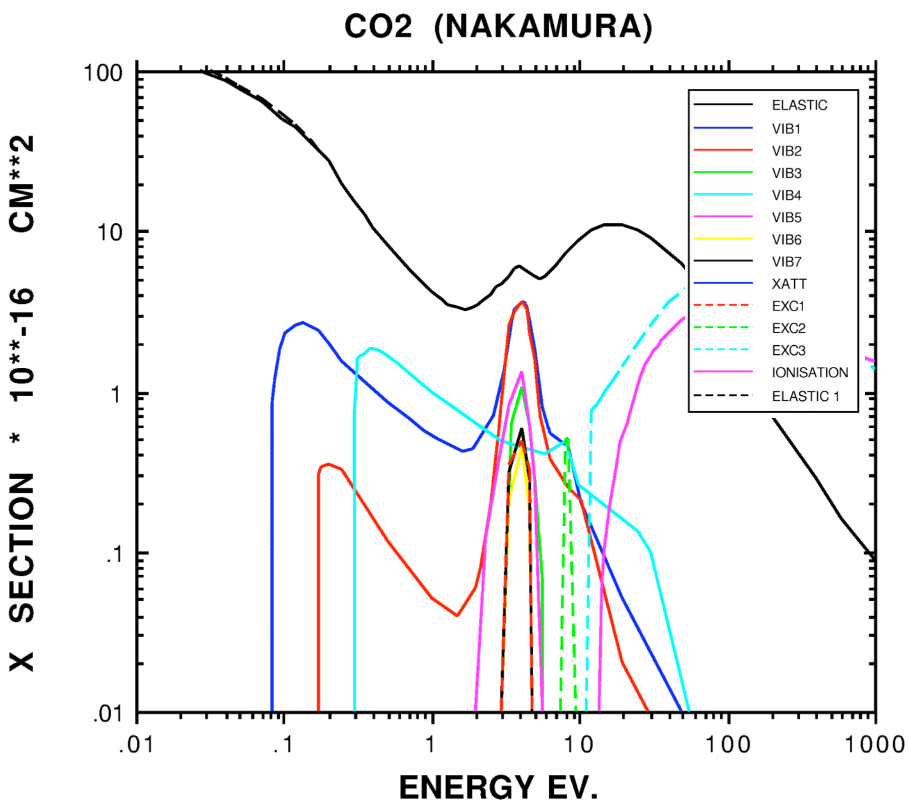
$\sigma_L \approx \frac{1}{2}\sigma_T$ $\sigma_T = \sigma_0$ **(symmetric)**



H. Drumm et al, Nucl. Instr. and Meth. 176(1980)333

ELECTRON-MOLECULE CROSS SECTIONS:



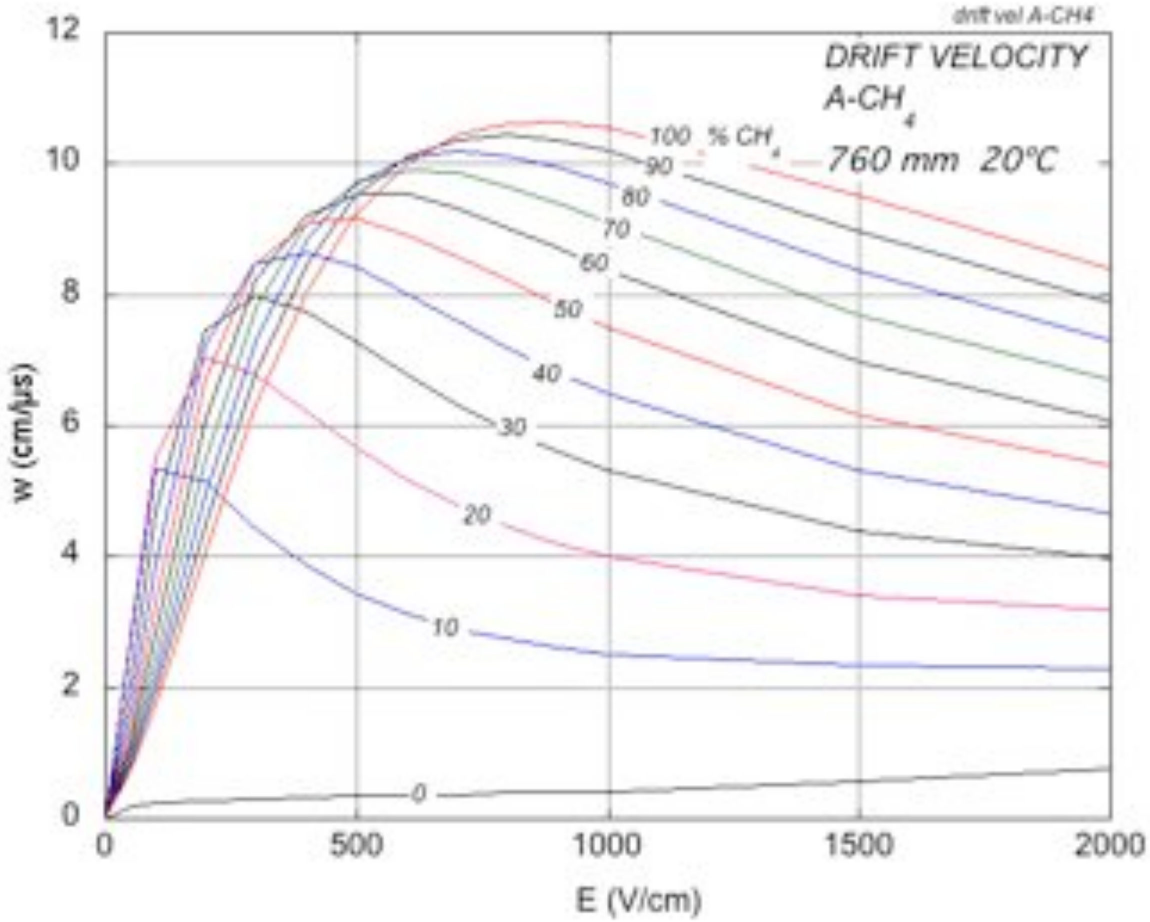


MAGBOLTZ:
Montecarlo program to compute electron drift and diffusion

S. Biagi, Nucl. Instr. and Meth. A421(1999)234

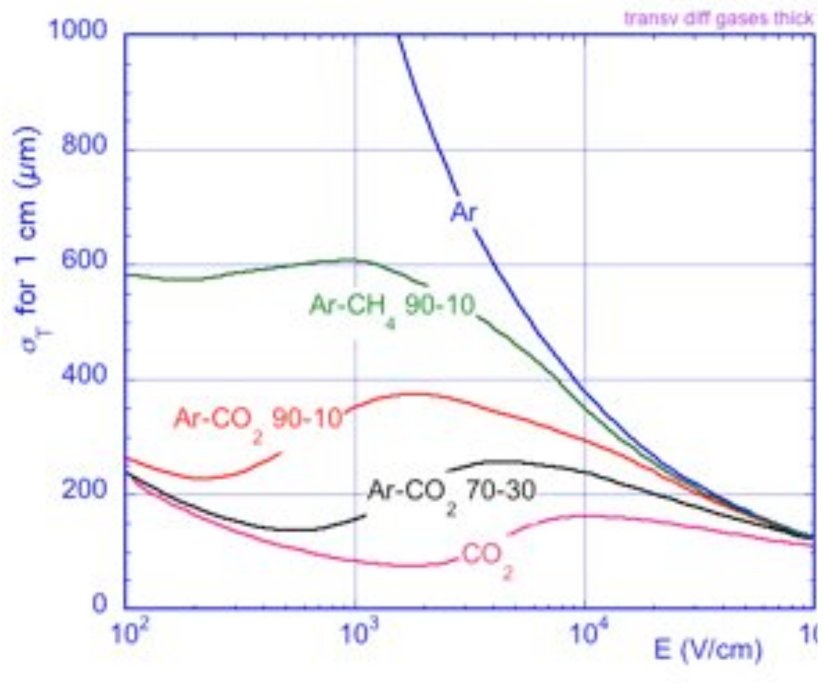
http://rjd.web.cern.ch/rjd/cgi-bin/cross

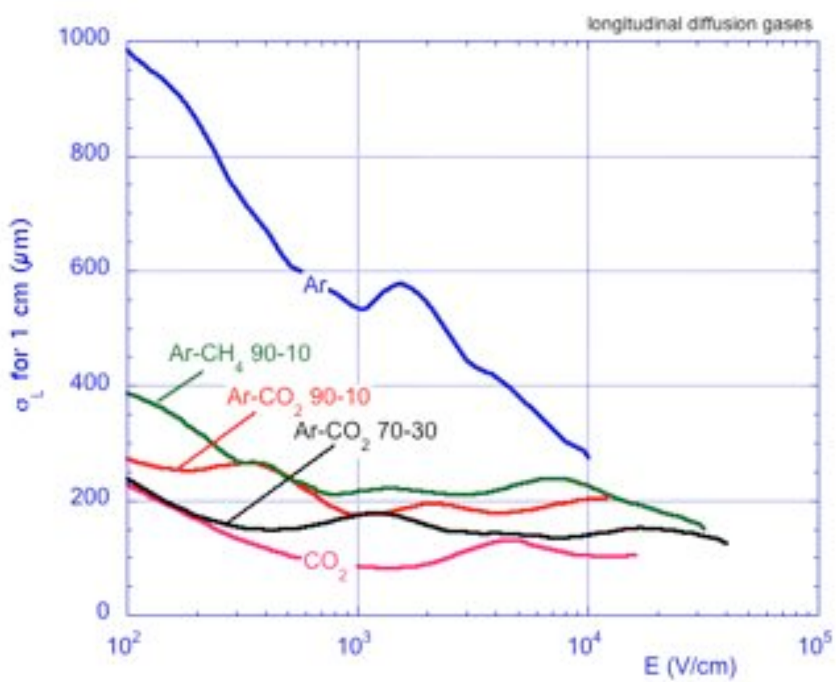
DRIFT VELOCITY IN ARGON-METHANE MIXTURES:



TRANSVERSE DIFFUSION:

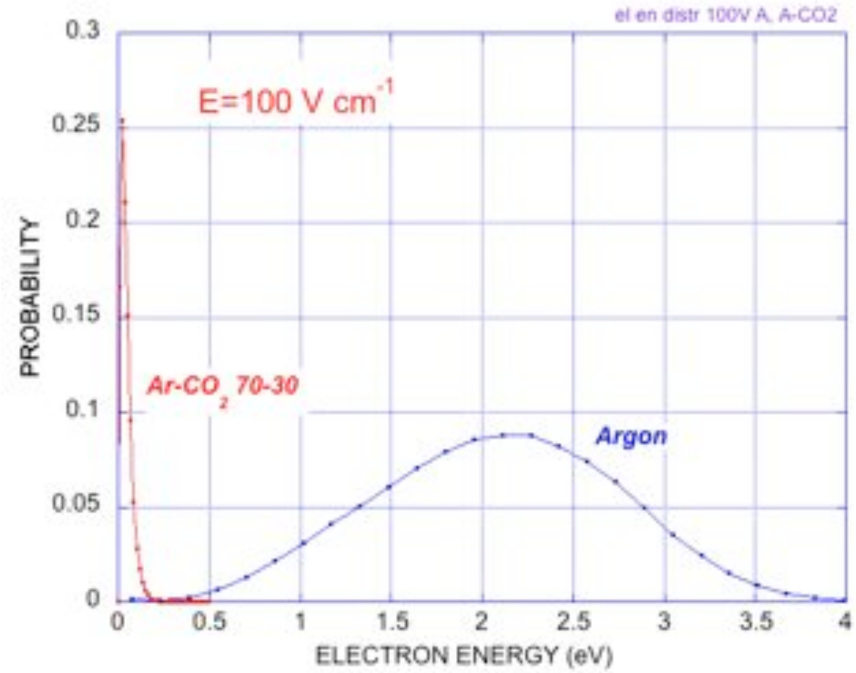
LONGITUDINAL DIFFUSION:



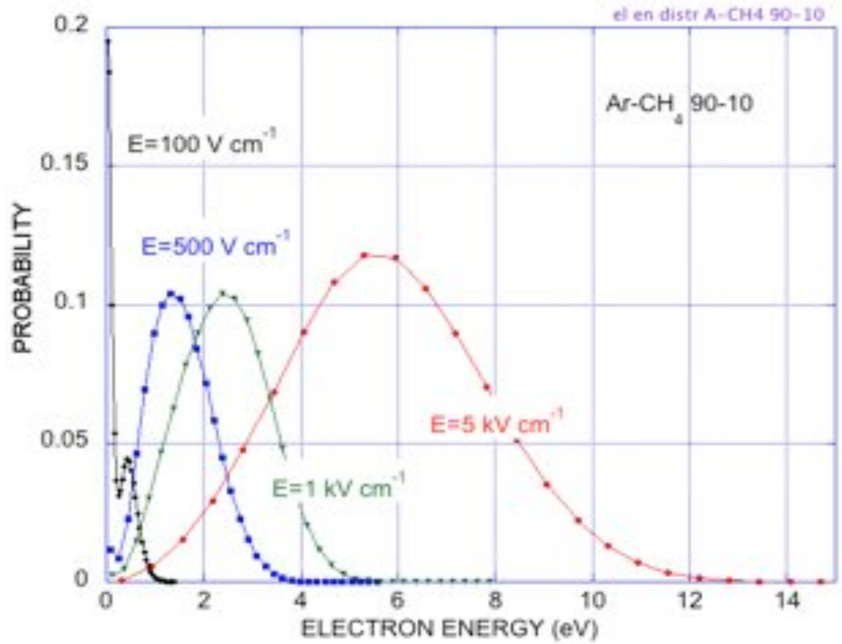


http://consult.cern.ch/writeup/garfield/examples/

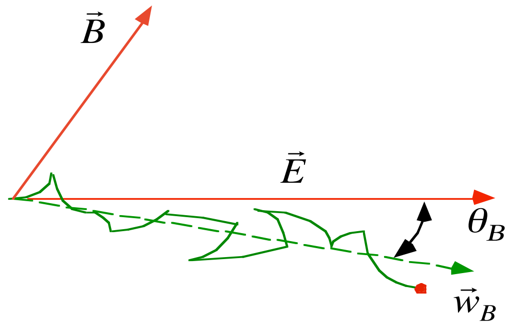
EQUAL FIELD, DIFFERENT GASES:



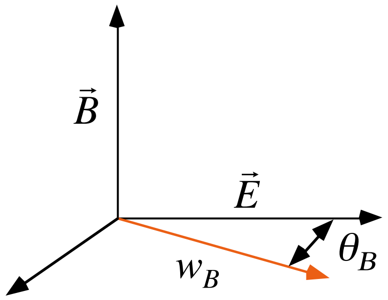
INCREASING FIELD, SAME GAS:



EFFECTS OF MAGNETIC FIELD ON DRIFTING ELECTRONS



$\vec{E} \perp \vec{B}$



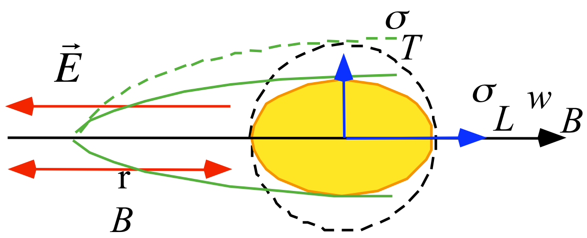
$$\tan\theta_B = \omega\tau$$

$$w_B = \frac{E}{B}\frac{\omega\tau}{\sqrt{1+\omega^2\tau^2}}$$

τ : mean collision time

$\omega = eB/m$ ***Larmor frequency***

$\vec{E} /\!/ \vec{B}$



$$w_B = w_0$$

$$\sigma_L = \sigma_0$$

$$\sigma_T = \frac{\sigma_0}{\sqrt{1+\omega^2\tau^2}}$$

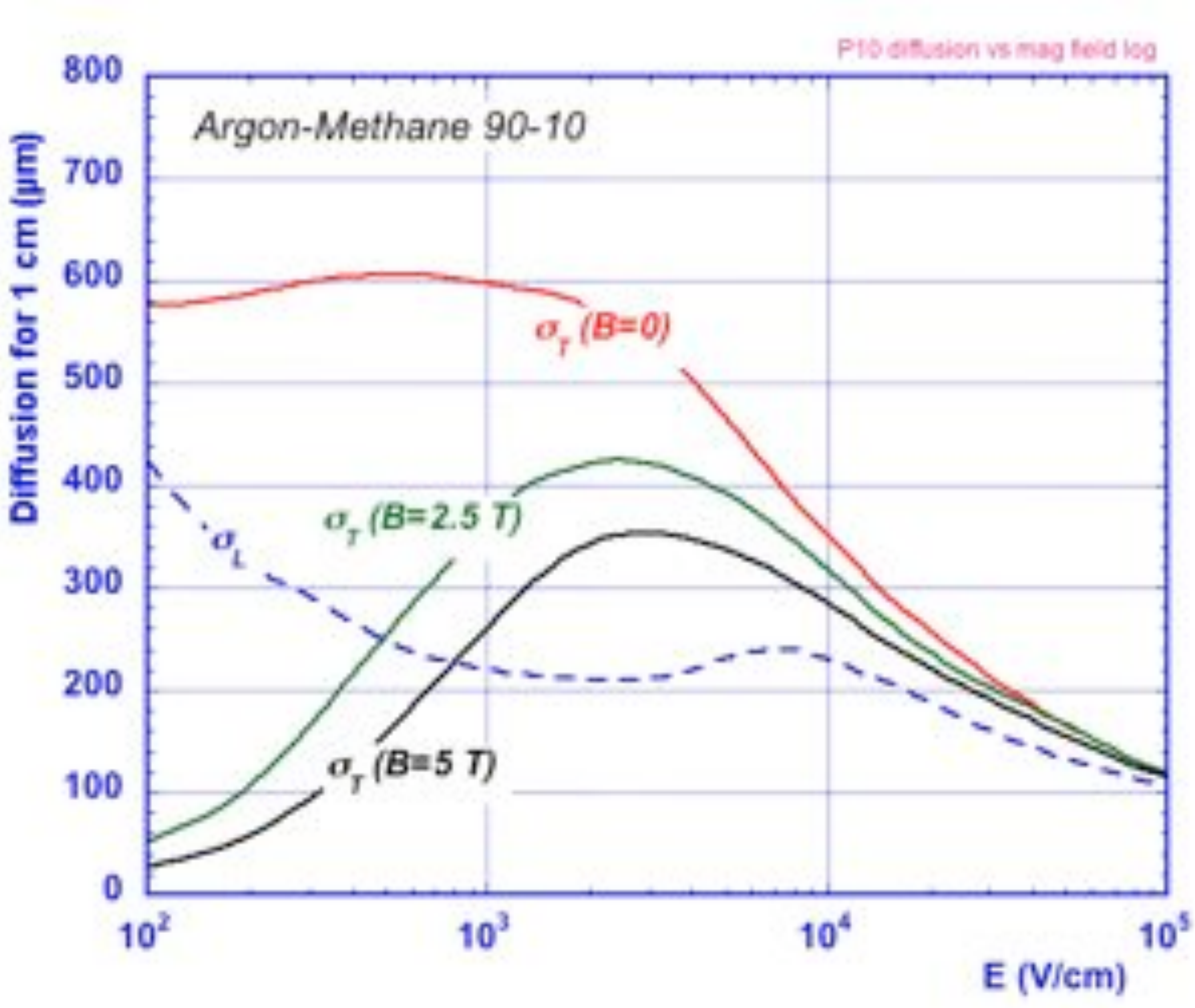
Drift velocity unchanged
Transverse diffusion reduced

$\vec{E} \neq \vec{B}$

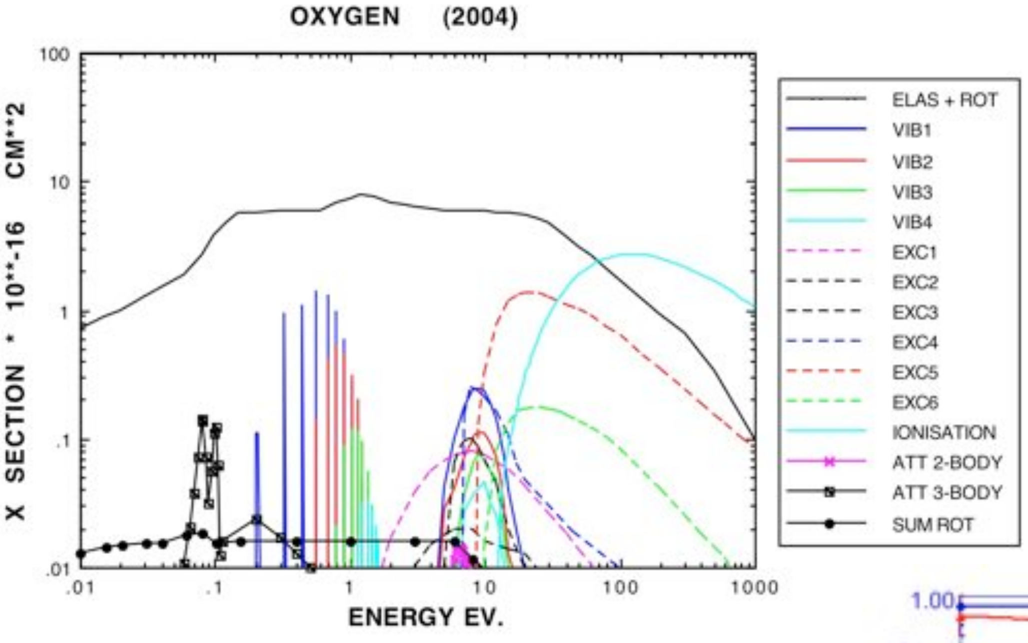
$$\vec{w} = \frac{e}{m}\frac{\tau}{1+\omega^2\tau^2}\left[\vec{E} + \omega\tau\frac{\vec{E}x\vec{B}}{B} + \omega^2\tau^2\frac{\vec{B}(\vec{E}\bullet\vec{B})}{B^2}\right]$$

Friction force theory

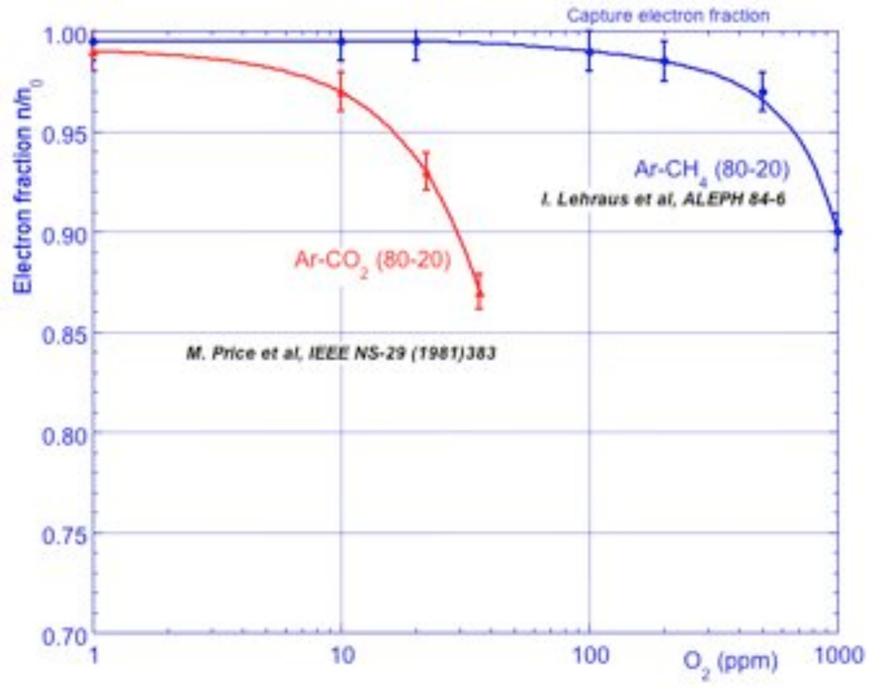
E // B (TIME PROJECTION CHAMBERS):



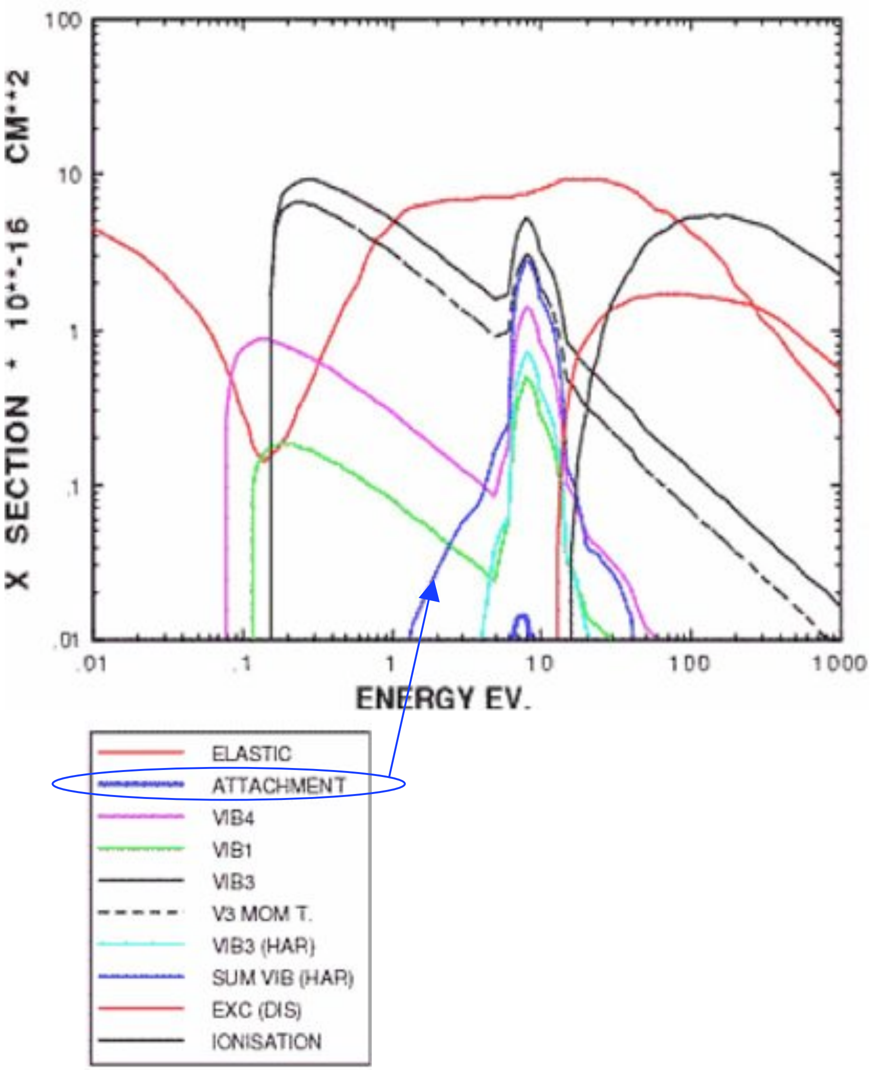
ELECTRON ATTACHMENT CROSS SECTIONS IN OXYGEN:



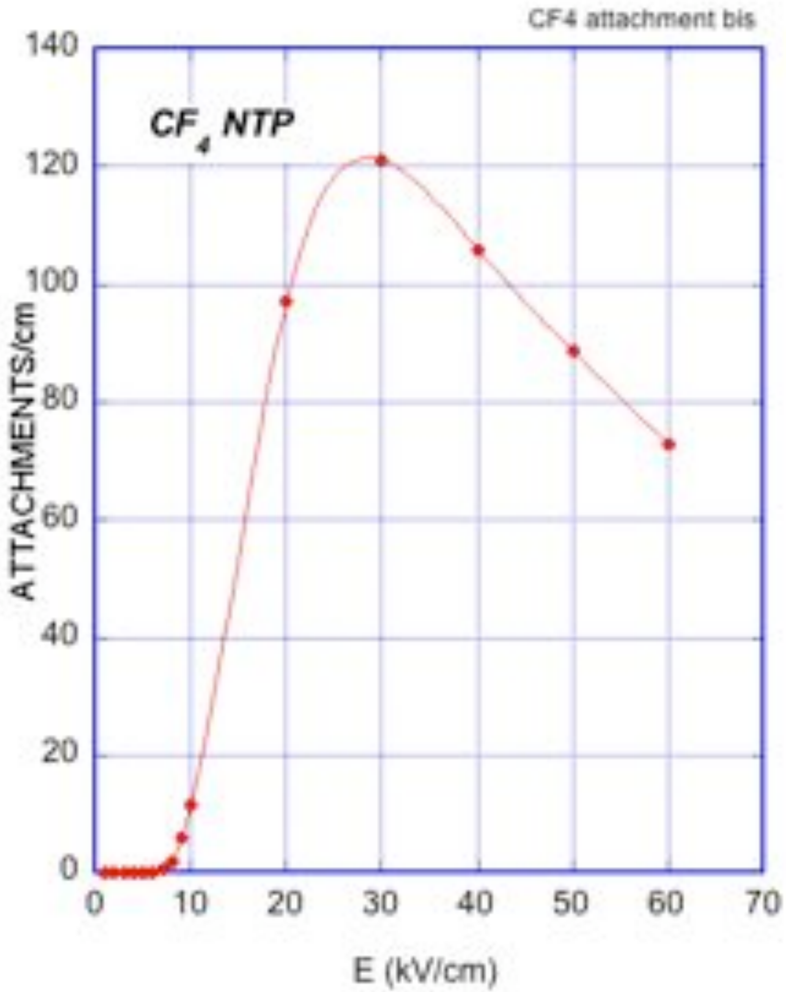
ELECTRONS SURVIVING AFTER 20 CM DRIFT (E = 200 V/cm):



ELECTRON CROSS SECTIONS IN CF_4

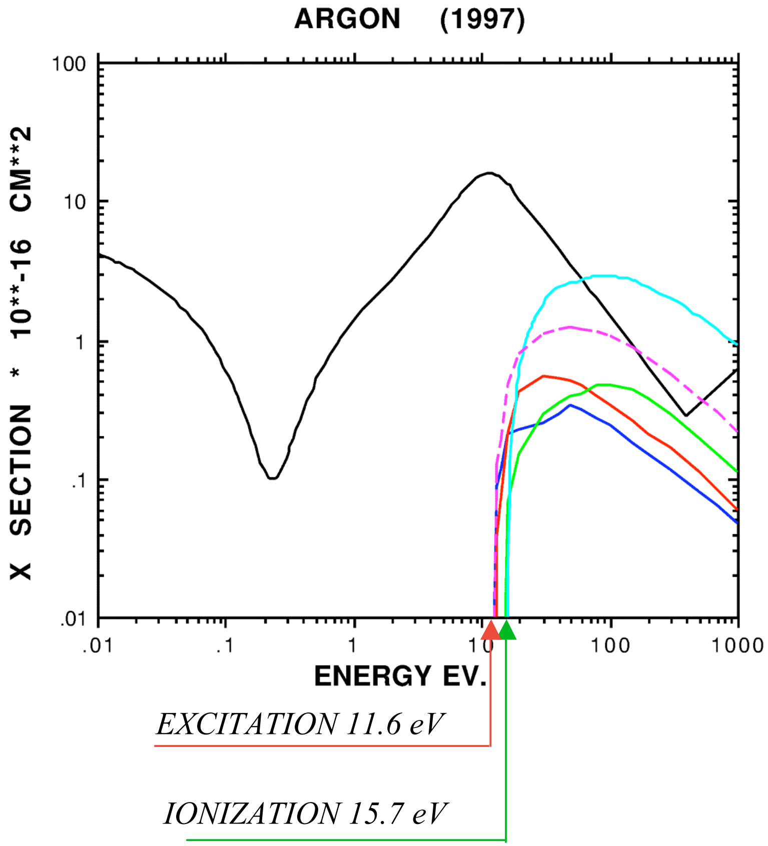


ELECTRON ATTACHMENTS IN CF_4: (MAGBOLTZ)

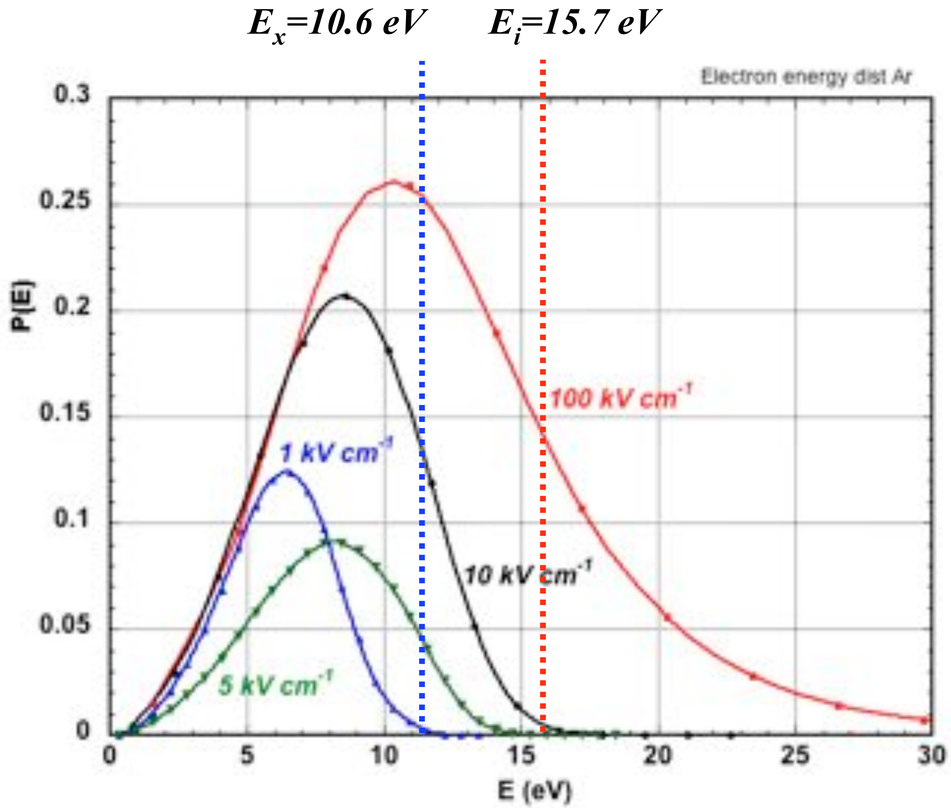


http://consult.cern.ch/writeup/magboltz/cross/

HIGH ELECTRIC FIELD: EXCITATION AND CHARGE MULTIPLICATION



ELECTRONS ENERGY DISTRIBUTION IN ARGON AT INCREASING FIELDS:



SECONDARY COLLISION PROCESSES IN GAS MIXTURES

1)	$A+e$	⇒	$A^{+}+e+e$	Ionisation by electronic impact.
2)	$A+e$	⇒	$A^{*}+e$	Excitation by electronic impact.
3)	$A^{*}+e$	⇒	$A+e$	Deexcitation by electronic collision.
4)	$A+h\nu$	⇒	A^{*}	Photo-excitation (absorption of light).
5)	A^{*}	⇒	$A+h\nu$	Photo-emission (radiative deexcitation).
6)	$A+h\nu$	⇒	$A^{+}+e$	Photoionisation.
7)	$A^{+}+e$	⇒	$A+h\nu$	Radiative recombination.
8)	$A^{+}+B+e$	⇒	$A+B$	Three body recombination.
9)	$A^{*}+B$	⇒	$A+B^{*}$	Collisional deexcitation.
10)	$A^{*}+B$	⇒	$A+B^{+}+e$	Penning effect.
11)	$A^{+}+B$	⇒	$A+B^{+}$	Charge exchange.
12)	$A^{+}+B$	⇒	$A^{+}+B^{+}+e$	Ionisation by ionic impact.
13)	$A+B$	⇒	$A^{*}+B$	Excitation by atomic impact.
14)	$A+B$	⇒	$A^{+}+B+e$	Ionisation by atomic impact.
15)	$A+e$	⇒	A^{-}	Formation of negative ions.
16)	A^{-}	⇒	$A+e$	Electrons release by negative ions.
17)	$A^{**}+A$	⇒	$A_2^{+}+e$	Associative ionisation.
18)	$A^{+}+2A$	⇒	$A_2^{+}+A$	Molecular ion formation.
19)	$A^{*}+A+A$	⇒	$A_2^{*}+A$	Excimer formation.
20)	A_2^{*}	⇒	$A+A+h\nu$	Radiative excimer dissociation.
21)	$(XY)^{*}$	⇒	$X+Y^{*}$	Dissociation.
22)	$(XY)^{+}+e$	⇒	$X+Y^{*}$	Recombinational dissociation

MAJOR PROCESSES:

PROCESS		
Excitation	$A+e$	$A^{*}+e$
Ionization	$A+e$	$A^{+}+e+e$
De-excitation	$A^{*}+e$	$A+e$
Photo-excitation	$A+h\upsilon$	A^{*}
Photo-ionization	$A+ h\upsilon$	$A^{+}+e$
Photo-emission	A^{*}	$A+h\upsilon$
Electron capture	$A++e$	A^{-}
Radiative recombination	$A^{*}++e$	$A+h\upsilon$
Excimers formation	$A^{*}+A+A$	$A_2^{*}+A$
Radiative excimer dissociation	A_2^{*}	$A+A+ h\upsilon$
Collisional de-excitation	$A^{*}+B$	$A+B^{*}$
Charge exchange	$A^{+}+B$	$A+B^{+}$
Penning effect	$A^{*}+B$	$A+B^{+}+e$

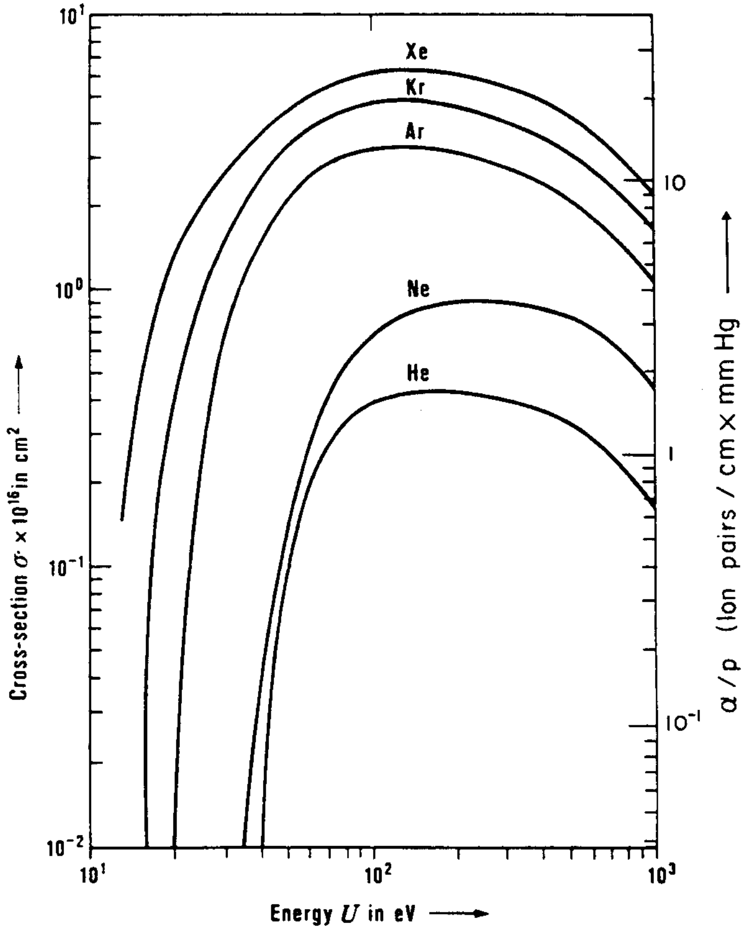
J.Meek and J. D. Cragg, Electrical Breakdown of Gases (Clarendon Press, Oxford 1953)

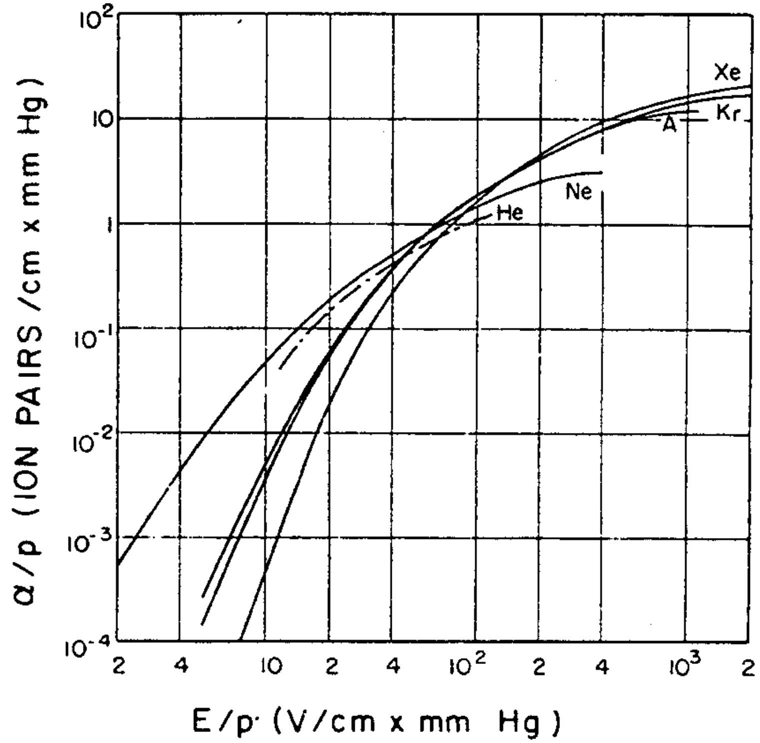
Mean free path for ionization:

$$\lambda = \frac{1}{N\sigma}$$ *N: molecules/cm³*

First Townsend coefficient:

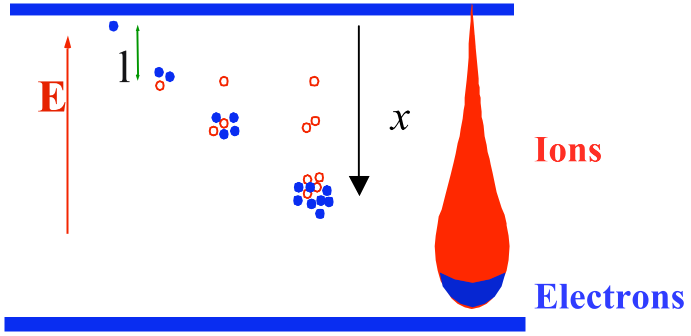
$$\alpha = \frac{1}{\lambda}$$ *Ionizing collisions/cm*





S.C. Brown, Basic Data of Plasma Physics (MIT Press, 1959)

CHARGE MULTIPLICATION IN UNIFORM FIELD

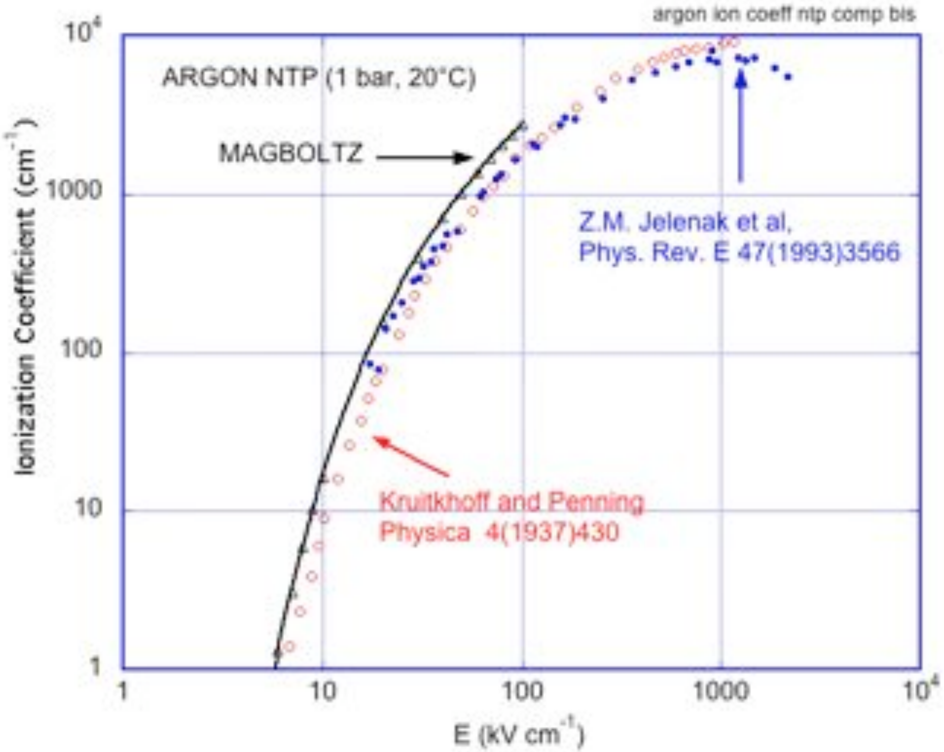


Incremental increase of the number of electrons in the avalanche:

$$dn = n\,\alpha\,dx \qquad n(x) = n_0 e^{\alpha x}$$

Multiplication factor or Gain: $M(x) = \frac{n}{n_0} = e^{\alpha x}$

MAGBOLTZ CALCULATION OF TOWNSEND COEFFICIENT:

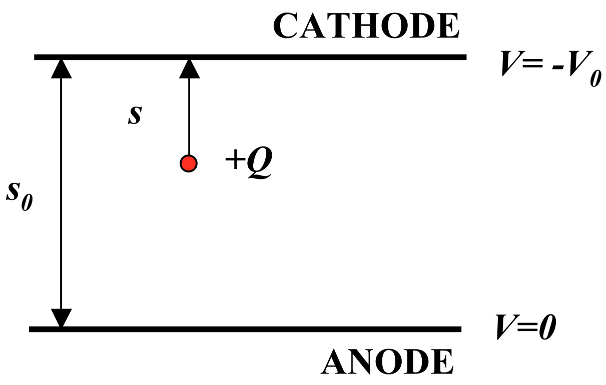


Maximum Avalanche size before discharge (Raether limit):

$Q_{MAX} \approx 10^7$ e

H. Raether, Electron Avalanches and Breakdown in Gases (Butterworth 1964)

IONIZATION CHAMBER: SIGNAL DEVELOPMENT BY A MOVING CHARGE +Q



Charge induced on each electrode by +Q moving through the difference of potential dV:

$$dq = Q\frac{dV}{V_0} = Q\frac{ds}{s_0}$$

Integrating over s (or time t):

$$q(s) = \frac{Q}{s_0}s \qquad q(t) = \frac{Q}{s_0}wt \qquad i(t) = \frac{dq}{dt} = \frac{Q}{s_0}w$$

Electrons- ion pair (-Q and +Q) released at the same distance s from the cathode :

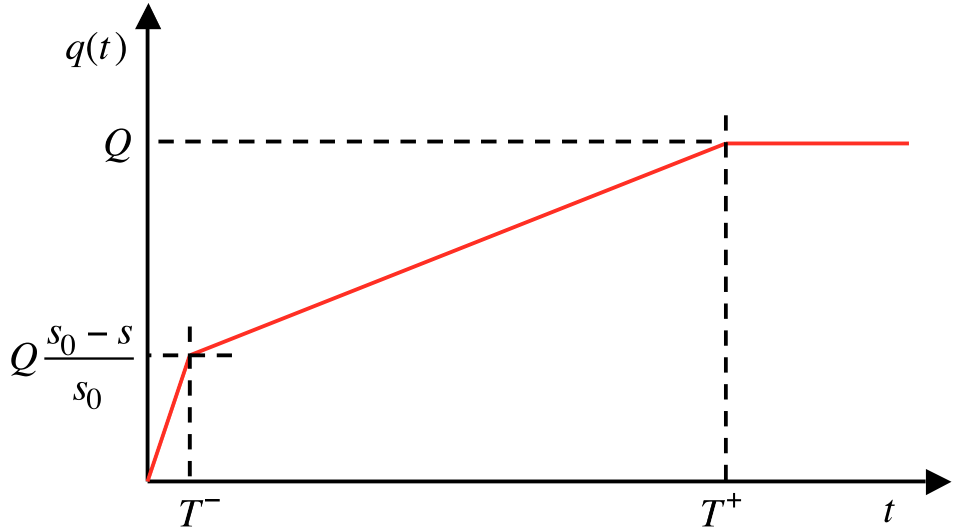
$$q(t) = Q\left(\frac{w^- t}{s_0} + \frac{w^+ t}{s_0}\right) \qquad 0 \le t \le T^-$$

$$q(t) = Q\left(\frac{s - s_0}{s_0} + \frac{w^+ t}{s_0}\right) \qquad T^- \le t \le T^+$$

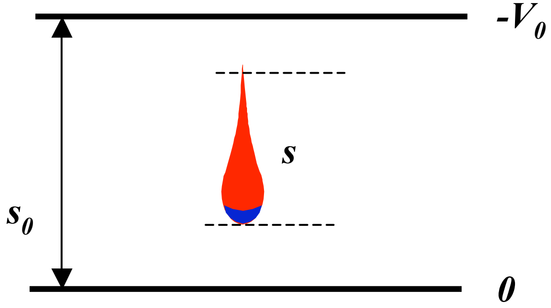
w^- (w^+) **: electron (ion) drift velocity**

T^- (T^+) **: total electron (ion) drift time**

(+Q **on cathode ,** -Q **on anode)**



PARALLEL PLATE COUNTERS: SIGNAL DEVELOPMENT WITH CHARGE MULTIPLICATION



Increase in the number of charges after a path ds is:

$$dn = n\alpha ds \qquad n = n_0 e^{\alpha s}$$

Charge induced by electrons: $dq^- = -en_0 e^{\alpha s}\dfrac{ds}{s_0}$

$$q^-(s) = \frac{en_0}{\alpha s_0}(e^{\alpha s} - 1) \approx \frac{en_0}{\alpha s_0} e^{\alpha s} = \frac{en_0}{\alpha s_0} e^{\alpha w^- t}$$

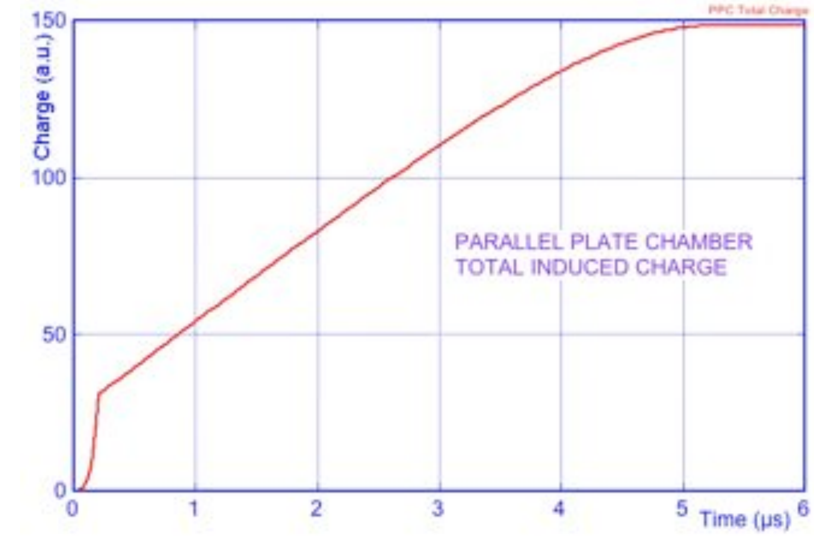
$$i^-(t) = \frac{dq^-}{dt} = \frac{en_0 w^-}{s_0} e^{\alpha w^- t} = \frac{en_0}{T^-} e^{\alpha w^- t}$$

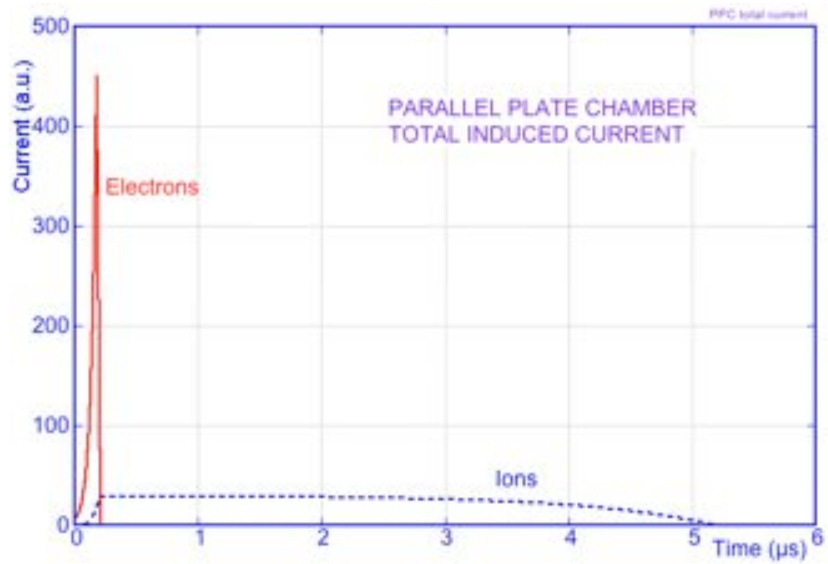
Current signal induced by ions:

$$i^+(t) = \frac{en_0}{T^+}\left(e^{\alpha w^- t} - e^{\alpha w^* t}\right) \quad 0 \le t \le T^-$$

$$i^+(t) = \frac{en_0}{T^+}\left(e^{\alpha s} - e^{\alpha w^* t}\right) \quad T^- \le t \le T^+$$

$$\frac{1}{w^*} = \frac{1}{w^+} + \frac{1}{w^-}$$





SINGLE ELECTRON AVALANCHE MULTIPLICATION

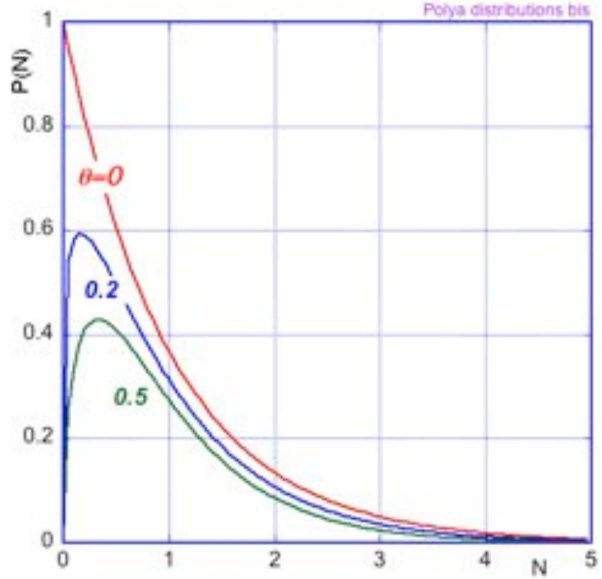
In constant electric field, the probability of an avalanche started by a single electron to have a size *N* is given by (Furry's law):

$$P(N) = \frac{1}{\overline{N}} e^{-\frac{N}{\overline{N}}} \qquad \overline{N} = e^{\alpha s} \qquad \text{s: gap}$$

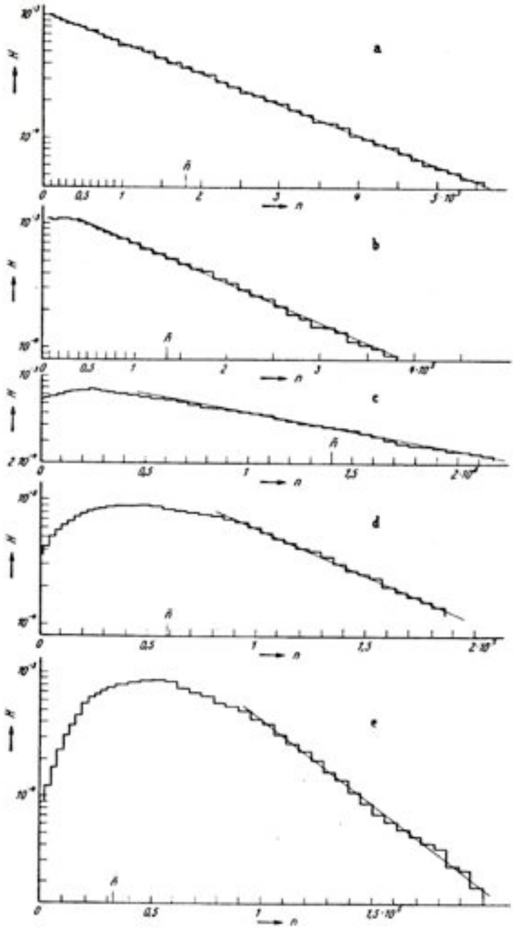
maximum probability for N=0 (no multiplication!).

At large gains (high fields) the avalanche distribution is described by a Polya function:

$$P(N) = \left[\frac{N(1+\theta)}{\ddot{N}}\right]^{\theta} e^{-\frac{N(1+\theta)}{\ddot{N}}} \qquad \theta \geq 0$$

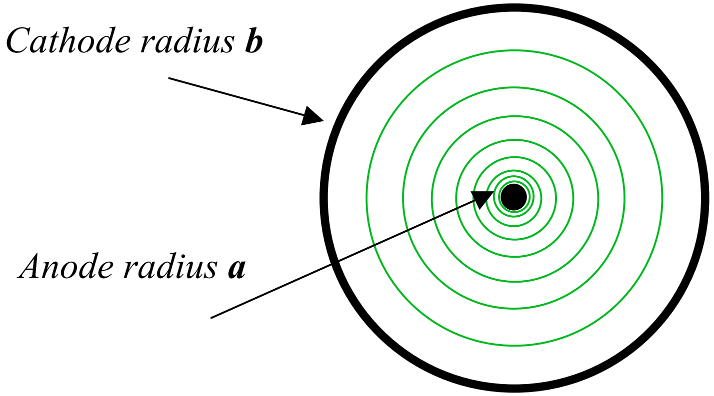


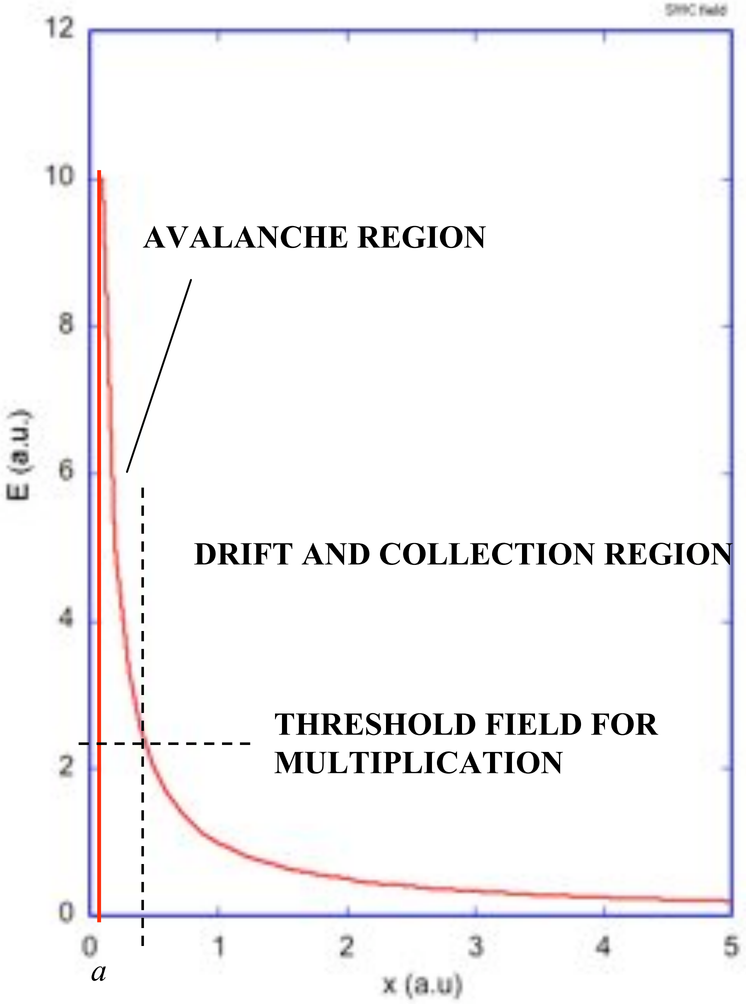
EXPERIMENTAL AVALANCHE SIZE DISTRIBUTION AT INCREASING FIELDS:



H. Sclumbohm, Zeit. Physik 151(1958)563

THIN ANODE WIRE OF RADIUS a, COAXIAL WITH A CYLINDRICAL CATHODE OF RADIUS b



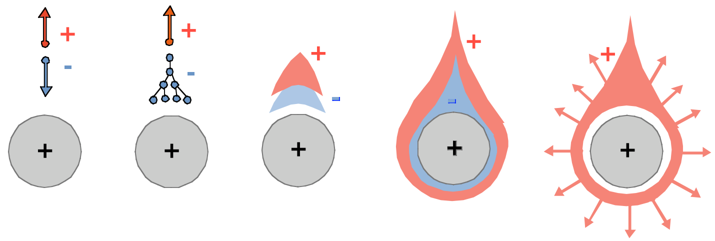


Electric field: $E(r) = \frac{CV_0}{2\pi\varepsilon_0}\frac{1}{r}$

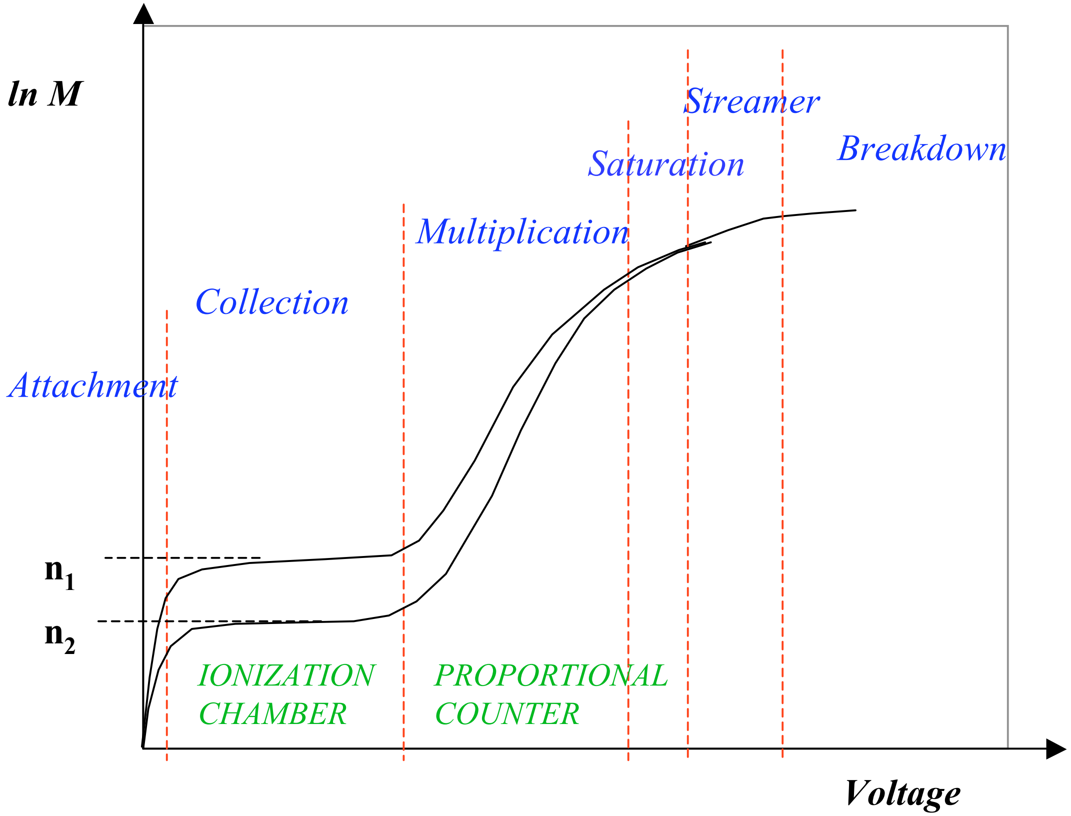
Capacitance per unit length: $C = \frac{2\pi\varepsilon_0}{\ln(b/a)}$

Potential: $V(r) = \frac{CV_0}{2\pi\varepsilon_0}\ln\frac{r}{a}$ $\quad V(b) = V_0$ $\quad V(a) = 0$

AVALANCHE DEVELOPMENT AROUND THIN WIRES:



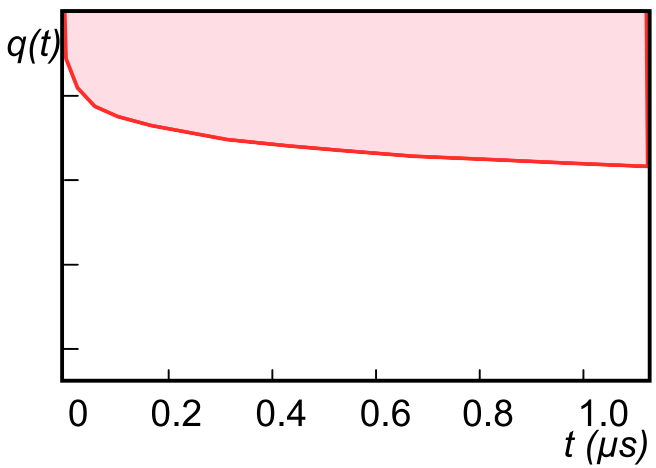
OPERTING REGIMES:

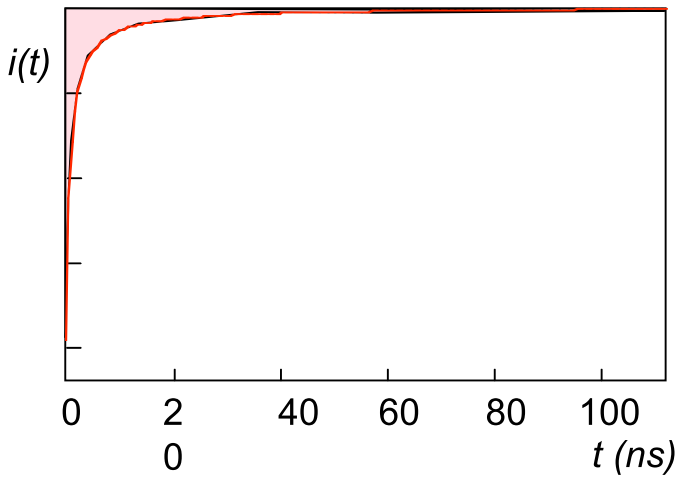


TIME DEVELOPMENT OF THE SIGNALS

$$q(t) = -\frac{QC}{2\pi\varepsilon_0}\ln\left(1 + \frac{\mu^+ CV_0}{2\pi\varepsilon_0 a^2}t\right) = -\frac{QC}{2\pi\varepsilon_0}\ln\left(1 + \frac{t}{t_0}\right)$$

$$i(t) = -\frac{QC}{2\pi\varepsilon_0}\frac{1}{t_0 + t}$$





S. C. Curran and J. D. Craggs, Counting Tubes (Butreworth 1949)

F. Sauli, Principles of Operation of Multiwire Proportional and Drift Chambers (CERN 77-09)