4. Measurement of Ionization

4.1 Gaseous Ionization Detectors

- Ionization chamber
- Ionization yield, charge multiplication
- Proportional counter
- Geiger-Müller counter
- Streamer tubes

4.2 Ionization in liquids

4.3 Drift and diffusion in gases

History of Instrumentation

1906:	Geiger Counter	H. Geiger, E. Rutherford
1910:	Cloud Chamber	C.T.R. Wilson
1928:	Geiger-Müller Counter*	W. Müller
1929:	Coincidence Method	W. Bothe
1930:	Emulsion	M. Blau
1940/50:	Scintillator, Photomultiplier*	
1952:	Bubble Chamber	D. Glaser
1962:	Spark Chamber	
1968:	Multi-Wire Prop. Chamber*	G. Charpak
1972:	Drift Chamber*	F. Sauli, J. Heintze et al.
1974:	Time Projection Chamber*	D. Nygren
1983:	Silicon strip detectors*	J. Kemmer, R. Klanner, G. Lutz et al.
1990:	Silicon pixel detectors*	

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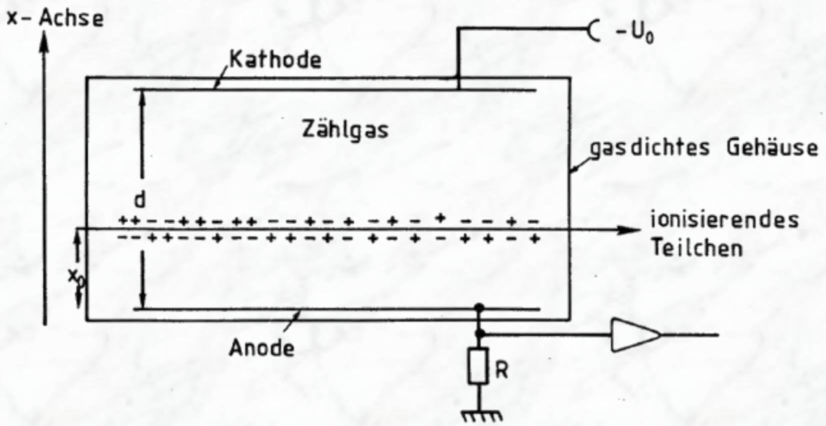
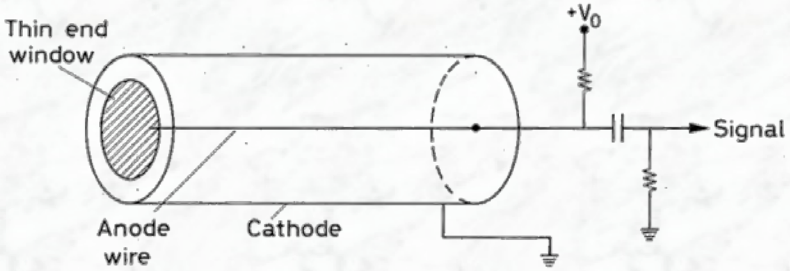
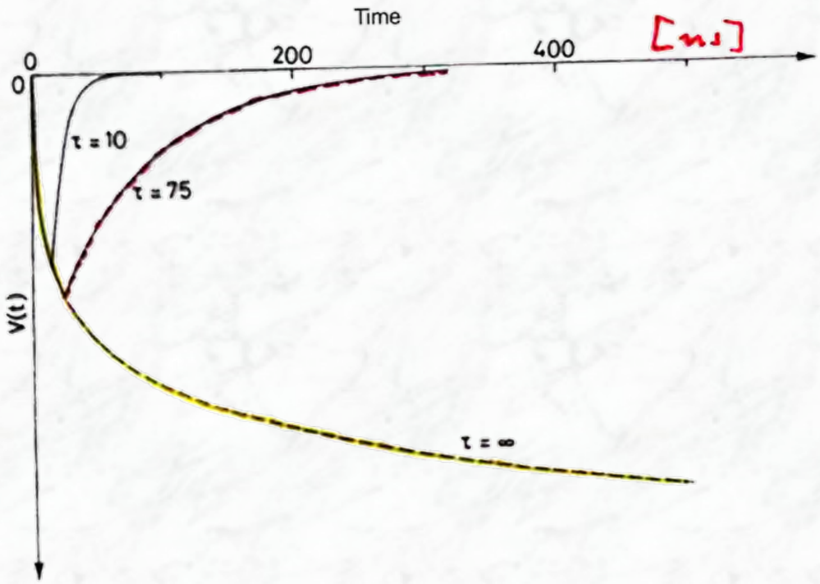
*covered during this lecture series



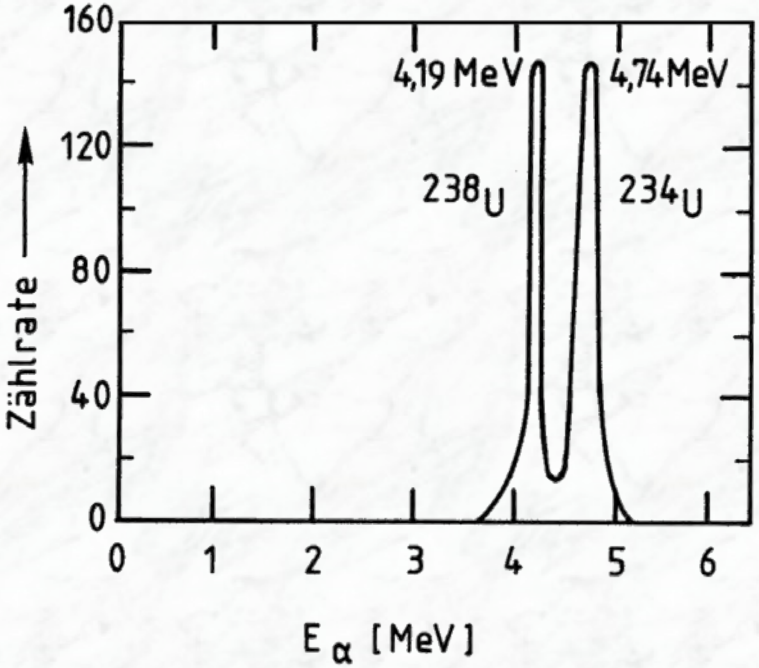
Principle of a planar ionization chamber
[from Ref. 3]



Principle of a cylindrical ionisation chamber
[from Ref. 2]



Voltage pulse in a cylindrical proportional counter for different electronic time constants (shaping times [from Ref. 2]



Measured pulse height spectrum of α particles of a ^{234}U / ^{238}U mixture;   [from Ref. 3]

Gas	Dichte $\varrho[g/cm^3]$	$I_0[eV]$	$W[eV]$	$n_p[cm^{-1}]$	$n_T[cm^{-1}]$
H_2	$8.99 \cdot 10^{-5}$	15.4	37	5.2	9.2
He	$1.78 \cdot 10^{-4}$	24.6	41	5.9	7.8
N_2	$1.25 \cdot 10^{-3}$	15.5	35	10	56
O_2	$1.43 \cdot 10^{-3}$	12.2	31	22	73
Ne	$9.00 \cdot 10^{-4}$	21.6	36	12	39
Ar	$1.78 \cdot 10^{-3}$	15.8	26	29	94
Kr	$3.74 \cdot 10^{-3}$	14.0	24	22	192
Xe	$5.89 \cdot 10^{-3}$	12.1	22	44	307
CO_2	$1.98 \cdot 10^{-3}$	13.7	33	34	91
CH_4	$7.17 \cdot 10^{-4}$	13.1	28	16	53
C_4H_{10}	$2.67 \cdot 10^{-3}$	10.8	23	46	195

Tabelle 1.2: Zusammenstellung einiger Eigenschaften von Gasen. Angegeben sind der mittlere Energieverlust W pro erzeugtes Ionenpaar, das mittlere effektive Ionisationspotential pro Hüllen-Elektron I_0, die Anzahl der primär (n_p) und insgesamt (n_T) gebildeten Elektron-Ion-Paare pro cm bei Normaldruck für minimalionisierende Teilchen [94, 32, 104, 8].

[from Ref. 3]

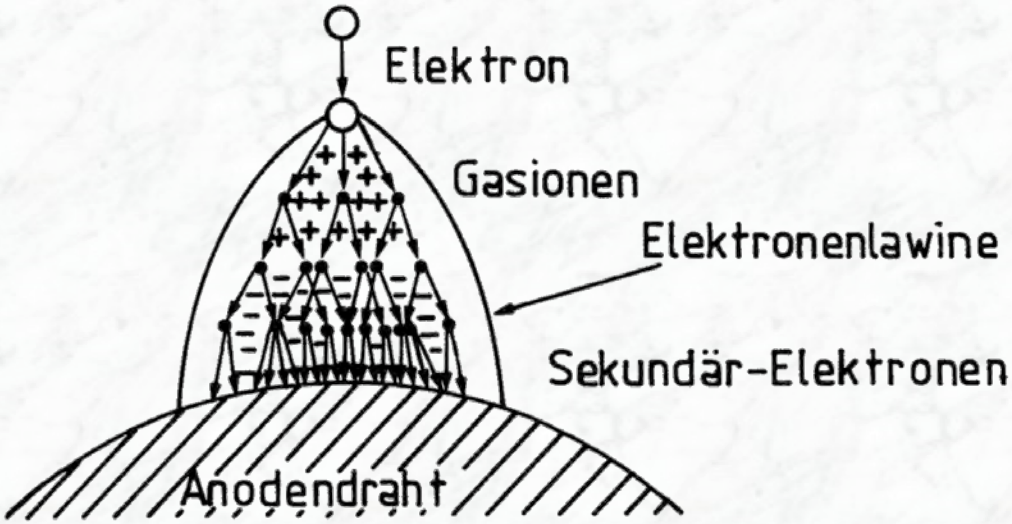
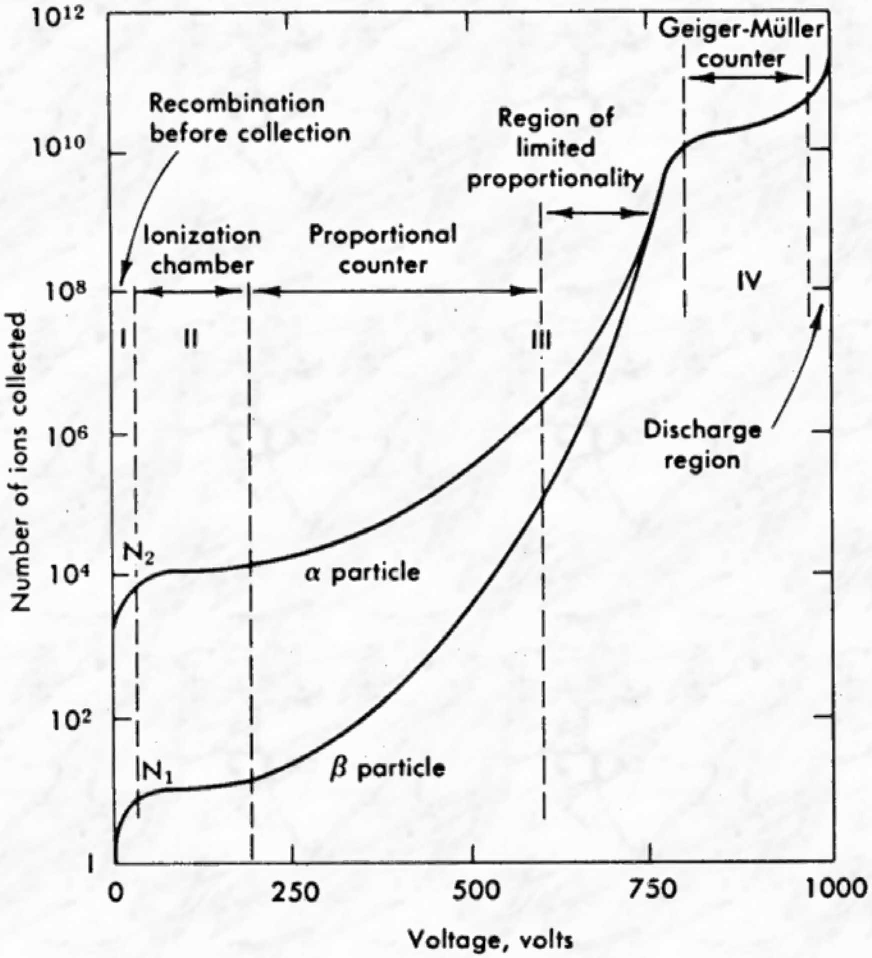


Illustration of avalanche charge multiplication in the vicinity of the anode wire in a proportional counter. Due to lateral diffusion, a drop-like avalanche develops. [from Ref. 3]



Number of collected charge carriers (ions) as a function of the applied voltage in a cylindrical gas-filled detector [from Ref. 2]

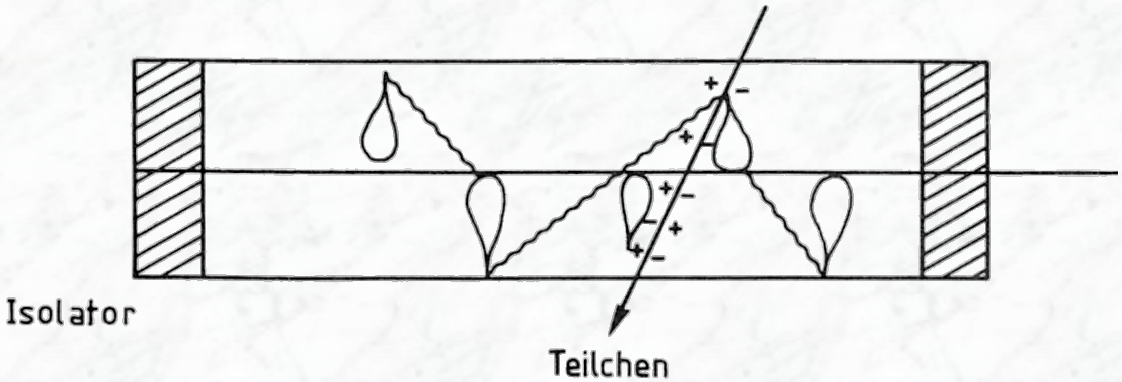
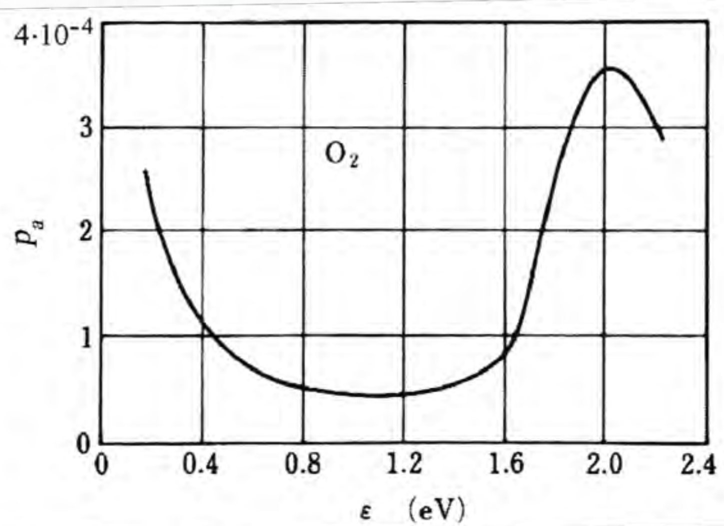


Illustration of the transverse avalanche propagation in a Geiger-Müller counter [from Ref. 3]

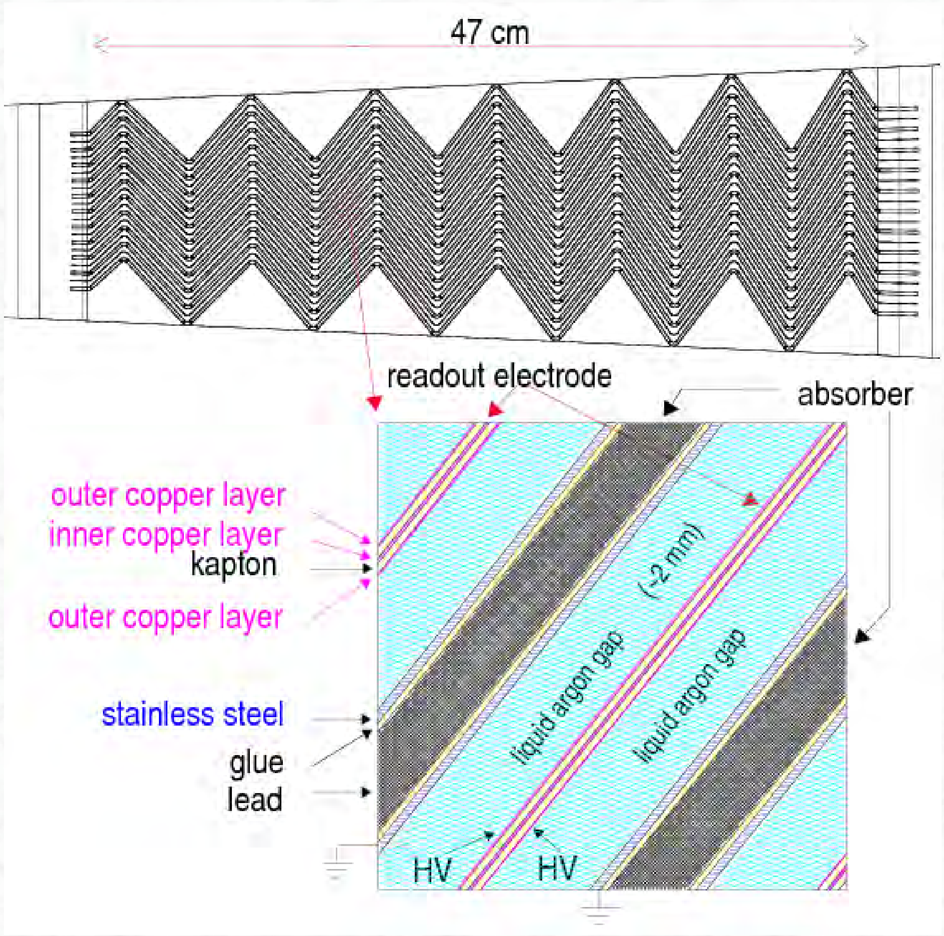
Gas	p_a	n_s (s^{-1})	t_a (ns)
CO_2	6.2×10^{-9}	2.2×10^{11}	7.1×10^{5}
O_2	2.5×10^{-5}	2.1×10^{11}	1.9×10^{2}
H_2O	2.5×10^{-5}	2.8×10^{11}	1.4×10^{2}
Cl	4.8×10^{-4}	4.5×10^{11}	5.0×10^{0}

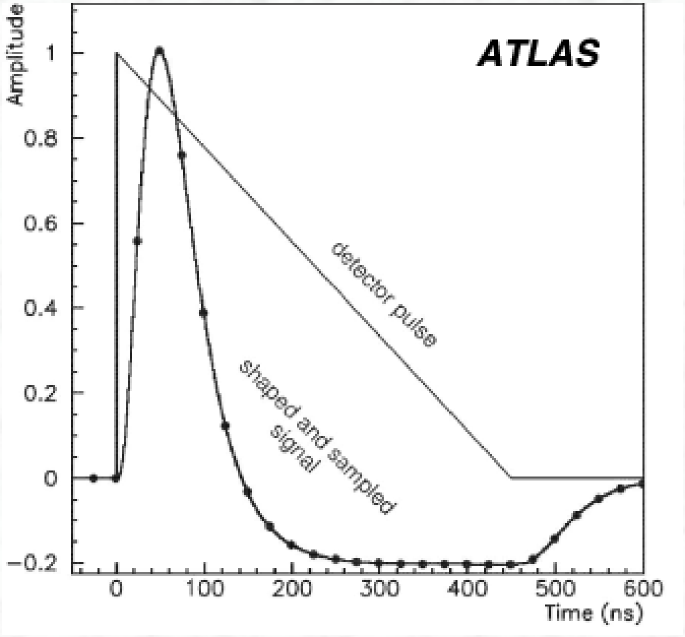
Attachment probability for electrons p_a, number of collisions per second n_s and average time for attachment t_a without an electric field [from Ref. 1]



Attachment probability p_a for electrons in O_2 per collision as function of the electron energy ε [from Ref. 3]

Example: the liquid argon calorimeter of the ATLAS experiment

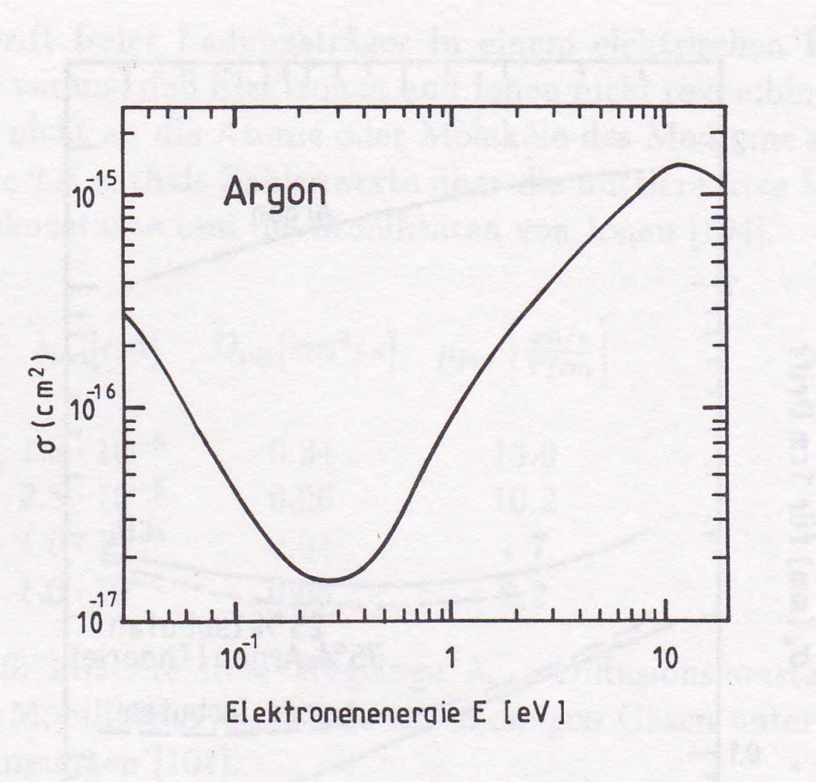




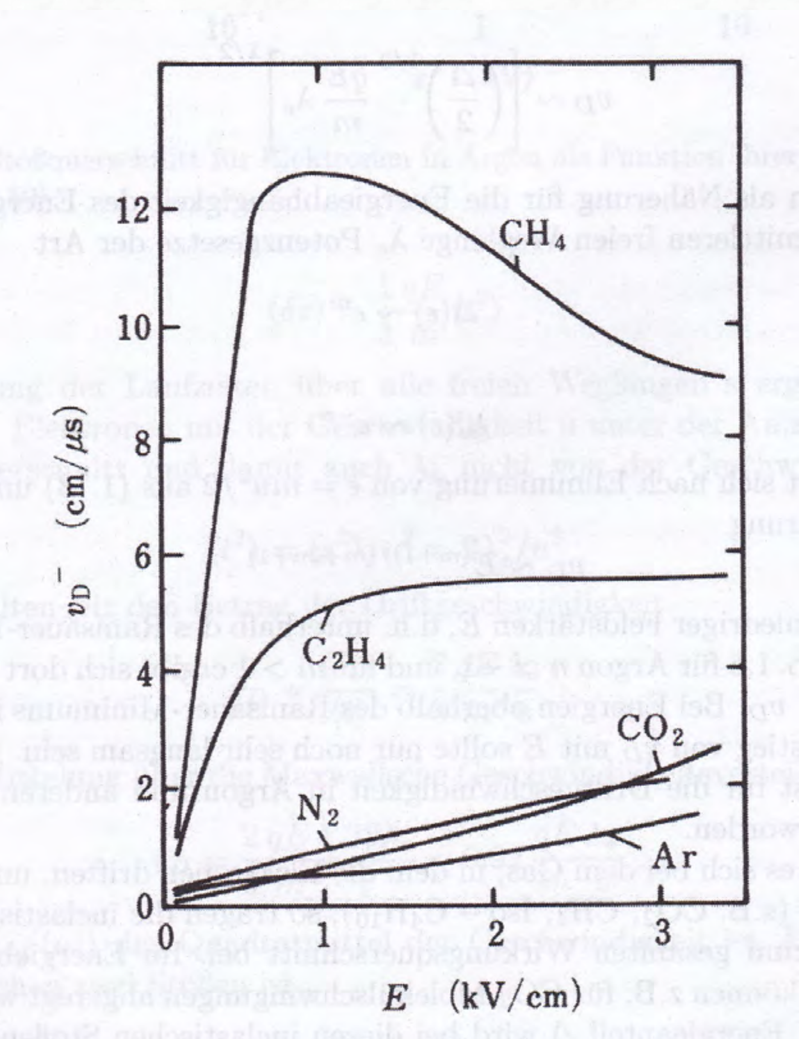
(the ATLAS liquid argon calorimeter uses current-sensitive amplifiers; measurement of the initial current!)

Gas	Massenzahl	u (cm/s)	D^+ (cm^2/s)	μ^+ ($\mathrm{cm}^2\mathrm{s}^{-1}\mathrm{V}^{-1}$)	λ (10^{-5} cm)
H_2	2.02	1.8×10^5	0.34	13.0	1.8
He	4.00	1.3×10^5	0.26	10.2	2.8
Ar	39.95	0.41×10^5	0.04	1.7	1.0
O_2	32.00	0.46×10^5	0.06	2.2	1.0
H_2O	18.02	0.61×10^5	0.02	0.7	1.0

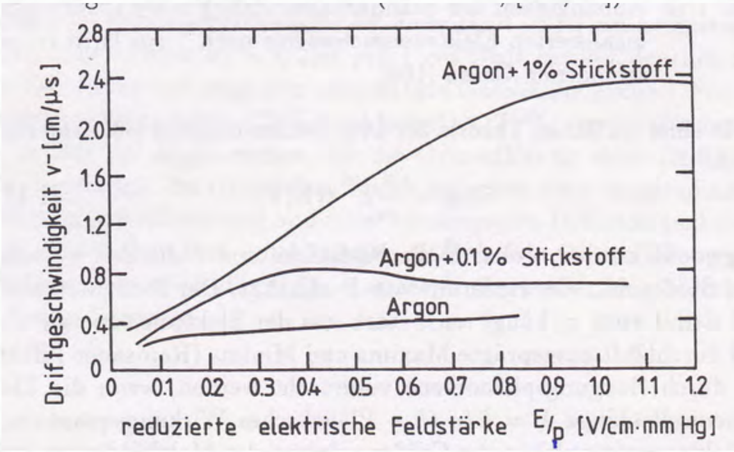
Thermal velocities u, diffusion coefficients D^+, mobilities μ^+ and mean free path lengths λ for positive ions in different gases at normal pressure p_0 [from Ref. 1].

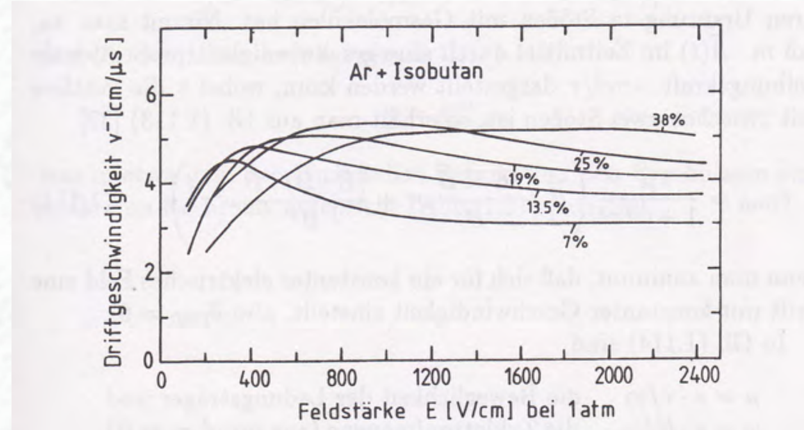


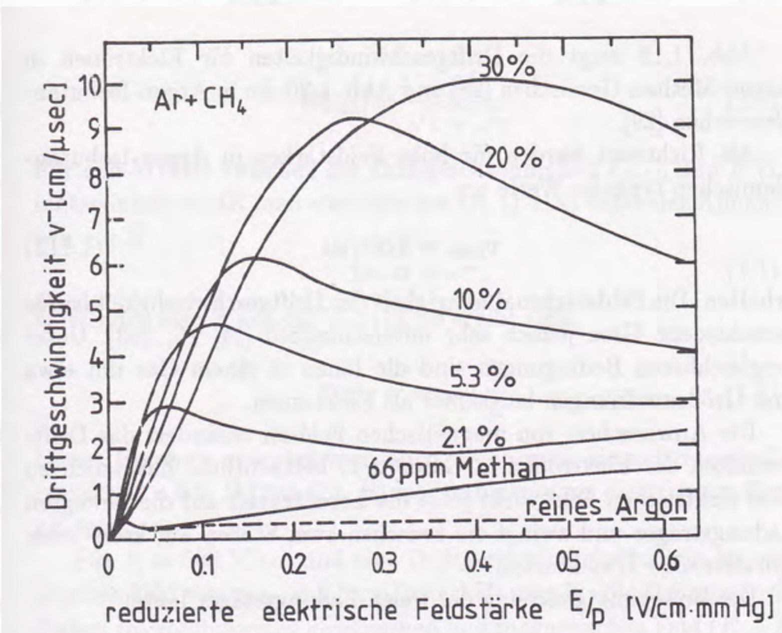
Scattering cross section σ for electrons in argon gas as a function of their kinetic energy [from Ref. 1].



Drift velocity of electrons in various gases at normal pressure as a function of the electric field strength [from Ref. 1].



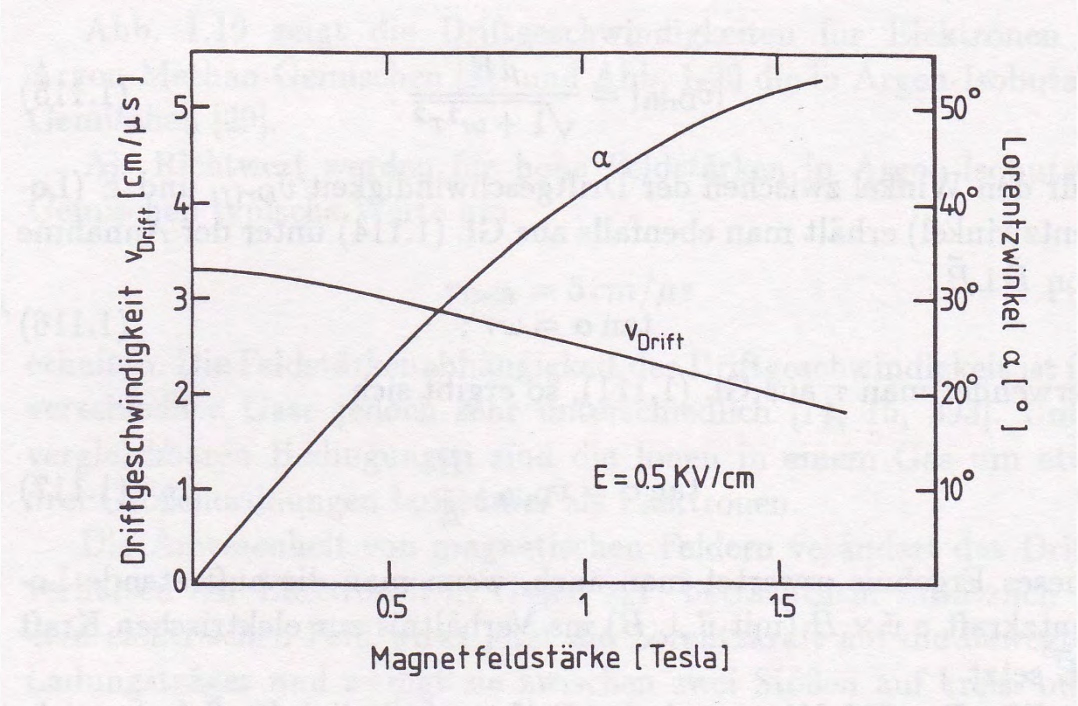




- The drift velocity in argon is relatively low, compared to other gases

- It can be significantly increased by the admixture of other gases, like (Ar, N_2), (Ar, CO_2), (Ar, CH_4) or (Ar, C_4H_{10})

Drift velocities of electrons in pure argon and in argon with admixtures of nitrogen, methane, and isobutane as a function of the reduced field strength (E/p) or field strength (E) [from Ref. 3].

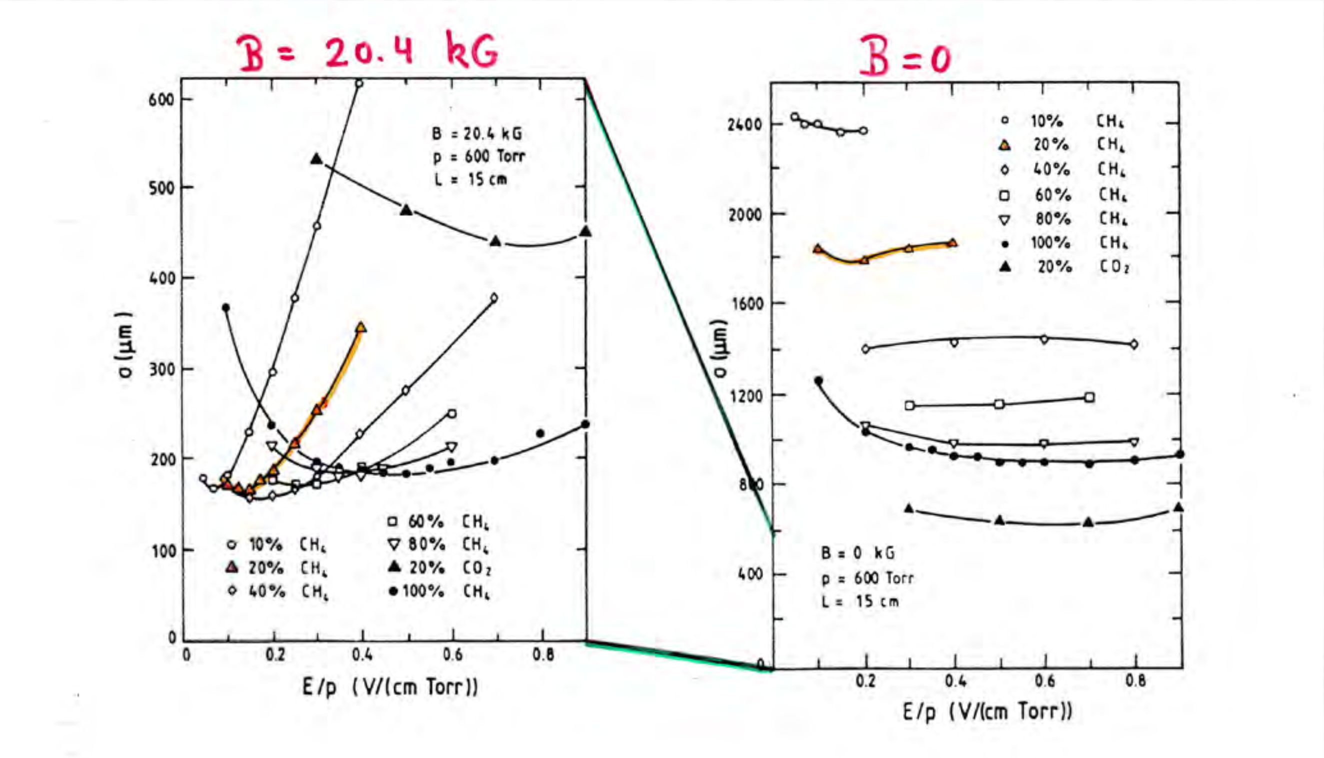


Drift velocities of electrons and Lorentz angle in a gas mixture of argon (67.2%), isobutane (30.3%) and methylal (2.5%) as a function of the magnetic field strength. The magnetic field is oriented perpendicular to the electric field [from Ref. 3].

Typical magnetic field strengths in particle physics experiments in the (inner detector volume, used for momentum determination)

LEP and Tevatron experiments: ~1.5 Tesla → sizeable effects
ATLAS: 2.0 Tesla
CMS: 3.8 Tesla

Diffusion with and without a magnetic field:



Standard deviation of an originally point-like electron cloud transverse to the drift direction (E-field) due to diffusion after a drift distance of 15 cm without a magnetic filed (right) and within a 2.04 T magnetic field parallel to the electric field (left), i.e. drift parallel to E [from Ref. 1].

→ significantly lower diffusion inside a magnetic field

important for position sensitive detectors (tracking detectors) like drift chambers and time projection chambers (→ Chapter 5)