PAUL SCHERRER INSTITUT

Malte Hildebrandt :: Paul Scherrer Institute

Electron Transport Parameters in Gases

LTP Seminar, PSI, November 29, 2021

Motivation

How large is the
Lorentz angle α_L of drifting electrons
in Helium under the following conditions?

$p = 8$ mbar

$T = 12$ K

$E = 1$ kV/cm

$B = 5$ T

$\angle(E,B) = 90°$

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$B = 5$ T

$\angle(E,B) = 90°$

$0° \leq \alpha_L \leq 90°$

Can somebody use
Magboltz(*) to calculate α_L?

(*)Magboltz: computer programm (CERN) that solves the Boltzmann transport equation (2-term approximation) for electrons in gases under the influence of E and B fields and calculates transport parameters

Charges in Gaseous Medium

1) Can one calculate (or estimate) α_L without 'tensor gymnastics' of exact transport theory?

complete set of cross-sections $\sigma_{ij}(\varepsilon)$ for electron atom / molecule scattering

$\xrightarrow{\text{transport theory (Boltzmann's equation)}}$

v_{drift}
$\tan\alpha_L$
D_T, D_L
$\alpha_{ionisation}$
$\alpha_{attachment}$

e.g. using momentum transfer theory: 'approximate formulas' for and relationships between experimentally measurable transport properties

2) Is this possible based only on pure E-field data, e.g. from a measurement or a calculation?

Transport Parameters - 1

volume filled with gas

free charges:
- energy loss of charged particle along its track or conversion of γ
- electron emission from hot cathode

external E- and B-field (homogenous, constant)
- electrons and positive ions drift towards their corresponding electrode
- after a few collisions: equilibrium of energy loss in collisions and energy gain between collisions

→ constant transport properties: v_{d,e^-} , v_{d,ion^+} , D_T, D_L , α_L , ε

remark:
- characteristic energy: $\frac{D}{K}$ → $\varepsilon = \frac{3}{2} \cdot \frac{D}{K}$
- transport coefficient: mobility K ↔ $v_d = K \cdot E$
  (linking the flow of a property with the "force" which causes it)

Transport Parameter - 2

drift of charge:

- typical values in operation of gaseous detectors :
  - v_{d,e^-} ≈ 1-10 cm/μs
  - v_{d,ion^+} ~ 1000-times slower
    usually kT-limit → constant mobility K → $v_{d,ion^+} = K \cdot E$
  - D_T, D_L ≈ 100-500 μm/√1cm
  - mean energy ε ≈ few eV
  - magnetic deflection angle / Lorentz angle α_L ≈ up to few tens of degrees

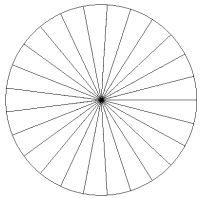
Why are these properties of interest? In particular the electron drift velocity v_d?

Large Area Gaseous Detectors

1908: first wire counter to study natural radioactivity

E.Rutherford, H.Geiger, 1908

Geiger, 1913



1928: Geiger-Müller counter with single electron sensitivity

H.Geiger, W.Müller, 1928

H.Geiger, W.Müller, 1928, 1929

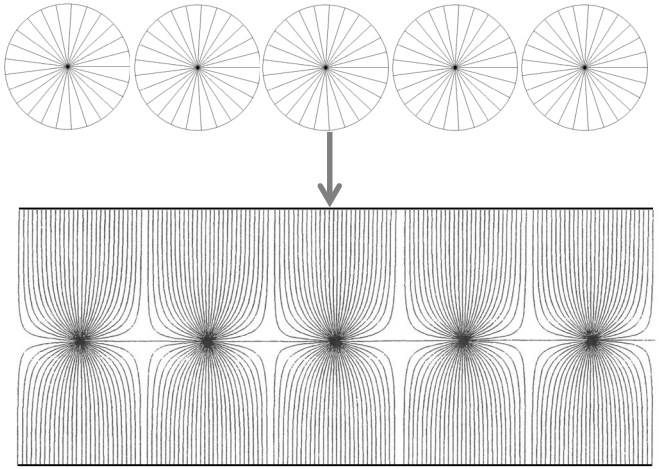
1945: proportional tubes

H.Raether, 1949

1968: multi-wire proportional chambers

G.Charpak, 1968

G.Charpak *et al.*, 1968



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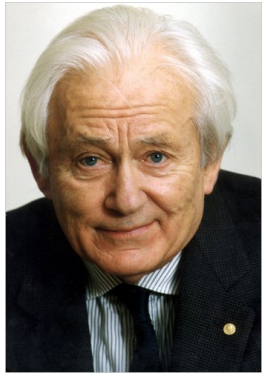
G.Charpak *et al.*, 1968

1992: Nobel Price in Physics: G.Charpak

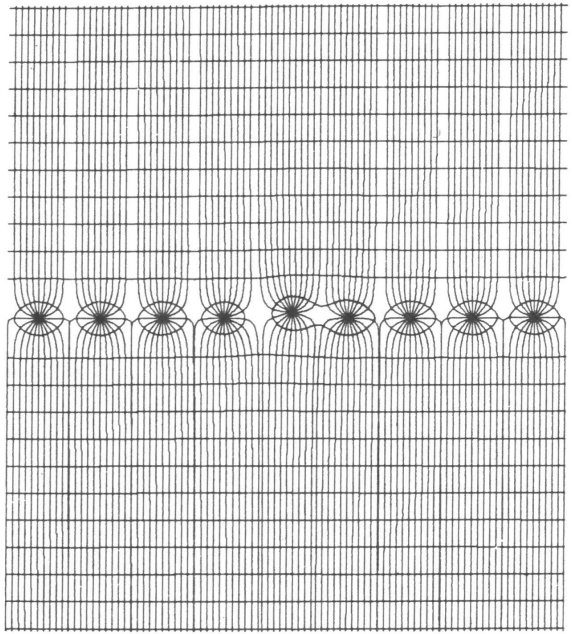
"…for his invention and development of particle detectors, in particular the multiwire proportional chamber."

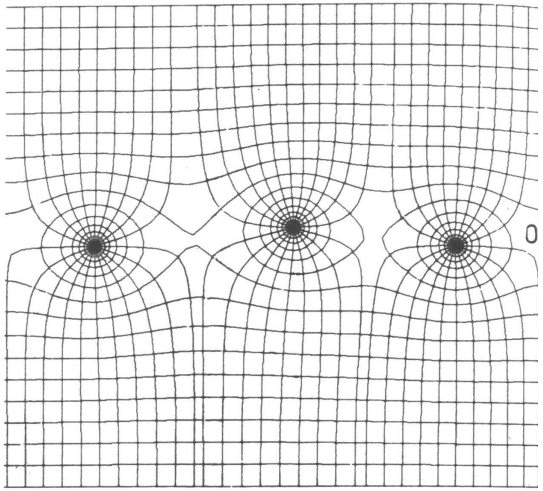


Large Area Gaseous Detectors - Limitations

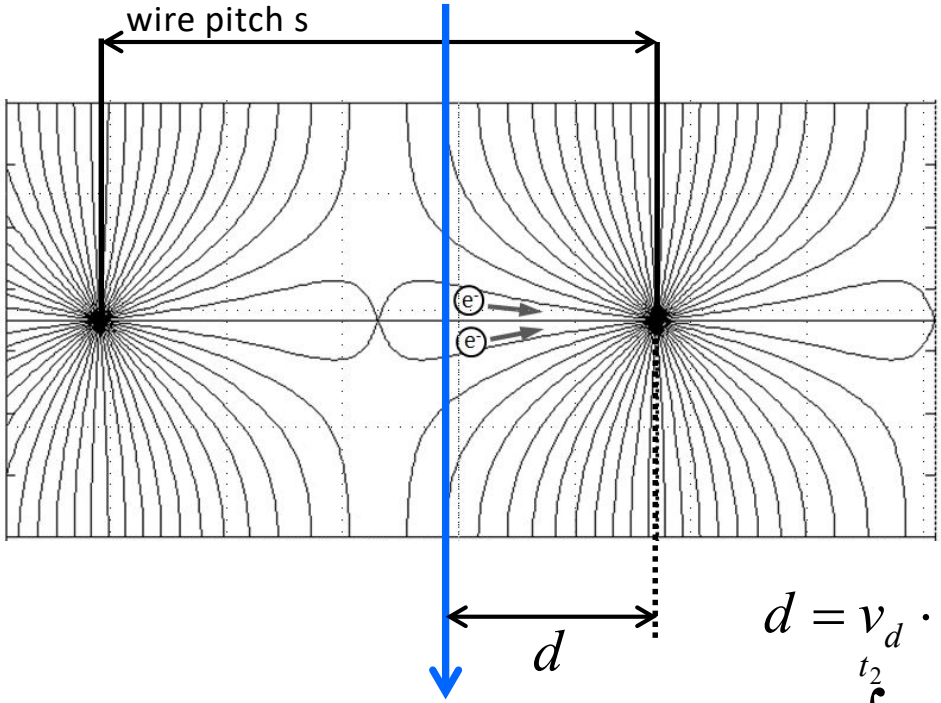
multi-wire proportional chamber (MWPC):

- spatial resolution given by granularity of anode wires (several mm)
- field distortions due to (electrostatic) displacements of anode wires





Drift Chamber - Principle



$$d = v_d \cdot t$$ in case v_d = constant

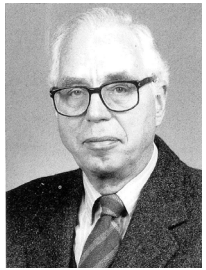
$$d = \int_{t_1}^{t_2} v_d(t)\,dt$$ in case $v_d = v_d(E)$

Drift Chamber

The drift chamber was "born" in Heidelberg:

- 1971: A. H. Walenta, J. Heintze and B. Schürlein, Nuclear Instruments and Methods 92 (1971) 373-380
- 1972: PhD thesis A. H. Walenta: "Lokalisierung von Teilchenspuren durch Messung der Elektronendriftzeiten in grossflächigen Proportionalzählern“

A.H.Walenta



J.Heintze

«electron swarm experiments» in Heidelberg

NUCLEAR INSTRUMENTS AND METHODS 92 (1971) 373–380; © NORTH-HOLLAND PUBLISHING CO.

THE MULTIWIRE DRIFT CHAMBER
A NEW TYPE OF PROPORTIONAL WIRE CHAMBER*

A. H. WALENTA, J. HEINTZE and B. SCHÜRLEIN

I. Physikalisches Institut der Universität Heidelberg, Heidelberg, Germany

Received 27 November 1970

σ = 0.2 mm with wire pitch ~10 mm

In this article a new type of proportional wire chamber is described with large wire distances and accurate position determination by drift time measurement. The electronic circuitry required has been considerably reduced while the space resolution has been improved as compared to a conventional proportional wire chamber. The limit for position accuracy seems to be at present $\sigma = 0.2$ mm.

The complete system with computer read out described in this article has a location accuracy of $\sigma = 0.47$ mm.

Botzmann's Transport Equation

transport of charged particles in neutral gases under the influence of electric and magnetic fields is described by the Boltzmann equation

$$\frac{\partial f}{\partial t} + \vec{v}\frac{\partial f}{\partial \vec{r}} + \vec{a}\frac{\partial f}{\partial \vec{v}} = -J(f)$$

with $f(\vec{r},\vec{v},t)$ velocity distribution function

<u>left-hand side:</u>

- changes of f due to the independent (collision less) motion of the ions:

$\frac{\partial f}{\partial t}$ → with time

$\vec{v}\frac{\partial f}{\partial \vec{r}}$ → due to free motion of ions

$\vec{a}\frac{\partial f}{\partial \vec{v}}$ → due to external forces: $\vec{a} = \frac{q}{m}(\vec{E} + \vec{v} \times \vec{B})$

<u>right-hand side:</u>

- changes due to binary collisions with the neutral particles:

$\vec{J}(f)$ → charged-particle – neutral-molecule collision operator

required:
complete set of cross-sections $\sigma_{ij}(\varepsilon)$

Transport Theory - 1

transport parameters (e.g. v_d, ε, $\tan\alpha_L$, D_T, D_L) are calculated from appropriate velocity moments of $f(\vec{r},\vec{v},t)$.

$$v_{drift} = \langle \vec{v} \rangle = \frac{1}{n(\vec{r},t)} \cdot \int \vec{v} f(\vec{r},\vec{v},t) d\vec{v}$$

$$\varepsilon_{mean} = \frac{1}{2} m \langle v^2 \rangle = \frac{1}{n(\vec{r},t)} \cdot \int (\frac{1}{2} m v^2) f(\vec{r},\vec{v},t) d\vec{v}$$

with: $n(\vec{r},t) = \int f(\vec{v},\vec{r},t) d\vec{v}$

The basic tasks in kinetic theory:

- „formulate“ collision operator J
- solve Boltzmann equation to get $f(\vec{r},\vec{v},t)$
- calculate transport parameters

Transport Theory - 2

Boltzmann equation can be solved through a decomposition of $f(\vec{r},\vec{v},t)$ in spherical harmonics:

$$f(\vec{r},\vec{v},t)=\sum_{l=0}^{\infty}\sum_{m=-l}^{l} f_m^{(l)}(\vec{r},v,t)Y_m^{[l]}(\hat{v})$$

with:

$$f_m^{(l)}(\vec{r},\vec{v},t)=w(\alpha,v)\sum_{\nu=0}^{\infty}F(\nu lm;\alpha,\vec{r},t)R_{\nu l}(\alpha v)$$ ↔ decomposition in velocity-space

$$\alpha^2=\frac{m}{kT_b}$$ ↔ parameter to optimize convergence
T_b = „base temperature“

$$w(v;T_b)=\left(\frac{\alpha^2}{2\pi}\right)^{3/2}\cdot\exp\left(\frac{\alpha^2 v^2}{2}\right)$$ ↔ Maxwellian type weight function

$$R_{\nu l}(\alpha v)=N_{\nu l}\left(\frac{\alpha(t)v}{\sqrt{2}}\right)^l S_{l+1/2}^{(\nu)}\left(\frac{\alpha^2 v^2}{2}\right)$$

$$N_{\nu l}^2=\frac{2\pi^{3/2}\nu!}{\Gamma(\nu+l+3/2)}$$

$$S_{l+1/2}^{(\nu)}$$ ↔ Sonine polynomial

Transport Theory - 3

$$f(\vec{r},\vec{v},t) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} f_m^{(l)}(\vec{r},v,t) Y_m^{[l]}(\hat{v})$$

indices are a measure for:

l deviation from isotropy

m deviation from Maxwellian

→ necessary for numerical solution: truncate decomposition at $l = l_{max}$

- set l_{max} = 1 → l = 0, 1 (2-term approximation)
  Magboltz 1 (E- and B-field)
  Bolsig+ (only E-field)

Biagi, NIM A 273 (1988) 533-535
Biagi, NIM A 283 (1989) 716-722
Biagi, NIM A 310 (1991) 133-136

Hagelaar, Pitchford, Plasma Sources Sci. Technol. (2005) 722-722

- allow $l = l_{max}$ → multi-term codes

Robson, Ness, Phys.Rev. A, Vol.33 (1986) 2068
Ness, Robson, Phys.Rev. A, Vol.34 (1986) 2185
Ness, Phys.Rev. A, Vol.47 (1993) 327
White *et al.*, Phys.Rev. E, Vol.60 (1999) 2231

for completeness:

- MC → Magboltz 2 (E- and B-field)

Biagi, NIM A 421 (1999) 234-240

Units in Gaseous Electronics

collision operator in Boltzmann transport equation is proportional to N

→ gaseous electronics scales with parameter E/N and B/N

particle number density N

$$N = \frac{n}{V} = \frac{k_B \cdot T}{p}$$

→ E/N: 1 Townsend = 1 Td = 10^{-21} Vm^2

(Huxley, Crompton, Elford, 1966)

Sir J.S.E.Townsend
1868-1957

→ B/N: 1 Huxley = 1Hx = 10^{-27} Tm^3

(Ness, 1991)

(Heylen, 1980: 10^{-23} Tm^3)

Sir L.G.H.Huxley
1902-1988

@ 20°C, 1 bar:

1 Td ≈ 250 V/cm

1 Hx ≈ 0.025 T

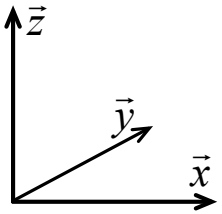
Reduced Fields

experimental conditions		extrapolation to room temperature		extrapolation to standard pressure
p = 8 mbar	24.4x →	p = 195 mbar	5.2x →	p = 1013 mbar
T = 12 K	24.4x →	T = 293 K		T = 293 K
$N = 4.83 \cdot 10^{24}\ 1/m^3$		$N = 4.83 \cdot 10^{24}\ 1/m^3$	5.2x →	$N = 2.5 \cdot 10^{25}\ 1/m^3$
E = 1 kV/cm		E = 1 kV/cm	5.2x →	E = 5.2 kV/cm
B = 5 T		B = 5 T	5.2x →	B = 25.9 T
E/N = 20.7 Td		E/N = 20.7 Td		E/N = 20.7 Td
B/N = 1036 Hx		B/N = 1036 Hx		B/N = 1036 Hx

Magnetic Deflection (Lorentz) Angle α_L

E-Feld:

$$E = \begin{pmatrix} 0 \\ 0 \\ -E_z \end{pmatrix} \longrightarrow v = \begin{pmatrix} 0 \\ 0 \\ v_z \end{pmatrix}$$



E×B-Feld:

Lorentzangle α_L

$$E = \begin{pmatrix} 0 \\ 0 \\ -E_z \end{pmatrix} \quad B = \begin{pmatrix} 0 \\ B_y \\ 0 \end{pmatrix} \longrightarrow v = \begin{pmatrix} v_x \\ 0 \\ v_z \end{pmatrix} \longrightarrow \boxed{\tan(\alpha_L) = \frac{v_x}{v_z}} = \frac{v_{E\times B}}{v_E}$$

- assumption: ratio of drift velocity components equal to ratio of average forces acting on e^- (only valid if drifting electrons follow Maxwellian velocity distribution):

Grupen 93, Kleinknecht 92
Sauli 77, Peisert / Sauli 84

$$\left.\begin{array}{lll} \vec{F}_L = q \cdot \vec{v}_0 \times \vec{B} & F_x = q \cdot v_0 \cdot B & v_0 = v(E, B = 0) \\ \vec{F}_E = q \cdot \vec{E} & F_z = q \cdot E & \end{array}\right\} \longrightarrow \tan(\alpha_L) = v_0(E, B = 0) \cdot \frac{B}{E}$$

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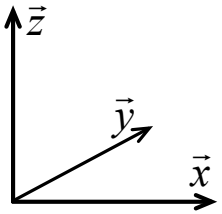


E×B-Feld:

$$E = \begin{pmatrix} 0 \\ 0 \\ -E_z \end{pmatrix} \quad B = \begin{pmatrix} 0 \\ B_y \\ 0 \end{pmatrix} \longrightarrow v = \begin{pmatrix} v_x \\ 0 \\ v_z \end{pmatrix} \longrightarrow \boxed{\tan(\alpha_L) = \frac{v_x}{v_z}} = \frac{v_{E\times B}}{v_E}$$

Lorentzangle α_L

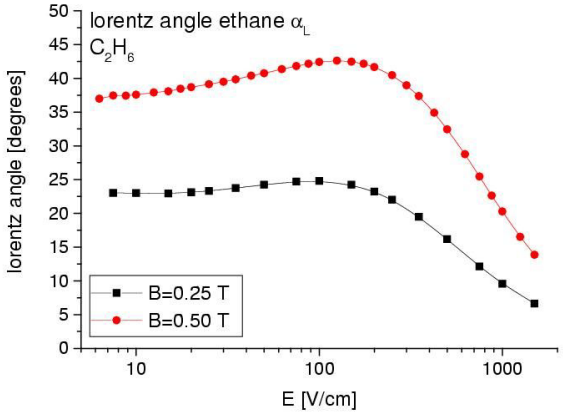
- in general:

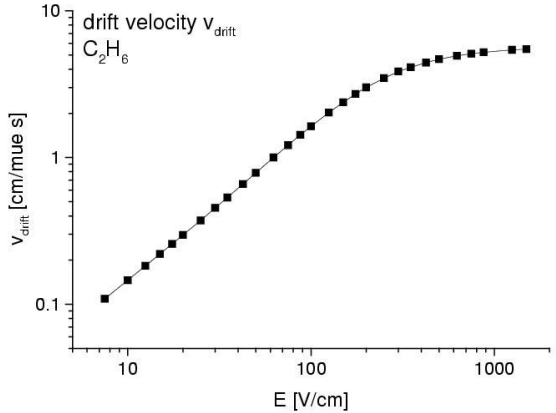
magnetic deflection coefficient $\psi = \psi(E,B) \longrightarrow$

$$\boxed{\tan(\alpha_L) = v_0(E, B=0) \cdot \frac{B}{E} \cdot \psi(E,B)}$$

Huxley, Aust. J. Phys. 13 (1960) 718-737
Frost, Phelps, Phys. Rev. 126 (1962) 1621-1633

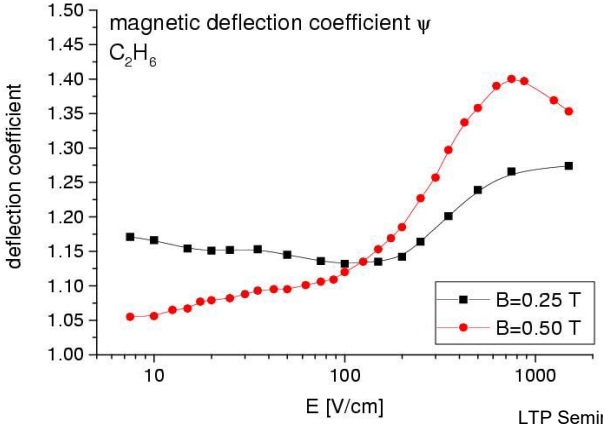
Transport Parameters C_2H_6





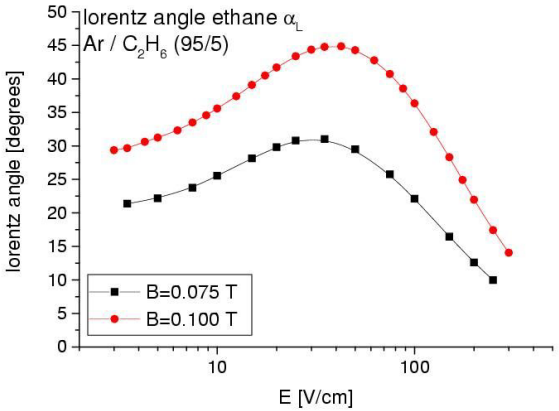
C_2H_6

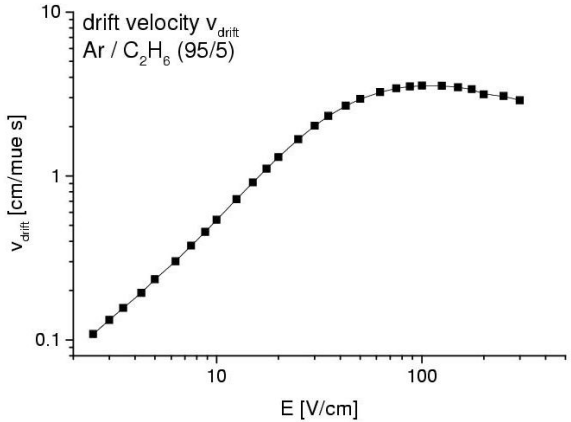
$$\tan(\alpha_L) = v_0 \cdot \frac{B}{E} \cdot \psi$$



Hildebrandt, diploma thesis, University Heidelberg, 1995

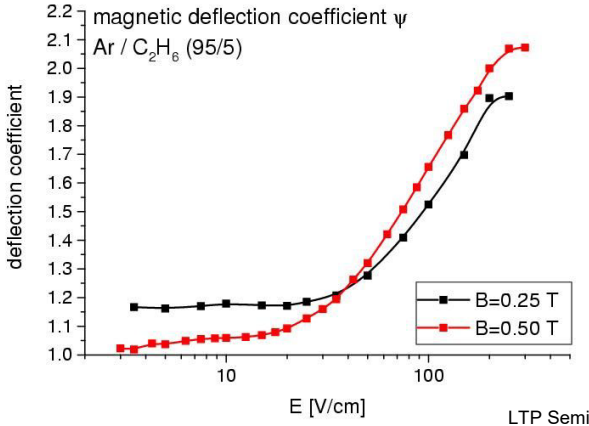
Transport Parameters Ar/C_2H_6





Ar/C_2H_6 (95/5)

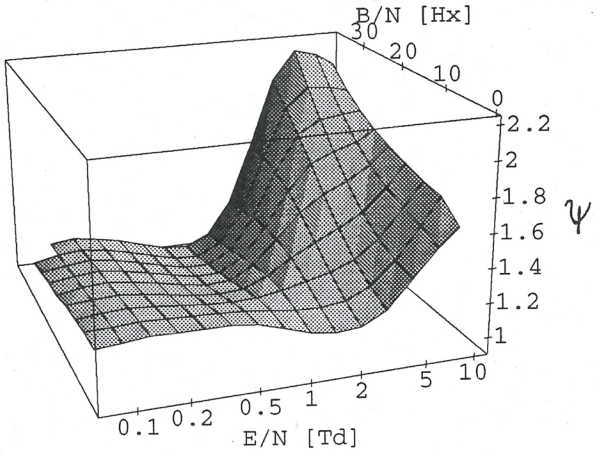
$$\tan(\alpha_L) = v_0 \cdot \frac{B}{E} \cdot \psi$$



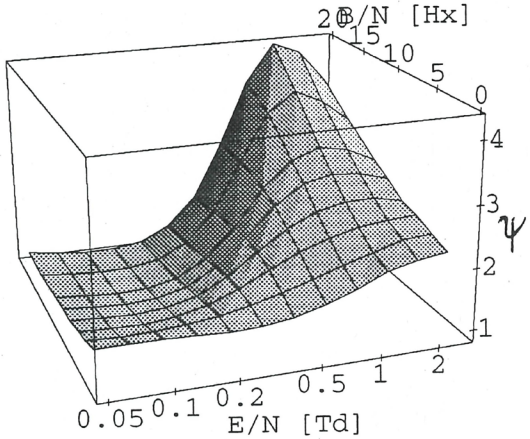
Hildebrandt, diploma thesis, University Heidelberg, 1995

Magnetic Deflection Coefficient

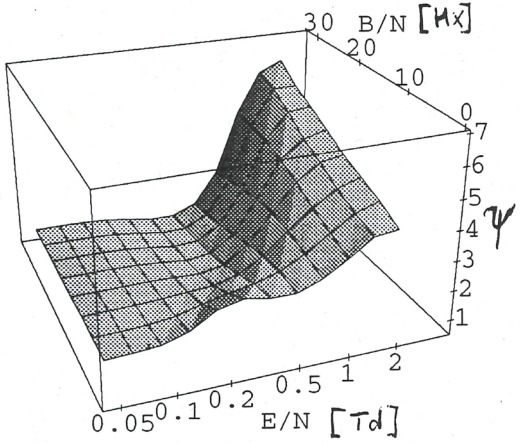
CH_4



Ar/CH_4 (90/10)



Kr/CH_4 (95/5)



Kunst, PhD thesis, University Heidelberg, 1992
Kunst, Götz, Schmidt, NIM A324 (1993) 127-140

Equation of Motion - 1

drift velocity $\vec{v}_d$ in case of $\vec{E}$ and $\vec{B}$ fields (derived from equation of motion):

$$\vec{v}_d = \frac{K(\varepsilon)\cdot E}{1+\omega^2/\nu^2(\varepsilon)}\left[\hat{E}+\frac{\omega}{\nu(\varepsilon)}\left(\hat{E}\times\hat{B}\right)+\frac{\omega^2}{\nu^2(\varepsilon)}\left(\hat{E}\cdot\hat{B}\right)\hat{B}\right]$$

$$K(\varepsilon) = \frac{e}{\mu\cdot v_m(\varepsilon)}$$

$$\mu = \frac{m\cdot M}{m+M}$$

$$\omega = \frac{e\cdot B}{m}$$

$$\nu_m(\varepsilon) = n_0\sqrt{\frac{2\varepsilon}{\mu}}\sigma_m(\varepsilon)$$

Equation of Motion - 1

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$$\mu=\frac{m\cdot M}{m+M}$$

$$\omega=\frac{e\cdot B}{m}$$

$$\nu_m(\varepsilon)=n_0\sqrt{\frac{2\varepsilon}{\mu}}\sigma_m(\varepsilon)$$

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

$$\vec{v}_d = \frac{K(\varepsilon)\cdot E}{1+\omega^2/\nu^2(\varepsilon)}\left[\hat{E}+\frac{\omega}{\nu(\varepsilon)}\left(\hat{E}\times\hat{B}\right)\right]$$

conclusion 1: $$\left|\vec{v}_{d\_Bfield}\right| = \sqrt{v^2_{d\_\hat{E}}+v^2_{d\_\hat{E}\times\hat{B}}} = \frac{K(\varepsilon)\cdot E}{\sqrt{1+K^2(\varepsilon)\cdot B^2}}$$

e.g. of interest in view of Tonks' theorem

Equation of Motion - 2

drift velocity $\vec{v}_d$ in case of $\vec{E}$ and $\vec{B}$ fields (derived from equation of motion):

$$\vec{v}_d = \frac{K(\varepsilon)\cdot E}{1+\omega^2/\nu^2(\varepsilon)}\left[\hat{E}+\frac{\omega}{\nu(\varepsilon)}\left(\hat{E}\times\hat{B}\right)+\frac{\omega^2}{\nu^2(\varepsilon)}\left(\hat{E}\cdot\hat{B}\right)\hat{B}\right]$$

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$$\mu=\frac{m\cdot M}{m+M}$$

$$\omega=\frac{e\cdot B}{m}$$

$$\nu_m(\varepsilon)=n_0\sqrt{\frac{2\varepsilon}{\mu}}\sigma_m(\varepsilon)$$

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

$$\vec{v}_d = \frac{K(\varepsilon)\cdot E}{1+\omega^2/\nu^2(\varepsilon)}\left[\hat{E}+\frac{\omega}{\nu(\varepsilon)}\left(\hat{E}\times\hat{B}\right)\right]$$

conclusion 2: $$\tan(\alpha_L)=\frac{v_{d\_\hat{E}\times\hat{B}}}{v_{d\_\hat{E}}}=\frac{\omega}{\nu(\varepsilon)}=K(\varepsilon)\cdot B$$

arbitrary angle between E and B field

from momentum transfer theory(*):

$$\tan(\alpha_L) = \frac{K(\varepsilon)\cdot B\cdot \sin\theta}{\sqrt{1+K^2(\varepsilon)\cdot B^2\cdot \cos^2\theta}}$$

$\theta = \angle(E,B)$

for θ = 90°:

$$\tan(\alpha_L) = K(\varepsilon)\cdot B$$

(*) momentum transfer theory:

- semi-quantitative alternative to rigorous numerical solution of Boltzmann's equation
- provides formulas for and relationships between experimentally measurable transport properties, e.g. Wannier energy relation, Blanc's law, generalised Einstein relation
- assumes weak energy dependencies of $\nu_m(\varepsilon)$, Taylor series around some reference energy $\bar{\varepsilon}$ converges rapidly, and assumes $\bar{\varepsilon} = \varepsilon_{CM}$
- based on energy and momentum balance equations
- exact for constant ν_m (Boltzmann model), works surprisingly well even if not the case (10% level)

Equivalent Field Concept

concept of equivalent electric field $\vec{E}_e$:

«$\vec{E}_e$ is the electrical field for B = 0 required to keep the mean energy ε at the same value as in the situation with E and B»

$$\varepsilon\left(E,B\right)=\varepsilon\left(E_e,0\right)$$

from momentum transfer theory:

$$E_e = E\cdot\cos(\alpha_L)$$

further more: Tonks' theorem $v_d\left(E,B\right)=v_{d\_Efield}\left(E_e\right)$

Tonks, Phys. Rev. 51 (1937) 744-747
Tonks, Allis, Phys. Rev. 52 (1937) 710-713
Tonks, Phys. Rev. 97 (1955), 1443-1445

in case of set of measurements, including α_L: $\kappa=\dfrac{v_d\left(E,B\right)}{v_{d\_Efield}\left(E_e\right)}$ = 1 ± 10%

Equivalent Field Concept

concept of equivalent electric field $\vec{E}_e$:

approach 1: $$E_e = \frac{E}{\sqrt{1 + K^2(\varepsilon) \cdot B^2}}$$

approach 2: $$E_e = \frac{1}{K(\varepsilon)} \sqrt{\frac{2}{M}\left(\varepsilon + \Omega(\varepsilon) - \frac{3}{2} k_B T\right)}$$

k_B = Boltzmann's constant

$$\Omega(\varepsilon) = \frac{M}{2m} \cdot \varepsilon^* \cdot \frac{\sigma_i(\varepsilon)}{\sigma_m(\varepsilon)} \cdot S(\varepsilon)$$

$$S(\varepsilon) = e^{-\frac{3}{2} \cdot \frac{\varepsilon^*}{\varepsilon}}$$

ε^* = excitation energy

Mean Energy ε

How can one estimate the mean energy ε?

1) drift velocity v_d

$$\varepsilon = \frac{3}{2} k_B T + \frac{1}{2} M v_d^2 - \Omega(\varepsilon)$$

Wannier relation

Wannier, Bell System Technical Journal, 32(1) (1953), 170-254
Wannier, Phys. Rev. 83 (1951) 281-289

2) characteristic energy D/K

$$\varepsilon = \frac{3}{2} \frac{D}{K}$$

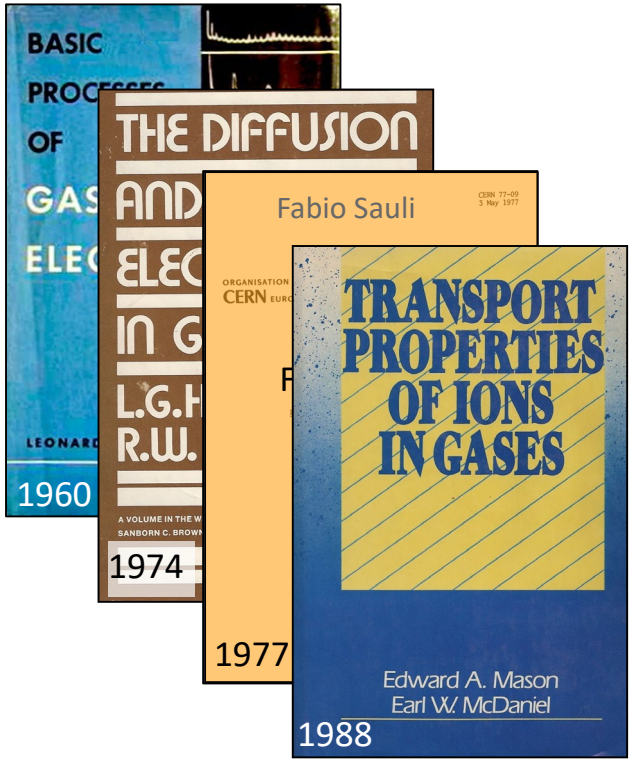
possible sources for v_d, K or D/K:

- data bases with experimental results
- Bolsig+(*) (E-field only calculation)

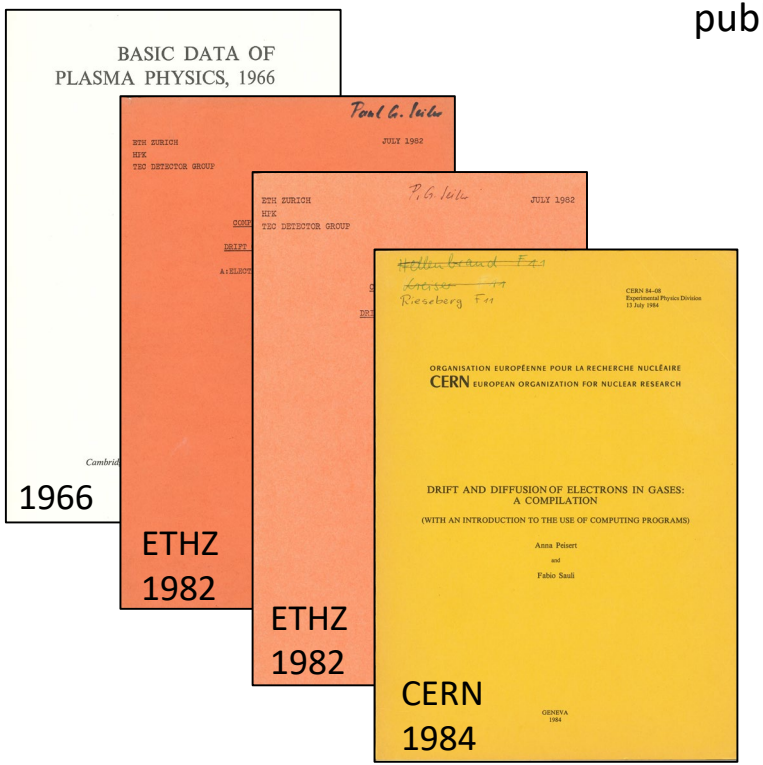
(*)BOLSIG+: computer programm (LAPLACE Laboratory, Toulouse, France) that solves the Boltzmann transport equation (2-term approximation) for electrons in gases under the influence of E field only and calculates transport parameters

Data Bases - Examples

tables in textbooks



…and compilations



…and many more (individual) publications!

Data Bases - LXCat

https://fr.lxcat.net/home/

HOME | HOW TO USE | CONTRIBUTORS | DATA CENTER | ONLINE CALCULATIONS | DOCS AND LINKS | DISCUSSION BOARD

about the project » news and events » statistics and geography » the lxcat team

About the project

The **Plasma Data Exchange Project** is a community-based project which was initiated as a result of a public discussion held at the 2010 Gaseous Electronics Conference (GEC), a leading international meeting for the **Low-Temperature Plasma** community. This project aims to address, at least in part, the well-recognized needs for the community to organize the means of collecting, evaluating and sharing data both for modeling and for interpretation of experiments.

At the heart of the Plasma Data Exchange Project is **LXCat** (pronounced "elecscat"), an open-access website for collecting, displaying, and downloading electron and ion scattering cross sections, swarm parameters (*mobility, diffusion coefficient, etc.*), reaction rates, energy distribution functions, etc. and other data required for modeling low temperature plasmas. The available data bases have been contributed by members of the community and are indicated by the contributor's chosen title.

Data Bases - LXCat

Bolsig+ (only pure gases, no mixtures)

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functions, etc. a ture plasmas. The av e
community and

- Budapest (Budapest Drift Tube Database)
- CDAP (State-to-state electron-impact excitation rate coefficients)
- Christophorou database
- Dutton database
- eMol-LeHavre (eMol group LeHavre)
- ETHZ (ETH Zurich, High Voltage Laboratory)
- Heidelberg database
- IST-Lisbon database
- LAPLACE (measurements after 1975)
- Phelps database
- UNAM database
- UT (University of Tartu)
- Viehland database
- BOLSIG+ solver

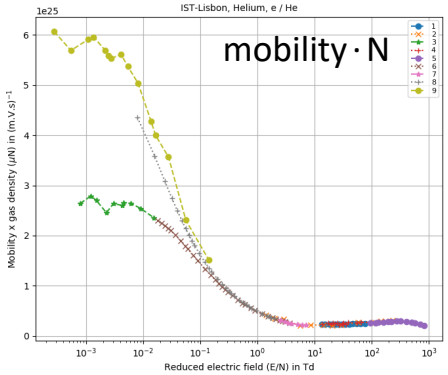
- SCATTERING CROSS SECTIONS
- DIFFERENTIAL SCATTERING CROSS SECTIONS
- INTERACTION POTENTIALS
- OSCILLATOR STRENGTHS
- SWARM / TRANSPORT DATA

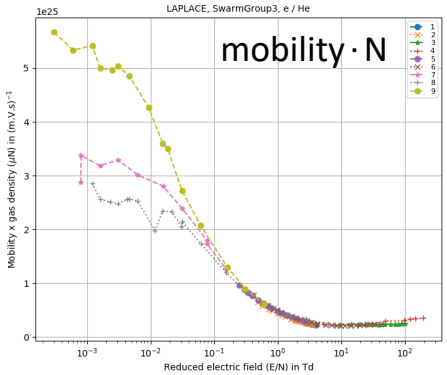
GLOBAL SPECIES FILTERING

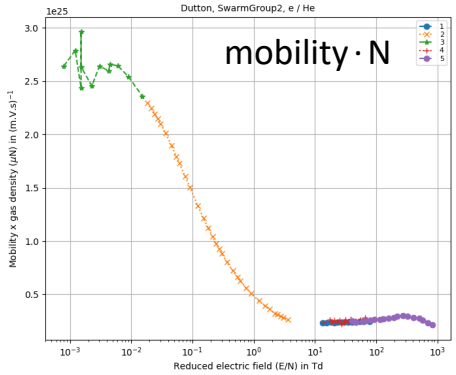
- ELECTRONS
- IONS

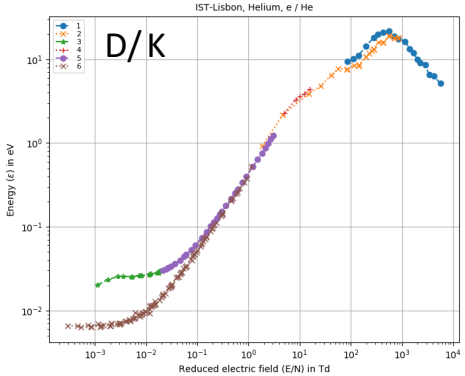
Electrons in Helium – Experimental Data

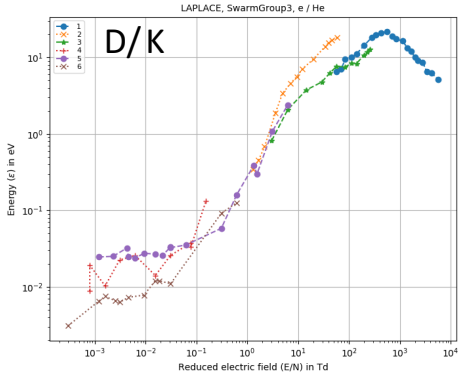
- E-field only configuration

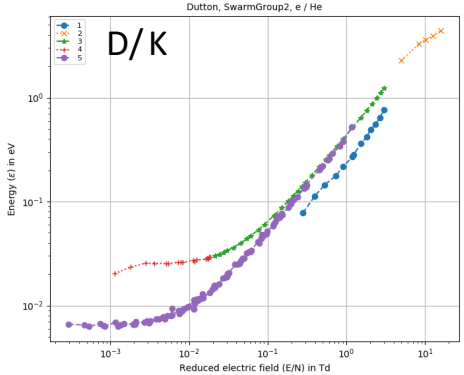






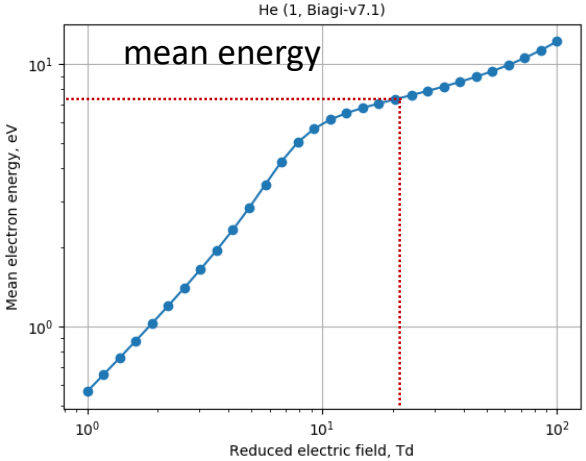


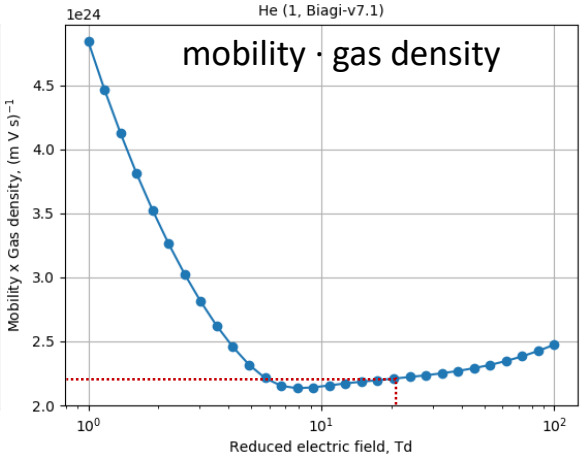


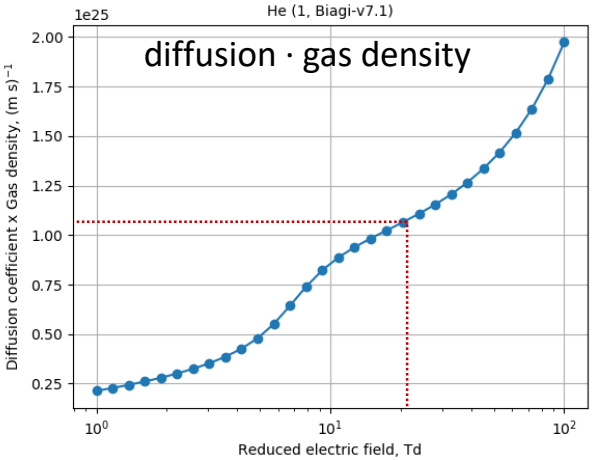


Electrons in Helium – Bolsig+ Calculation

- E-field only configuration







$$\rightarrow \quad \varepsilon = \varepsilon\left(E/N = 20.7Td\right)$$

$$\rightarrow \quad K(\varepsilon) = K\left(E/N = 20.7Td\right)$$

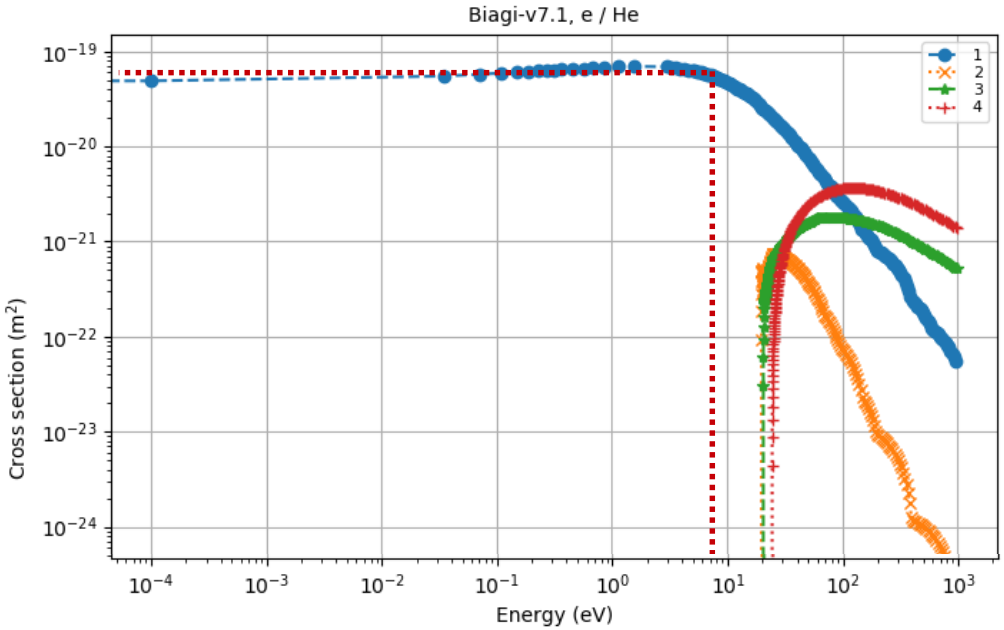
$$\rightarrow \quad \varepsilon = \frac{3}{2} \cdot \frac{D\left(E/N = 20.7Td\right)}{K\left(E/N = 20.7Td\right)}$$

$$\rightarrow \quad v_d = K(E/N) \cdot E \xrightarrow{\text{Wannier}} \varepsilon$$

Electron-Helium Scattering Cross Sections σ(ε)

- e^- in He

$\rightarrow \sigma_m(\varepsilon)$



Lorentz Angle α_L - Results

«How large is the Lorentz angle α_L of drifting electrons in Helium under the conditions N = 4.8310^{24} 1/m^3 , E = 1 kV/cm, B = 5 T, $\angle$(E,B) = 90°?»

→ calculation with Bolsig+ of ε, K(E,B=0) and D/K(E,B=0) to estimate ε and K
(experimental values from measurements agree more or less…)

→ LXCat database to extract values for $\sigma_{m\_He}(\varepsilon)$, $\sigma_{i\_He}(\varepsilon)$

$$\tan(\alpha_L) = K(\varepsilon)\cdot B\ ,\ \cos(\alpha_L) = \frac{E_e}{E}$$

Magboltz calculation

$64.7° \leq \alpha_L \leq 71.9$

$\alpha_L = 66.0°$

$\pm$ 10%

$$\tan(\alpha_L) = v_0(E, B=0)\cdot\frac{B}{E}\cdot\psi(E,B)$$

$0.92 \leq \psi \leq 1.33$

Summary

- Solving Boltzmann's equation and exact transport theory is not a task for the backside of an envelope
- Magboltz allows to calculate transport parameters and is common tool in gaseous detector community.
- Momentum transfer theory provides certain "approximate formulas" to estimate parameters or relations.
- LXCat offers a lot of valuable information!

Acknowledgement

- Aldo – thanks for the inspiring question!