Penning Effect

RD51 Collaboration Meeting and Lectures

22– 26 June 2020, CERN

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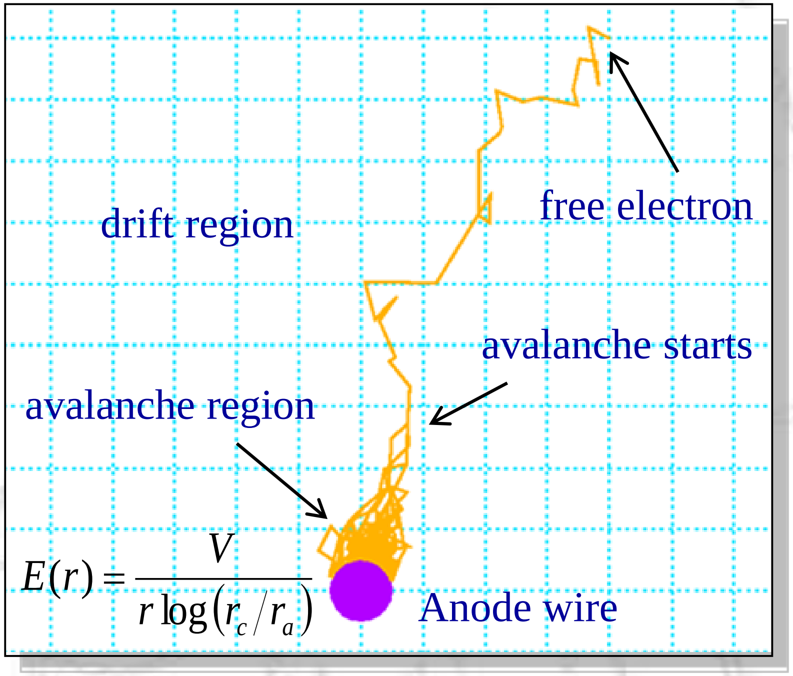
Gas gain (G) and Townsend coefficient



$e^- + A \rightarrow A^+ + 2e^-$: ionisation

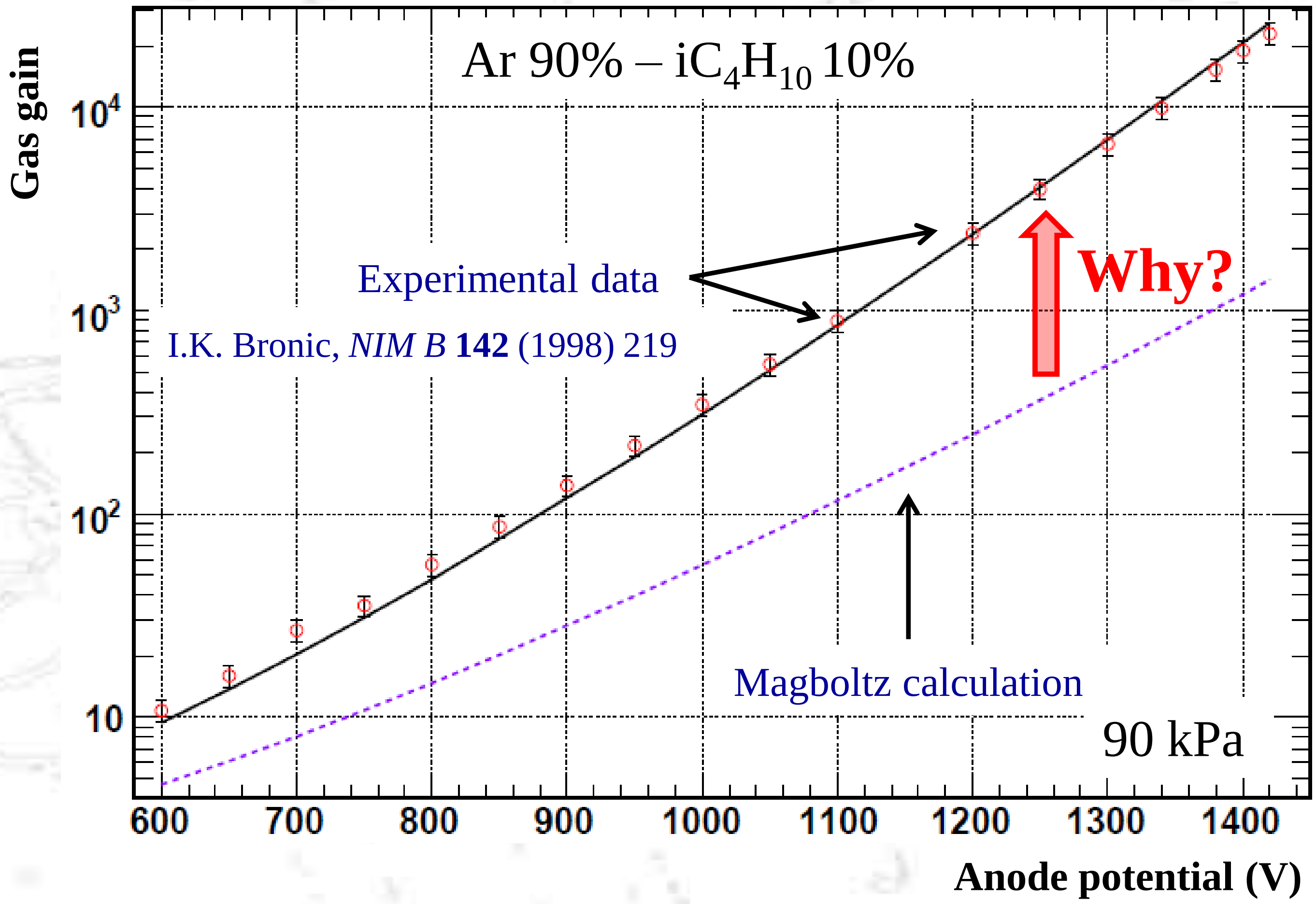
$$G = \frac{N}{N_0} = e^{\int \alpha(E(r))\, dr}$$

- N : number of total electron
- N_0 : number of primary electrons

- α, Townsend coefficient:
  - mean number of ion pairs created by a free electron per unit length
  - depends on the gas properties: pressure, temperature ...
    - and on the applied electric field
- Townsend coefficients can be calculated by **Magboltz** program

  S.F. Biagi, NIM A 421 (1999) 234–240.

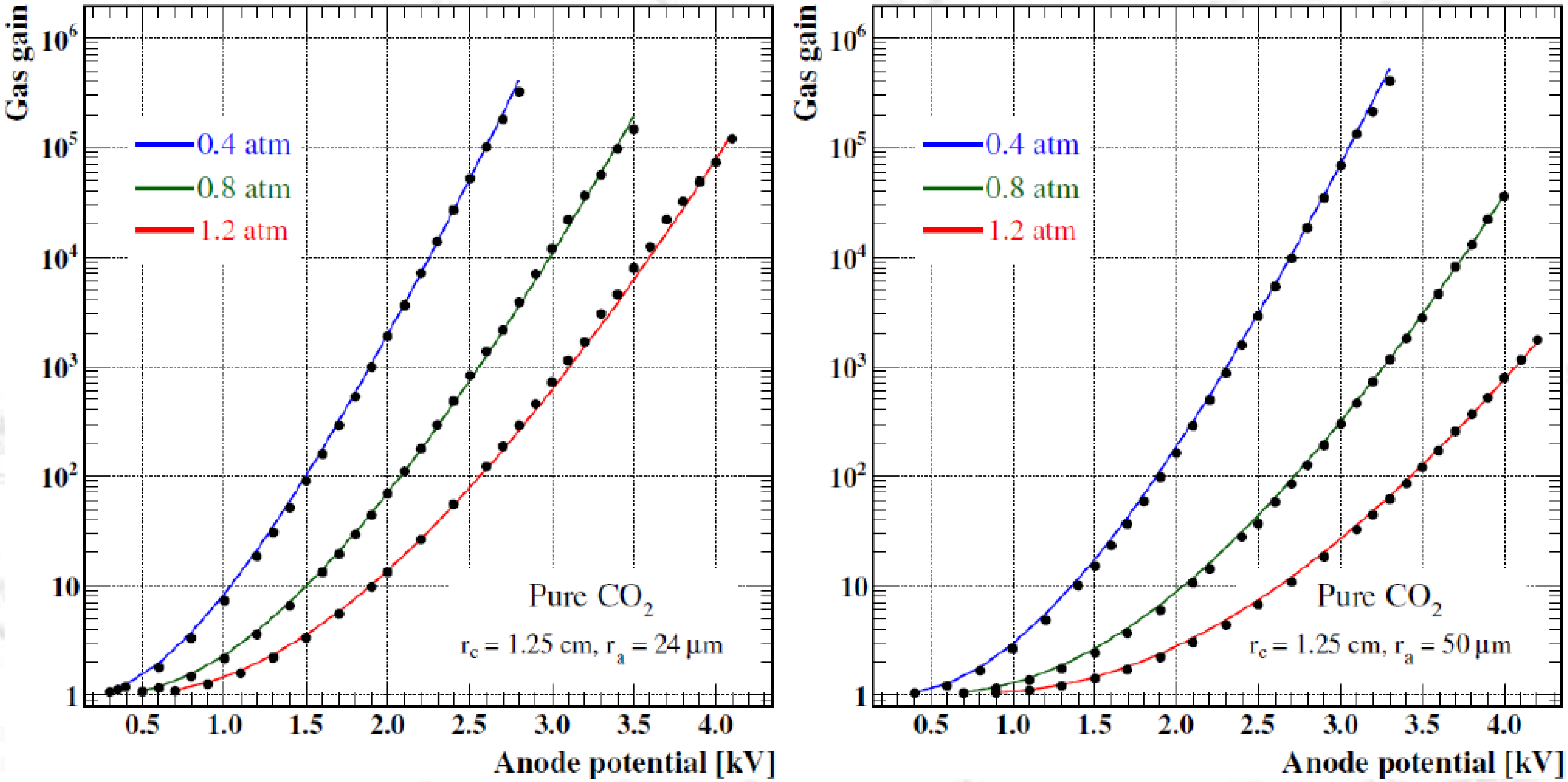
Calculation example



- α, Townsend coefficients: from ionisation cross section by Magboltz

Are ionisation cross sections wrong in Magboltz ???

Gain calculations for Pure CO_2



- ❖ Magboltz calculates the measured gains in pure CO_2 accuratelty
- ❖ Direct ionisation cross sections of CO_2 in Magboltz are correct
- ❖ **There should really be other physical processes in mixtures**

Penning energy transfers

$e^- + A \rightarrow A^+ + 2e^-$: ionisation $\rightarrow$ Townsend coefficients

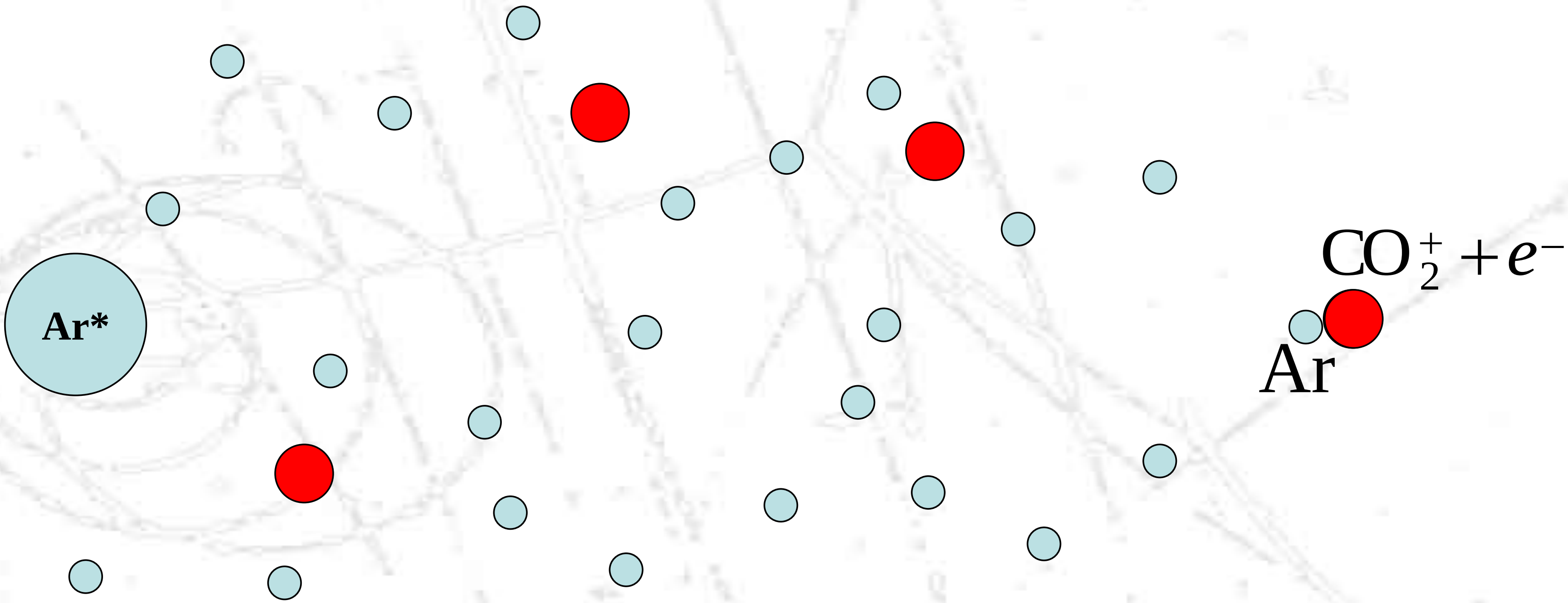
$e^- + A \rightarrow A^*$: excitation $\rightarrow$ **what happens ?**

- Assume a gas mixture ($A - B$)
  - A : noble gas (Ar, Xe, Ne, He ...)
  - B : mostly a molecular gas (CO_2, CH_4, C_2H_6, C_3H_8, iC_4H_{10} ...)

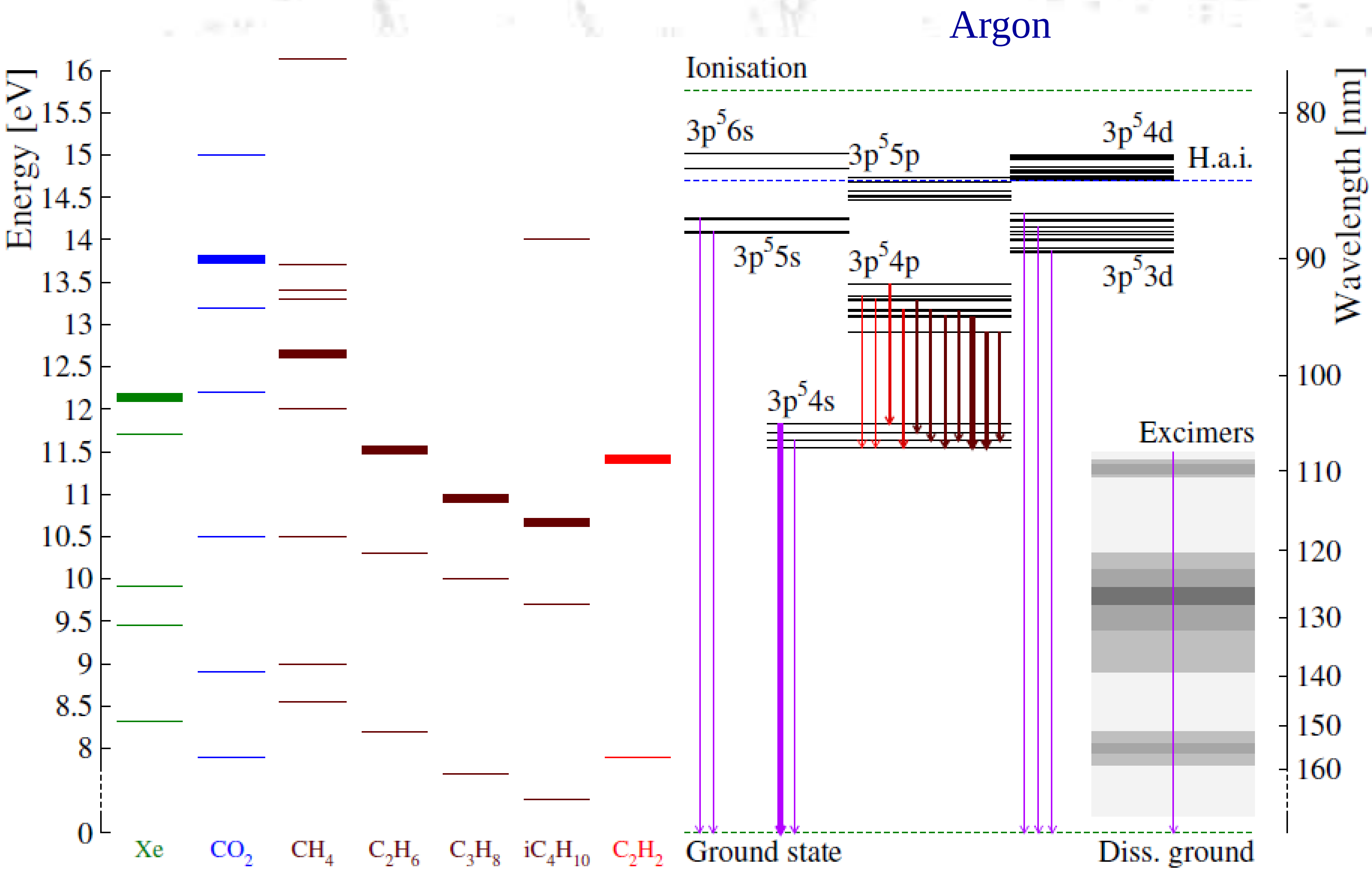
- The following can happen for an excited atom (A^*):
  - $A^* + B \rightarrow A + B^+ + e^-$: collisional ionisation,
  - $A^* + A \rightarrow A_2^+ + e^-$: homonuclear associative ionisation,
  - $A^* \rightarrow A + \gamma$: radiative decay
    - $\gamma + B \rightarrow B^+ + e-$: photo-ionisation

Collisional ionisation in Ar-CO_2

- Ar 90% - CO_2 10%
- Duration: 2 ns



Energy levels



Measuring the transfer probabilities

Townsend coefficient adjustment

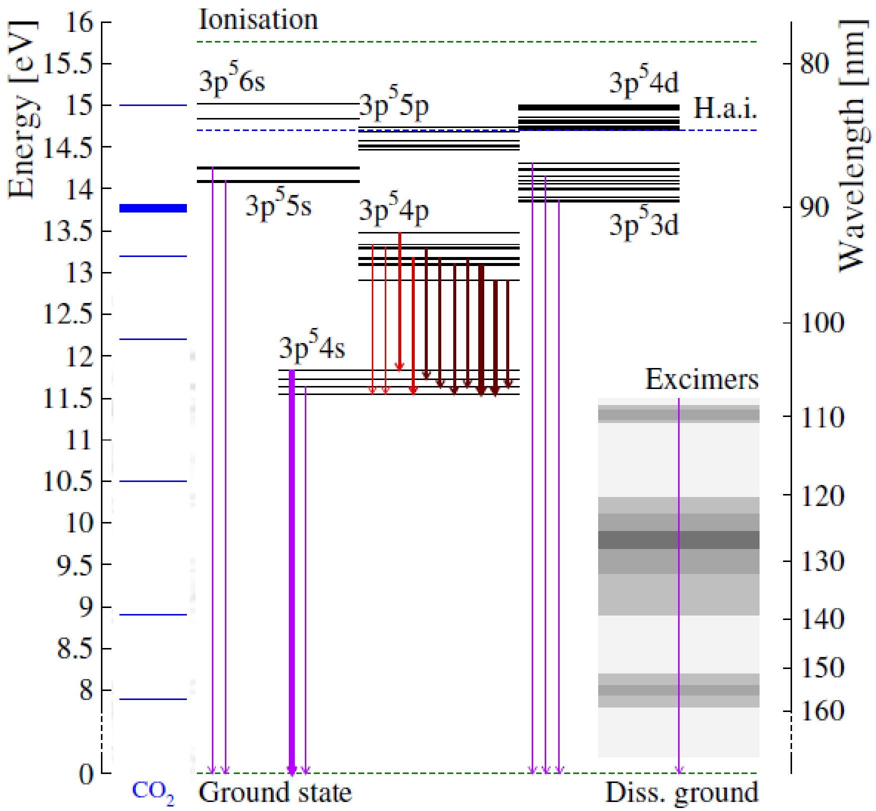
$$\alpha_{Pen} = \alpha \left(1 + \frac{\sum r_{Pen} \, \nu_i^{exc}}{\sum \nu_{mix}^{ion}} \right)$$

Penning corrected gas gain

$$G = e^{\int \alpha_{Pen}(E(r))\,dr}$$

- α : uncorrected Townsend coefficients;
- α_{Pen} : corrected Townsend coefficient including Penning transfers;
- ν^{ion} : production rates of the ionisations;
- ν^{exc} : production rates of the excitations of the noble gas atoms;
  - only excited states of noble gas which are eligible to ionise ;
- r_{Pen} : Penning transfer probabilities:
  - assuming α proportional to the sum of ν_{ion},
  - the gain curves are fitted using the same r_{Pen}
    - impossible to separate them, strong correlations
- α, ν^{ion}, ν^{exc} depends on gas properties (pressure, temperature) and **electric field**

Measuring energy transfer rates in Ar-CO_2 mixtures



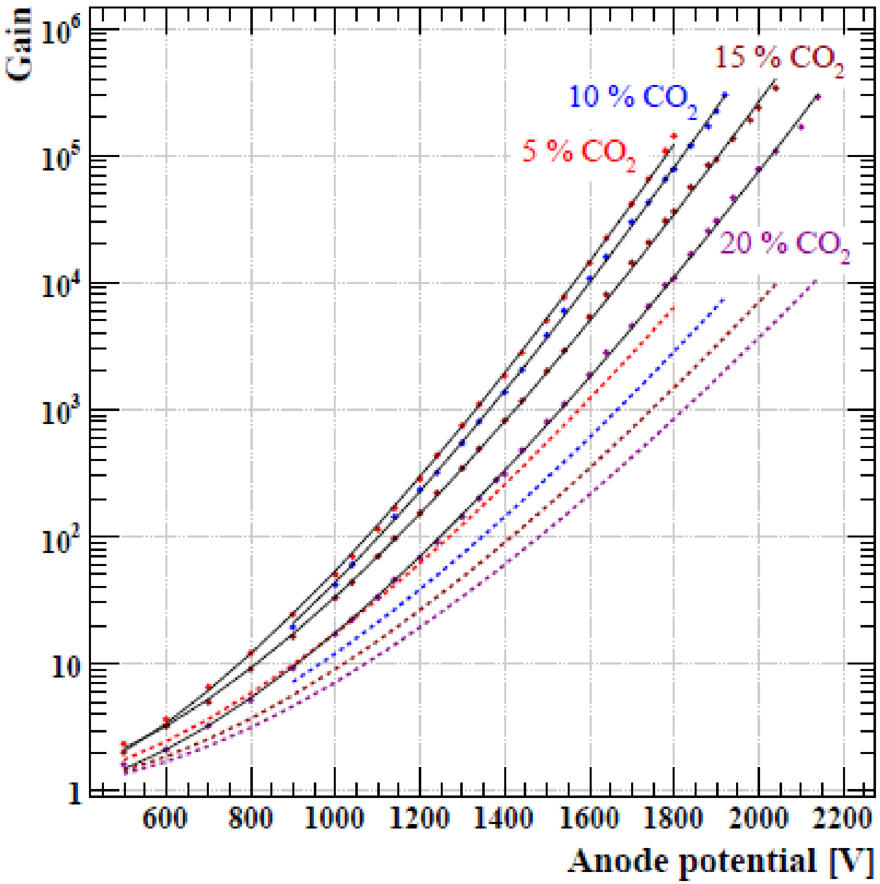
- $Ar^{*} + CO_2 \rightarrow Ar + CO_2^{+} + e^{-}$
- **Ar^{*} $3p^{5}3d$** (13.8 eV) and higher level excitations can ionise CO_2 (13.77 eV)

$$\alpha_{Pen} = \alpha \left(1 + r_{Pen} \frac{f_{Ar}^{exc}}{f_{mix}^{ion}} \right)$$

Townsend coefficients (α), production frequencies of the ionisations and excitations calculated with **Magboltz 9.01**

- f_{Ar}^{exc} : total production frequencies of Ar* $3p^{5}3d$ excitations
- f_{mix}^{ion} : total production frequencies of aAr and CO2 ionisations

Gain fits in Ar- CO_2 mixtures at 1070 hPa



- Experimental data
- ········ without any correction
- —— with Penning and gain scaling

❖ 1x1 cm² Square tube with 25 μm radius single anode wire,

- ❖ cylindrical approximation
  - ❖ r_c = 0.67 cm

Gain calibration

- ❖ uncertainty on the absolute gain,
- ❖ work function,
- ❖ calibration of the equipment.

$$G := g\, G_{meas}$$

- ❖ g = 1.06 were used for the gain fits

Experimental gain:

[T.Z. Kowalski *et al.*NIM *A* **323** (1992) 289–293]

Transfer fits:

[Ö. Şahin et al. JINST **P05002** (2010) 1–30]

Transfer rates in Ar-CO_2 mixtures at 1070 hPa

Model of the transfer rates

Collisional ionisation

$A^* + B \rightarrow A + B^+ + e^-$

homonuclear associative ionisation

$A^* + A \rightarrow A_2^+ + e^-$

$$r_{Pen} = \frac{pc\frac{f_{B^+}}{\tau_{A^*B}} + p(1-c)\frac{f_{A^+}}{\tau_{A^*A}} + \frac{f_{rad}}{\tau_{A^*}}}{pc\frac{f_{B^+} + f_{\bar{B}}}{\tau_{A^*B}} + p(1-c)\frac{f_{A^+} + f_{\bar{A}}}{\tau_{A^*A}} + \frac{1}{\tau_{A^*}}}$$

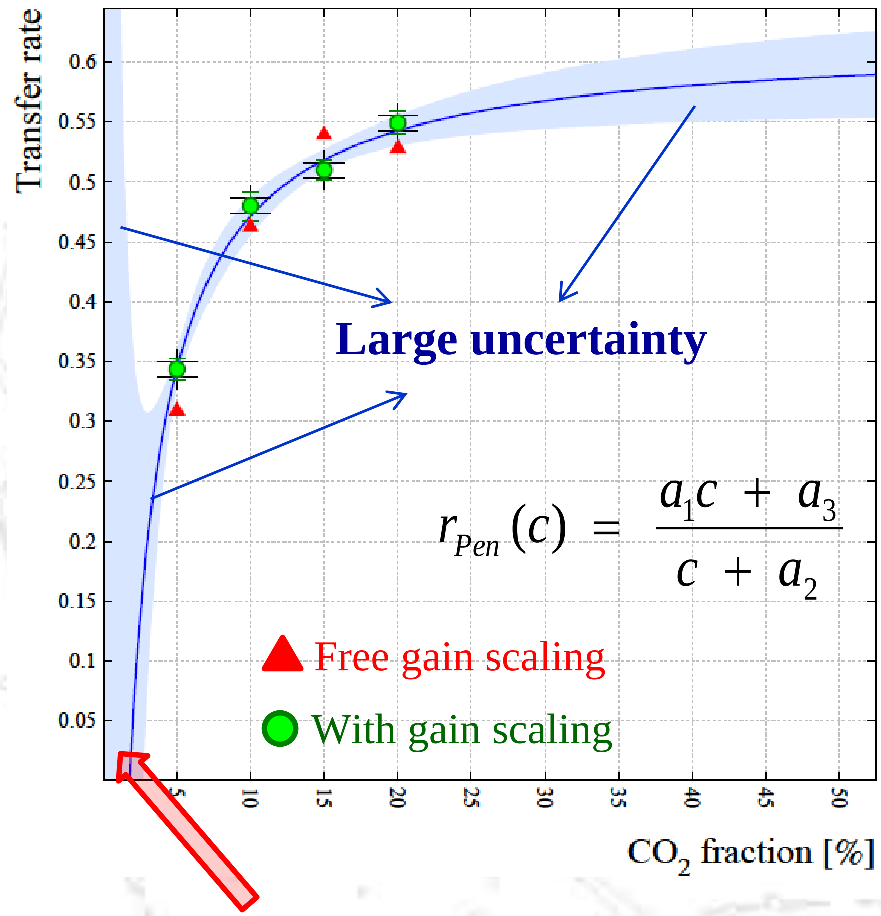
$A^* \rightarrow A + \gamma$

radiative decay

p : mixture pressure

c : admixture concentration

- Separations of the processes with pressure and concentration dependence of the transfer rates
  - lim $p \rightarrow 0$, $r_{\mathrm{Pen}} \rightarrow$ radiative transfer



- **Negative radiative term (a_3/a_2) ?**
- Wide error band, lack of experimental data for <5% and >20% CO_2 fractions
- **NEW MEASUREMENTS !!!**

Nuclear Instruments and Methods in Physics Research A 768 (2014) 104–111

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

High-precision gas gain and energy transfer measurements in Ar–CO_2 mixtures

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ARTICLE INFO

Article history:
Received 31 May 2014
Received in revised form
20 September 2014
Accepted 23 September 2014
Available online 2 October 2014

Keywords:
Gas detectors
Penning transfer
Excited states
Photon feedback

ABSTRACT

Ar–CO_2 is a Penning mixture since a fraction of the energy stored in Ar $3p^5 3d$ and higher excited states can be transferred to ionize CO_2 molecules. In the present work, concentration and pressure dependence of Penning transfer rate and photon feedback parameter in Ar–CO_2 mixtures have been investigated with recent systematic high-precision gas gain measurements which cover the range 1–50% CO_2 at 400, 800, 1200, 1800 hPa and gas gain from 1 to 5×10^5.

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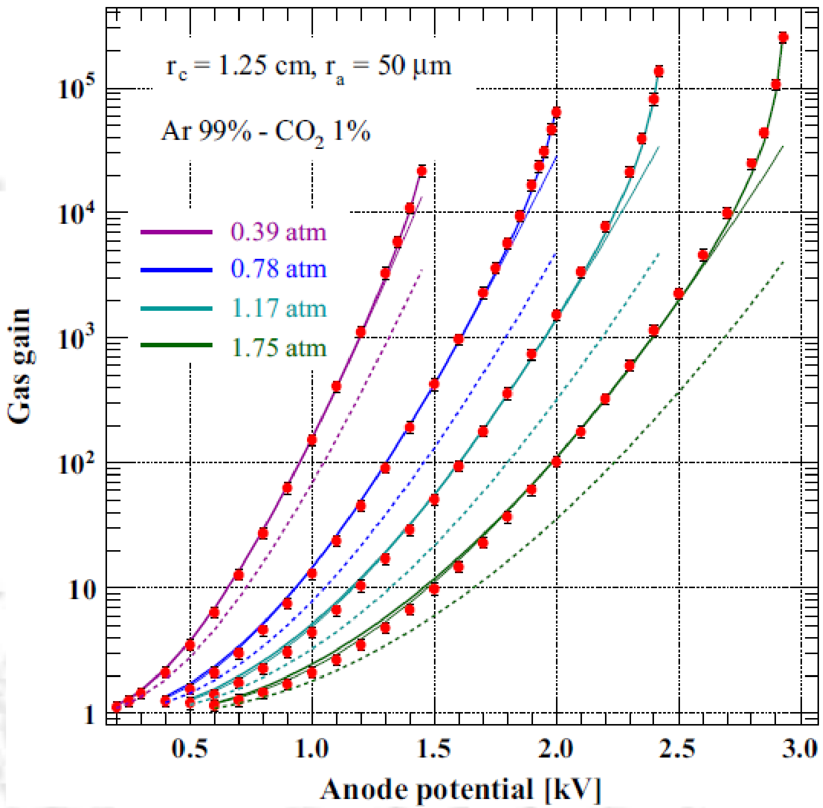
http://dx.doi.org/10.1016/j.nima.2014.09.061



Calculation method

❖**No** gain scaling factor needed

❖ **proof quality of the calibration !**

without any correction

with Penning transfer

with Penning and **feedback corrections**

$$G_{Total} := G/(1-\beta G)$$

$A^* \rightarrow A + \gamma$

Photo-electrons:

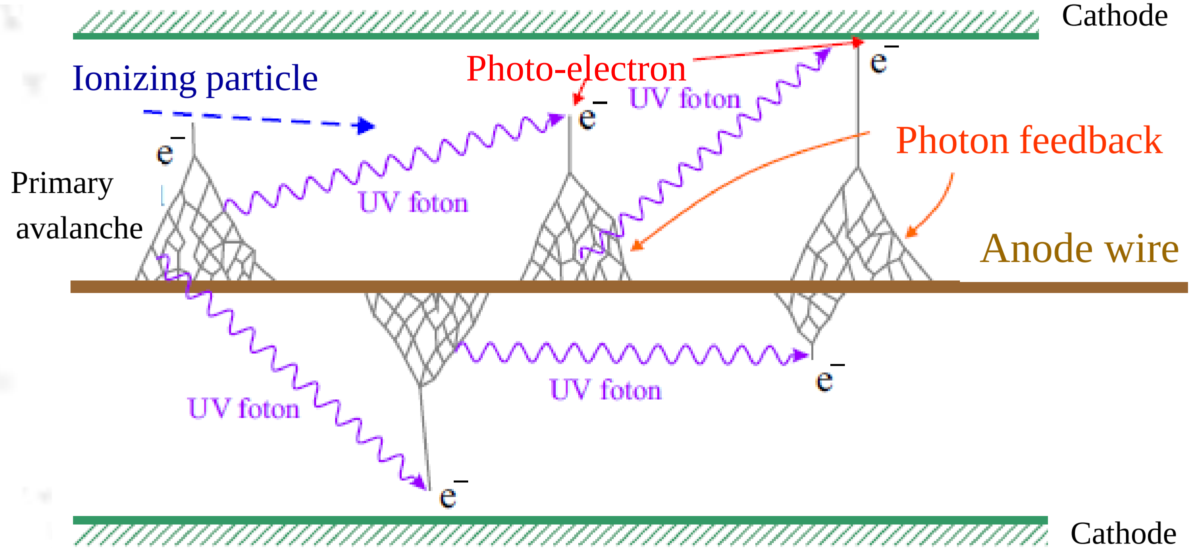
in gas itself

from cathode

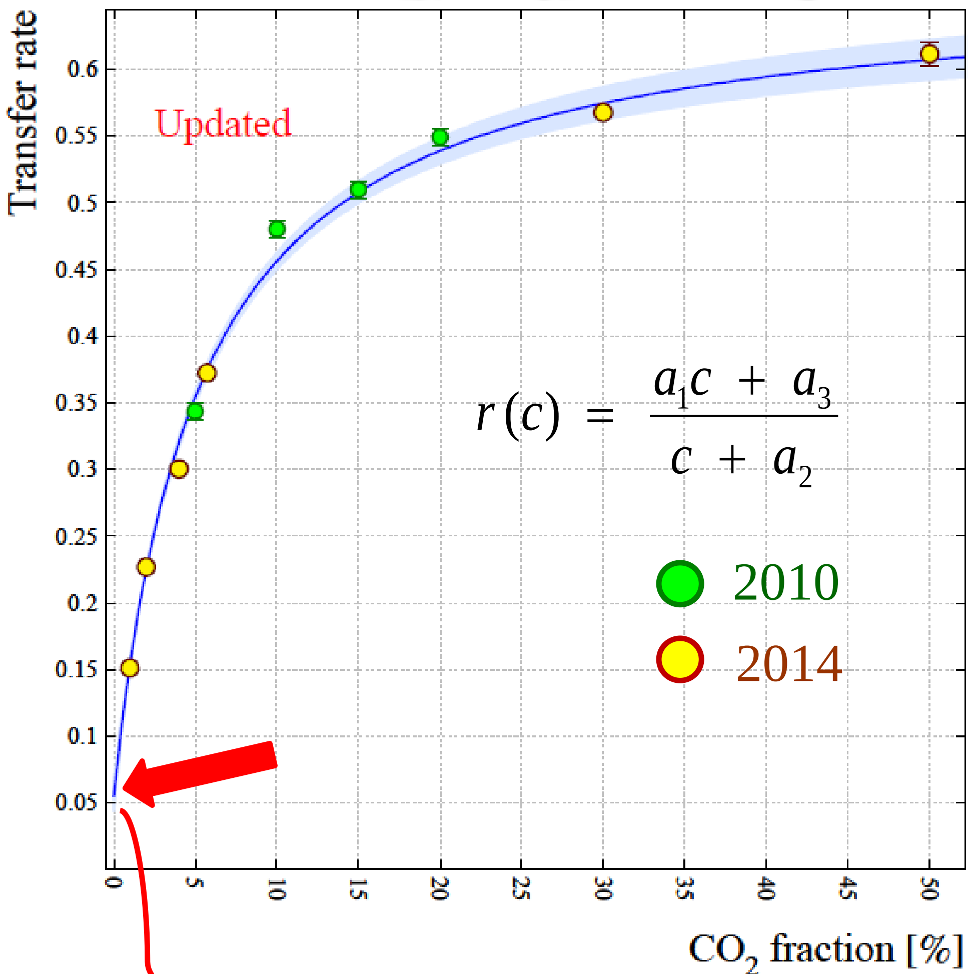
insufficiant absorption in gas

Secondary, delayed avalanches

over exponential increases at high gas gains



Transfer rates at 1070 hPa with the present data



- Joint fit gives transfer rates at1070 hPa,
- Narrow error band both at low and high CO_2 percentages,
- **All the fit parameters are physical,** relevant to learn about radiative transfers.

Parameter	This work
a_1	0.6643 ± 0.0208
a_2	0.0518 ± 0.0056
a_3	0.0028 ± 0.0009

http://dx.doi.org/10.1016/j.nima.2014.09.061

Positive radiative term !!!

a3/a2 = 0.0541 +/- 0.0183

Ar* → Ar + γ

$\gamma + CO_2 \rightarrow CO_2^+ + e^-$

*J*inst

PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

RECEIVED: *September 30, 2016*
ACCEPTED: *December 28, 2016*
PUBLISHED: *January 12, 2017*

18TH INTERNATIONAL WORKSHOP ON RADIATION IMAGING DETECTORS
3–7 JULY 2016,
BARCELONA, SPAIN

A comprehensive model of Penning energy transfers in $Ar\text{-}CO_2$ mixtures

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ABSTRACT: Ionizing energy transfer mechanisms due to the excited argon atoms, called Penning transfers, have been investigated for various $Ar\text{-}CO_2$ mixtures at 0.4, 0.8, 1.2 and 1.8 atm gas pressures. The Penning energy transfer probabilities are extracted from the systematic gas gain measurements carried out in cylindrical proportional counters. In this report, contributions of the several transfer processes are identified by studying the pressure and mixing proportion dependence of the transfer rates with a model.

$Ar\text{-}CO_2$

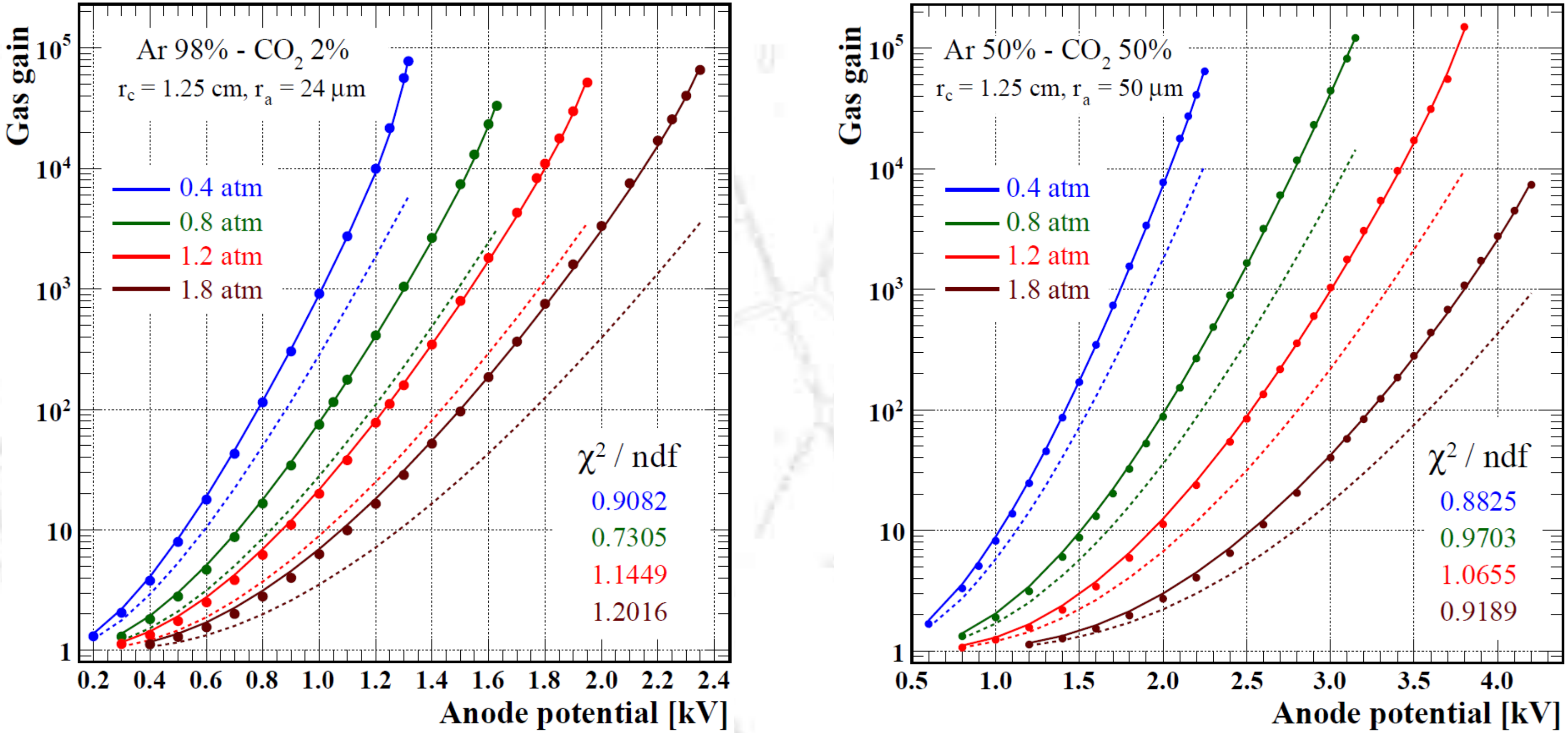
1 % CO_2
2 % CO_2
4 % CO_2
6 % CO_2
11 % CO_2
30 % CO_2
50 % CO_2

Combined energy transfer model:

Pressure (p) and Concentration (c) dependence

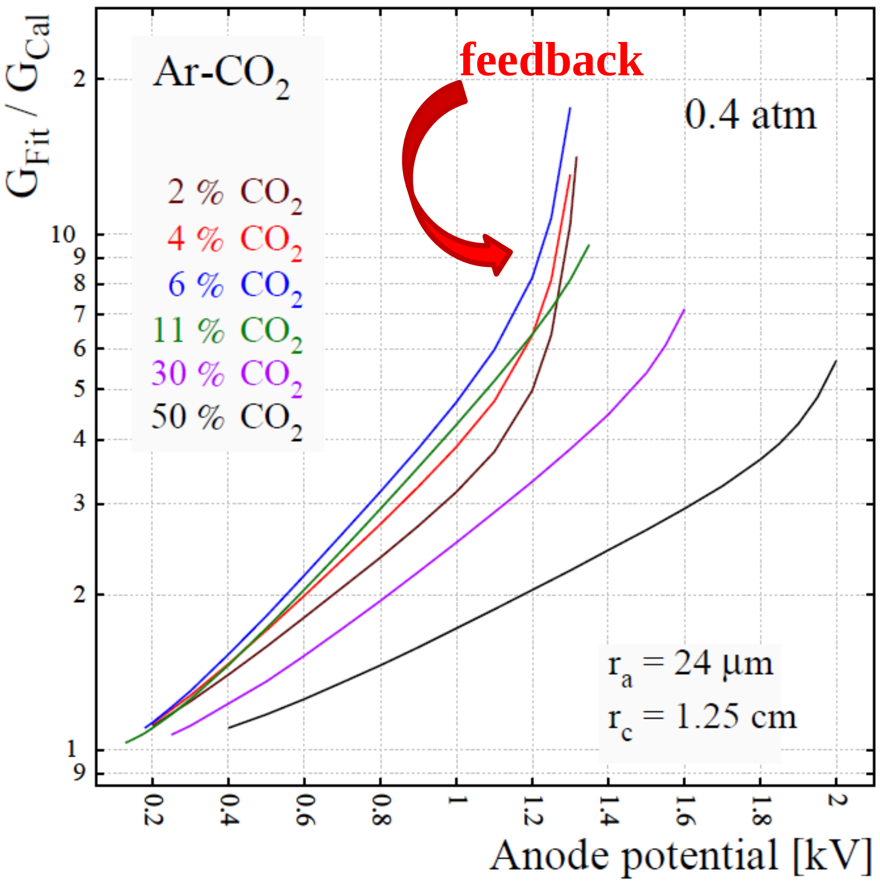
doi:10.1088/1748-0221/12/01/C01035

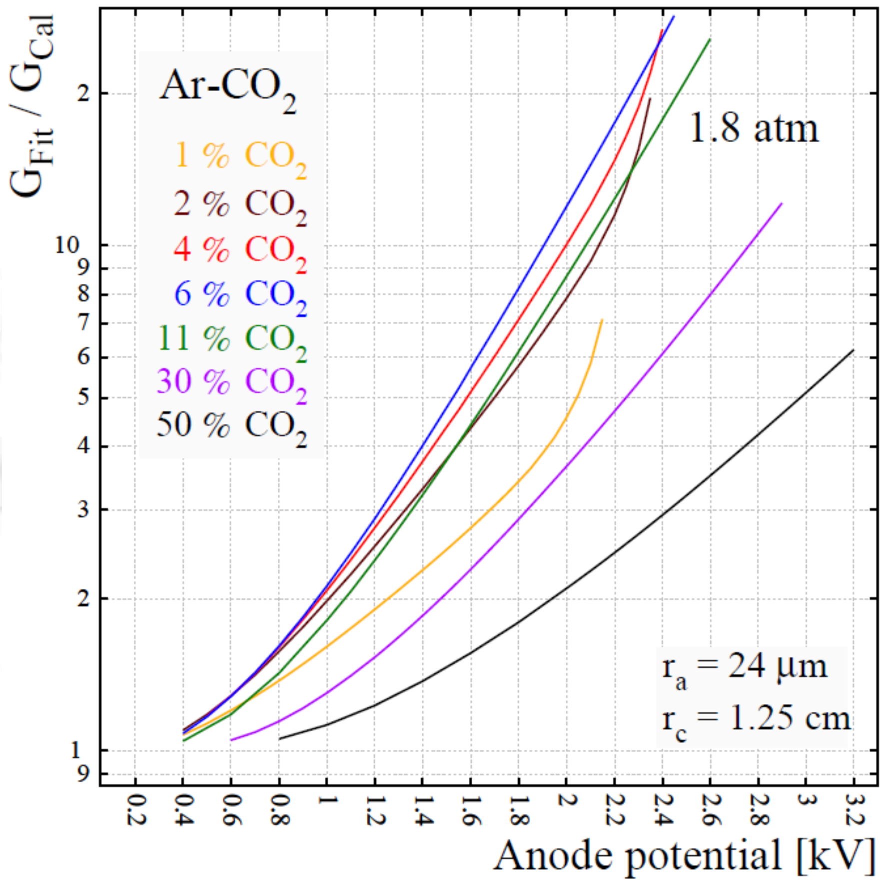
Gain measurements and fits in $Ar\text{-}CO_2$



- Wire chambers : two different anode radius,
- Dashed lines: **without** corrections (Penning, feedback),
- Points: experimental gas gains,
- Thick lines: final fits **with** Penning and feedback corrections.

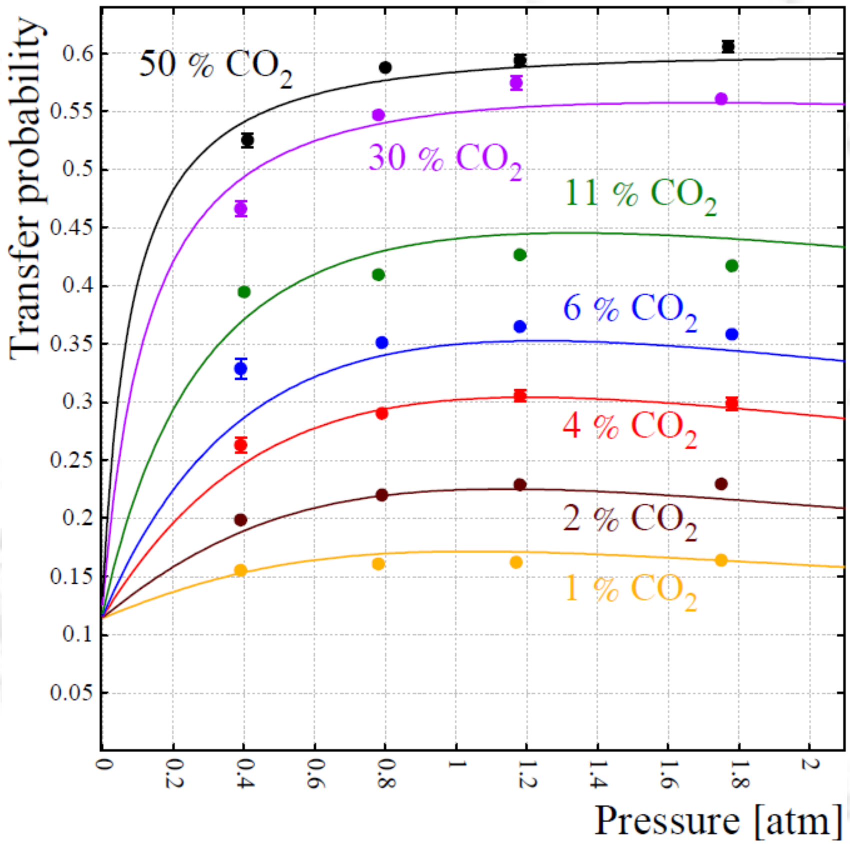
Penning effect on gas gain

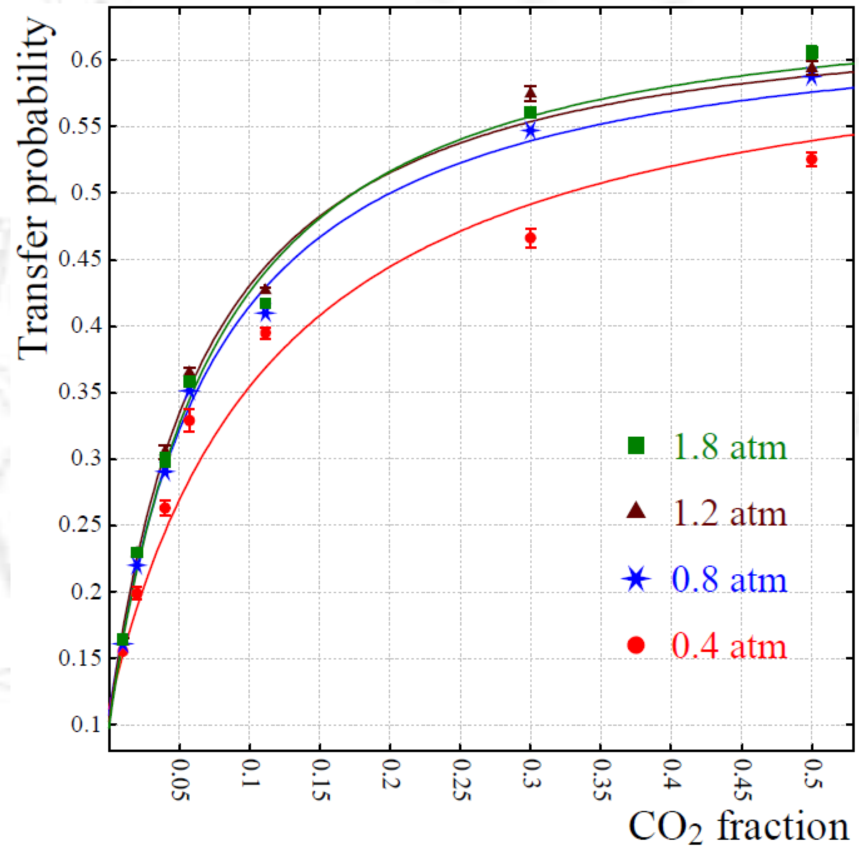




- **G_{Cal}**: Calculation without any correction
- **G_{Fit}**: Calculation with Penning and feedback corrections
- Ratios systematically increase with CO_2 fraction up to 6 %, then decrease for 11 % and higher CO_2 fractions

Model of the energy transfer probabilities





$$r_{Pen}(p,c) = \frac{a_5 p^2 (1-c)^2 + a_1 pc + a_4 c + a_3}{a_6 p^2 (1-c)^2 + pc + a_2}$$

Ar_2^*- CO_2 Ar^*- CO_2 Ar^*- γ

- **Numerator: increase the ionizations**
- **Denominator: excitation loses**

1) **Excimers**
2) **Collosional ionizations**
3) **Radiative energy transfers**

Meaning of the model parameters

Parameter	Value
a_1	0.627898 ± 0.018083
a_2	0.041394 ± 0.008297
a_3	0.004716 ± 0.001512
a_4	0.001562 ± 0.017566
a_5	0.002422 ± 0.001171
a_6	0.027115 ± 0.005836

- **a_1: collisional ionization efficiency**

  $Ar^* + CO_2 \rightarrow Ar + CO_2^+ + e^-$

- **a_2: decay by emitting photons**

  $Ar^* \rightarrow Ar + \gamma$

- **a_3: photo-ionization**

  $\gamma + CO_2 \rightarrow CO_2^+ + e^-$

- **a_3/a_2 = 0.114 ± 0.043** radiative transfer efficiency

- **a_4:** concentration dependence of the radiative transfer efficiency

- **a_5: ionization with argon excimers:**

  $Ar_2^+ + Ar^* \rightarrow Ar_2^+ + Ar + e^-$

  $Ar_2^+ + Ar_2^+ \rightarrow Ar_2^+ + Ar + Ar + e^-$

  $Ar_2^+ + Ar \rightarrow 2Ar + Ar^+ + e^-$

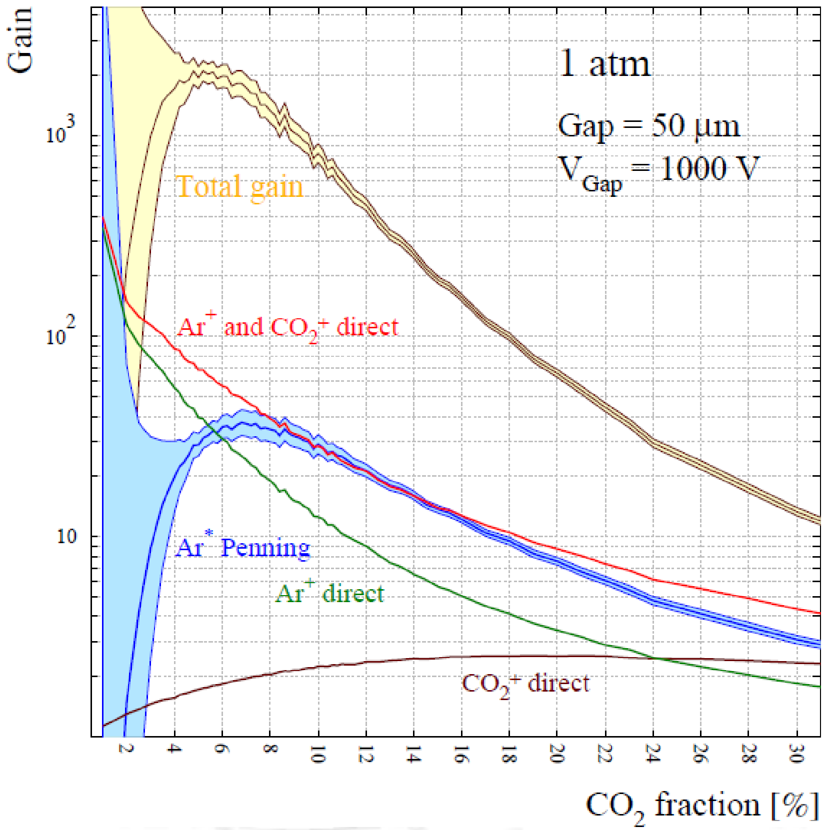
S.K. Lam et al., *Kinetics of Ar_2^+ in high-pure argon*, *J. Phys.* **D 33 (2000) 242.**

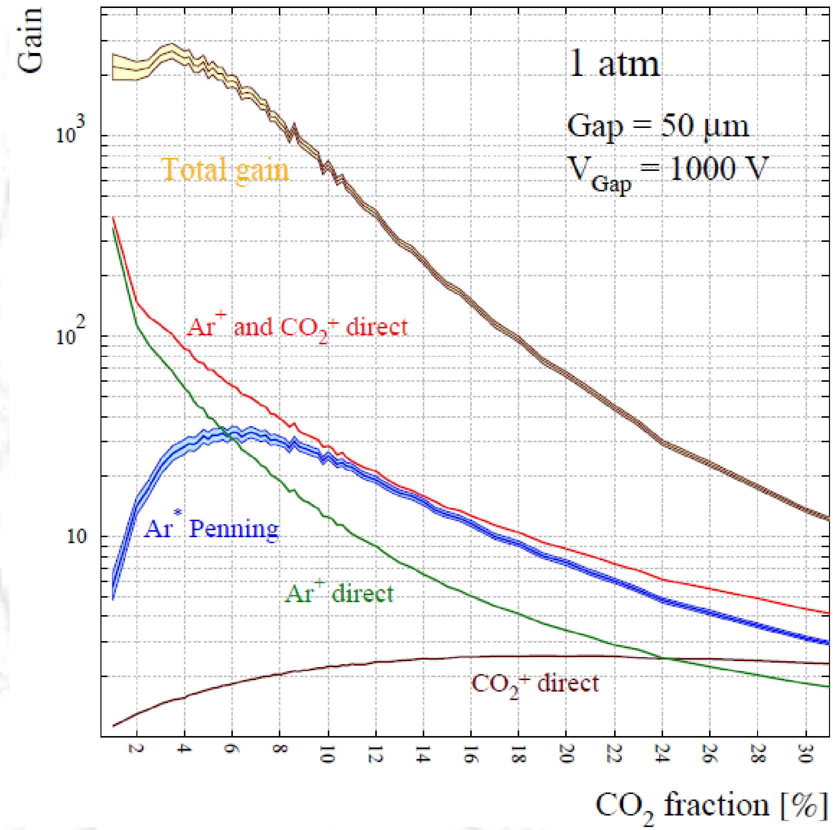
- **a_6: excimer formation probability in Ar* - Ar – Ar collisions**

  $Ar^* + Ar + Ar \rightarrow Ar_2^* + Ar$

- **$a_5/a_6 \approx 9$ % of the created excimers contribute to the ionizations**

Application of transfer rates





- MMs like simple geometry, 1% to large CO_2 concentrations (Magboltz 9.0.1),
- Possible to separate ionisation mechanisms contributing to total gain,
- High precision at low CO_2 fractions with updated transfer rates (plot on the right) ,
- Highest Penning transfer around 1% CO_2, maximum on total gas gain ≈ 3% CO_2,
- **Should be confirmed**, measurements with MMs in Ar – CO_2 mixtures **???**

Thanks and ???