Energy Transfer Model for Ne-CO_2 and Ne-N_2 Mixtures; news for ATLAS mixtures (Ar-CO_2-iC_4H_{10})

RD51 Mini-Week 15 – 19 February 2021 CERN

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Penning energy transfers

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

$e^- + A \rightarrow A^*$: excitation → **what happens ? Michel Penning explains**

1. F.M. Penning, *The starting potential of the glow discharge in neon argon mixtures between large parallel plates: II. Discussion of the ionisation and excitation by electrons and metastable atoms,* *Physica, Volume* **1** (1934).
2. M.J. Druyvesteyn and F.M. Penning, *The Mechanism of Electrical Discharges in Gases of Low Pressure,* *Rev. Mod. Phys.*, **12** (1940).

- 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
- **Other processes will be discussed in the transfer model**

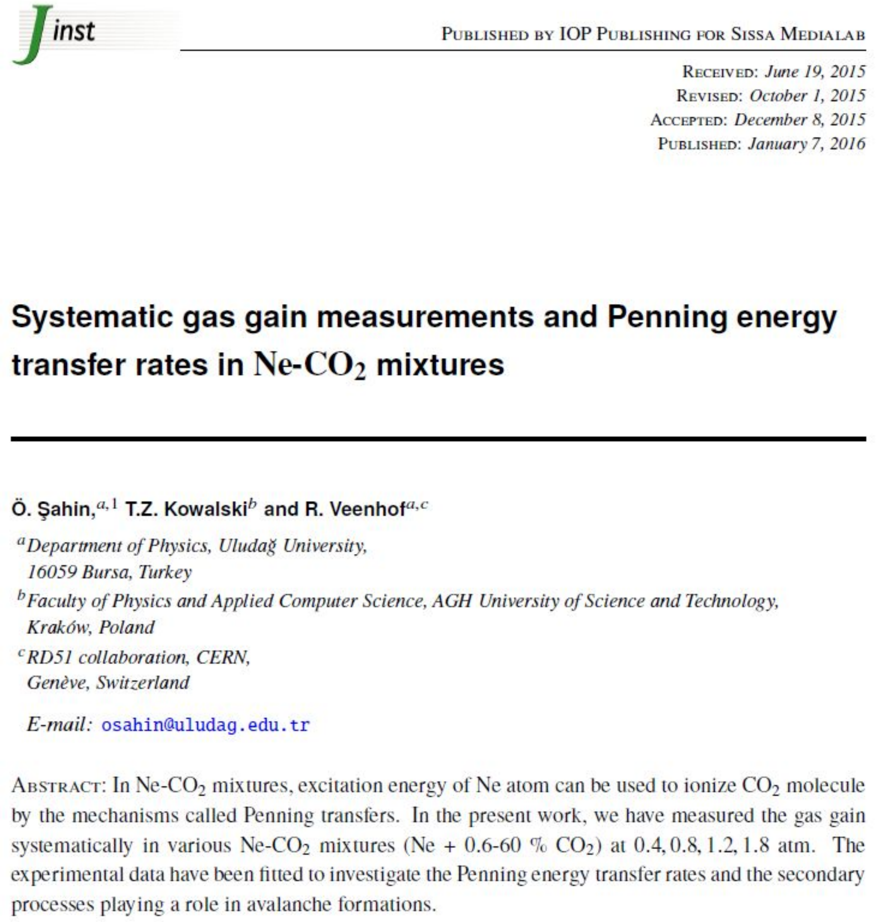
Townsend coefficient adjustment

$$\alpha_{Pen} = \alpha\left(1 + r_{Pen}\,\frac{\nu^{exc}}{\nu^{ion}}\right) \quad\Longrightarrow\quad G = e^{\int \alpha_{Pen}(E(r))\,dr}$$

Penning corrected gas gain

- $\boldsymbol{\alpha}$: uncorrected Townsend coefficients;
- $\boldsymbol{\alpha}_{\mathbf{Pen}}$: corrected Townsend coefficient including Penning transfers;
- $\boldsymbol{\nu}^{i\ on}$: production rates of the direct ionisations in the mixture;
- $\boldsymbol{\nu}^{exc}$: production rates of the excitations of the noble gas atoms;
  - only excited states of noble gas which are eligible to ionise ;
- $\boldsymbol{r}_{Pen}$: Penning transfer probabilities:
  - assuming α proportional to the sum of ν_{ion},
  - the gain curves are fitted using the same $\boldsymbol{r}_{\mathbf{Pen}}$
    - impossible to separate them, strong correlations
- α, ν^{ion}, ν^{exc} depend on gas properties (pressure, temperature) and **Magboltz calculates them**

Published Data



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Systematic gas gain measurements and Penning energy transfer rates in Ne-CO_2 mixtures

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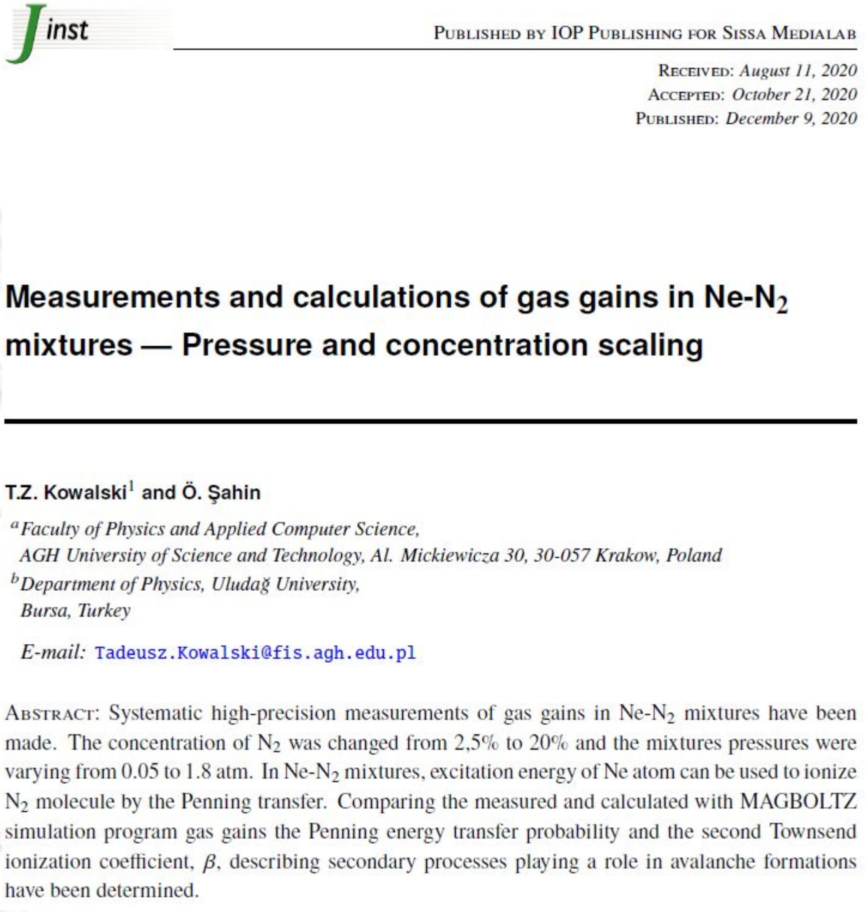
ABSTRACT: In Ne-CO_2 mixtures, excitation energy of Ne atom can be used to ionize CO_2 molecule by the mechanisms called Penning transfers. In the present work, we have measured the gas gain systematically in various Ne-CO_2 mixtures (Ne + 0.6-60 % CO_2) at 0.4, 0.8, 1.2, 1.8 atm. The experimental data have been fitted to investigate the Penning energy transfer rates and the secondary processes playing a role in avalanche formations.



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Measurements and calculations of gas gains in Ne-N_2 mixtures — Pressure and concentration scaling

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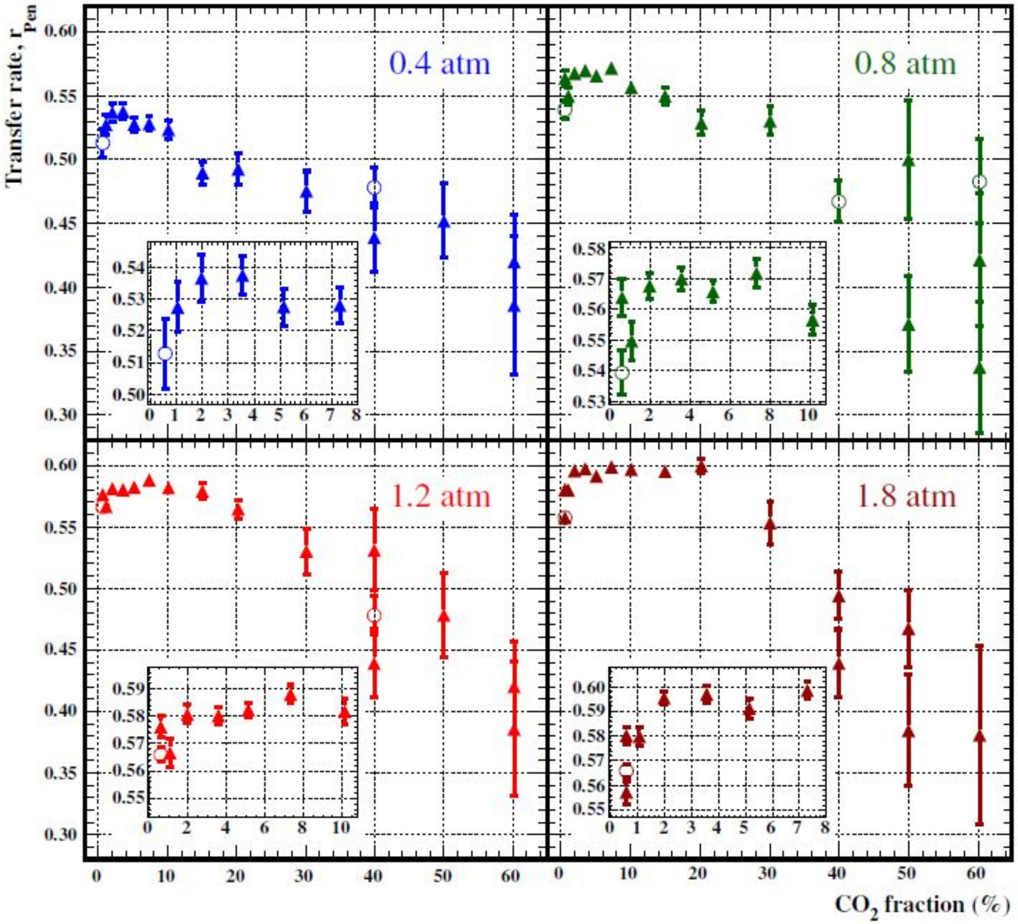
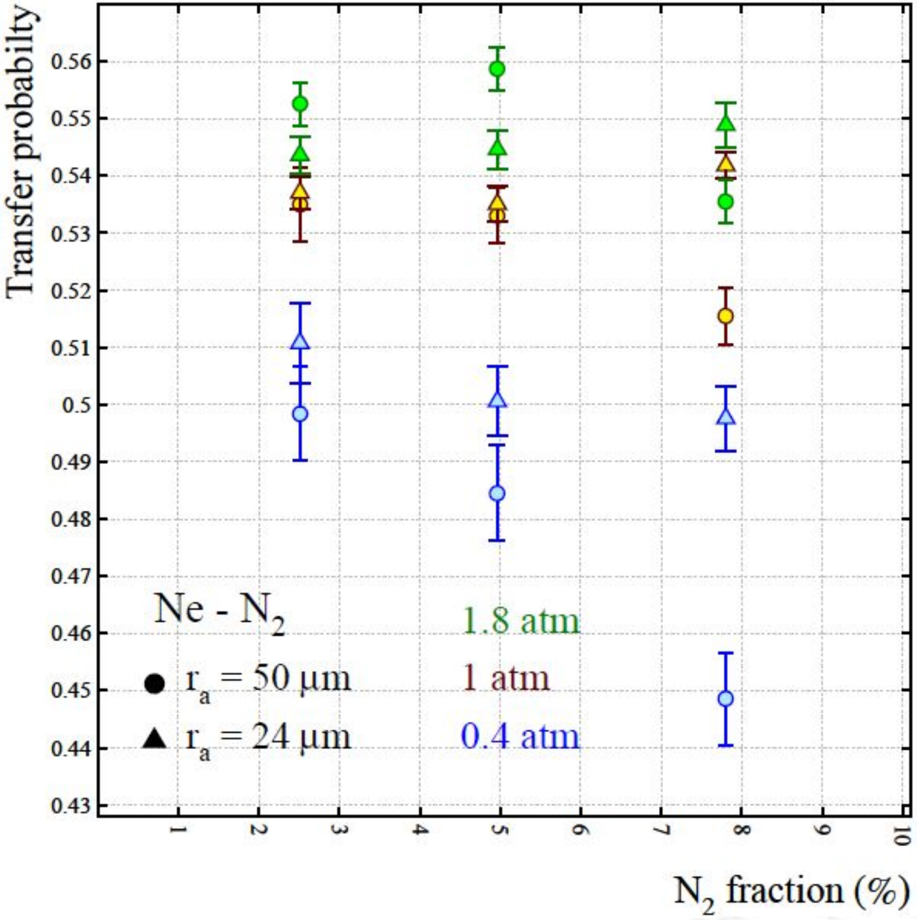
ABSTRACT: Systematic high-precision measurements of gas gains in Ne-N_2 mixtures have been made. The concentration of N_2 was changed from 2,5% to 20% and the mixtures pressures were varying from 0.05 to 1.8 atm. In Ne-N_2 mixtures, excitation energy of Ne atom can be used to ionize N_2 molecule by the Penning transfer. Comparing the measured and calculated with MAGBOLTZ simulation program gas gains the Penning energy transfer probability and the second Townsend ionization coefficient, β, describing secondary processes playing a role in avalanche formations have been determined.

Transfer Probabilities in Ne - CO_2 mixtures (problem)



- ❖ The transfer rates increase with pressure (for < 40 % CO_2)
  - ➢ This is easily understandable; Collision times
- ❖ **BUT**, at the same pressure, the rates first increase and then decrease with CO_2
  - ➢ **This a big question mark**
    - ■ Excited neon atoms finds more CO_2 molecule to transfer around
- **We made many efforts:**
  - ➢ The model we developed in our Penning paper (published 2010) does not fit the transfer data
    https://doi.org/10.1088/1748-0221/5/05/P05002
  - ➢ Discussions based on the production rates do not help to explain the drops
    - ■ See earlier RD-51 talks

Transfer Probabilities in Ne - N_2 mixtures (problem)



- ❖ Similar trend with increasing pressure; related to the collision times
- ❖ From the first measurements there were no obvious bumps (except 1.8 atm) for the transfer rates at the same pressure
  - ➢ they were seen clearly in Ne-CO_2 mixtures;
  - ➢ **BUT**, we had still the similar question mark
    - ■ the rates decrease with CO_2
- **The range of the measurements were increased to get better explanations**
  - ➢ N_2 concentration up to 20 %
  - ➢ Pressure down to 0.06 atm
- **We had to revisit to our transfer model to clarify the drops of the energy transfers**

Energy Transfer Model

$$r_{\text{Pen}}(p,c)=\frac{a_5p^2(1-c)^2+a_7c^2+a_1pc+a_3}{a_6p^2(1-c)^2+a_4c^2+pc+a_2}$$

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

- **p:** dimensionless pressure; $\boldsymbol{p_{gas} = p \times 1}$ **atm**
- **c:** quencher concentration (CO_2 or N_2)

❖**a_1: collisional ionization efficiency**

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

❖**a_2: decay by emitting photons**

$Ne^* \rightarrow Ne + \gamma$

❖**a_3: photo-ionization**

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

❖**a_3/a_2** radiative transfer efficiency

❖ **a_5: ionization with Neon excimers:**

$Ne_2^+ + Ne^* \rightarrow Ne_2^+ + Ne + e^-$

$Ne_2^+ + Ne_2^+ \rightarrow Ne_2^+ + Ne + Ne + e^-$

$Ne_2^+ + Ne \rightarrow 2Ne + Ne^+ + e^-$

❖ **a_6: excimer formation probability in collisions**

$Ne^* + Ne + Ne \rightarrow Ne_2^* + Ne$

❖ **a_5/a_6 : contribution of the created excimers to the ionizations**

Energy Transfer Model

$$r_{\mathrm{Pen}}(p,c) = \frac{a_5 p^2 (1-c)^2 + a_7 c^2 + a_1 p c + a_3}{a_6 p^2 (1-c)^2 + a_4 c^2 + p c + a_2}$$

- **a_4 and a_7 : describe the drops on the transfer rates** **FIRST TIME**
  - No pressure dependence
- **a_7 : excited neon atom leads to ionisation in the presence of two quencher molecules**

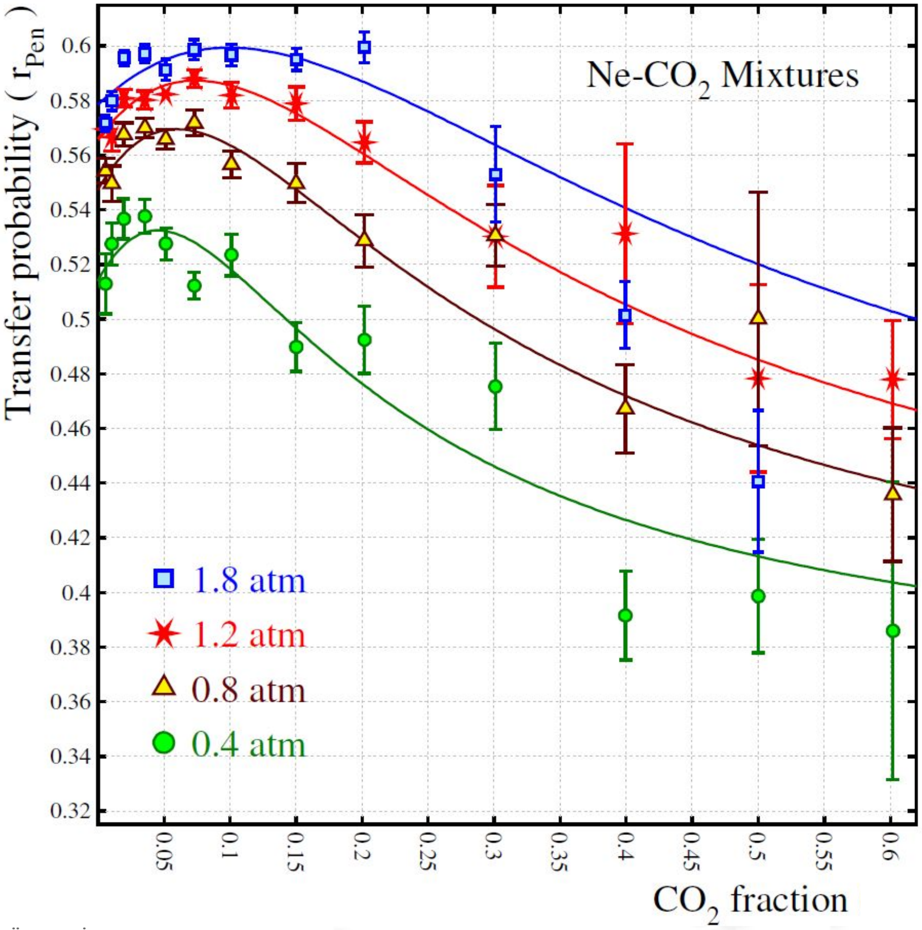
$Ne^* + B + B \rightarrow Ne + B^+ + e^- + B$ **(NEW)**

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

$Ne^* + N_2 + N_2 \rightarrow Ne + N_2^+ + e^- + N_2$

- **a_7/a_4 efficiency of the process NEW**

Model Results for Ne-CO_2 Mixtures

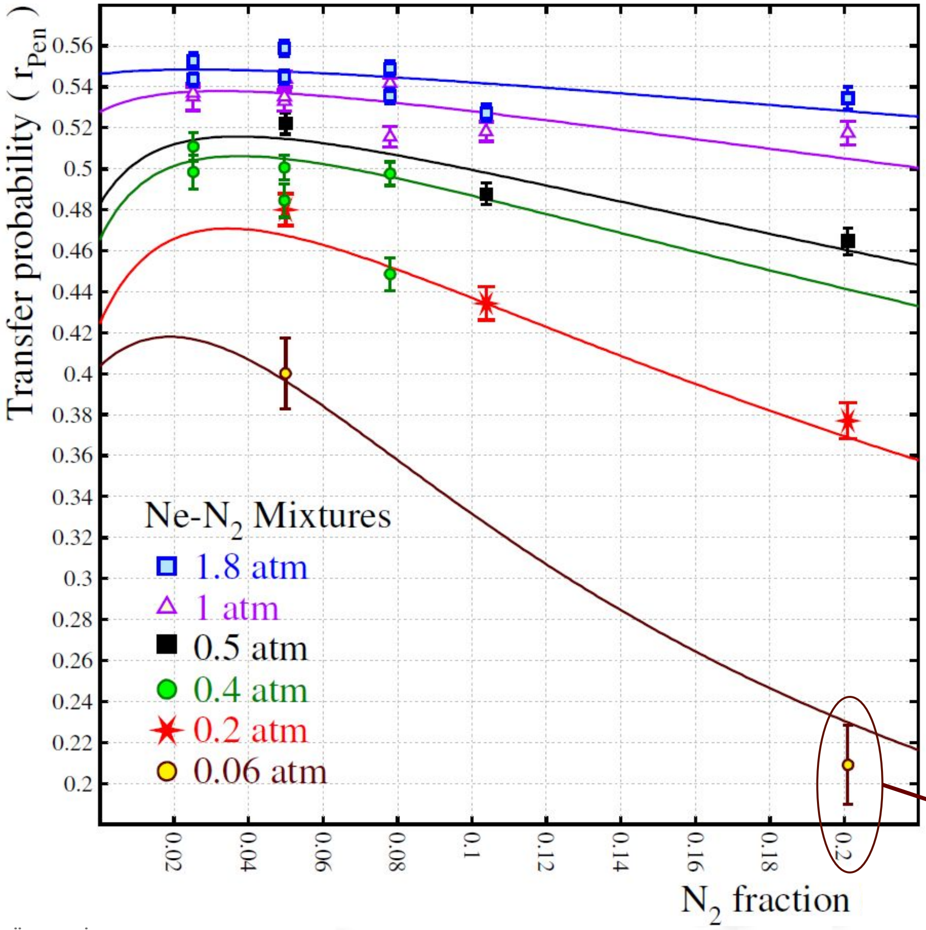


$$r_{\mathrm{Pen}}(p,c) = \frac{a_5 p^2(1-c)^2 + a_7 c^2 + a_1 pc + a_3}{a_6 p^2(1-c)^2 + a_4 c^2 + pc + a_2}$$

Parameter	**Ne-CO_2 mixtures**
a1	0.71104 ± 0.06527
a2	0.06323 ± 0.04238
a3	0.03085 ± 0.02140
a4	4.20089 ± 2.60772
a5	0.07831 ± 0.05328
a6	0.13235 ± 0.09036
a7	1.47470 ± 1.08256

- **a_7:** $Ne^* + CO_2 + CO_2 \rightarrow Ne + CO_2^+ + e^- + CO_2$
- The efficiency of the new physical process is $a_7/a_4 \approx 35\ \%$

Model Results for Ne-N_2 Mixtures



$$r_{\text{Pen}}(p,c) = \frac{a_5 p^2(1-c)^2 + a_7 c^2 + a_1 pc + a_3}{a_6 p^2(1-c)^2 + a_4 c^2 + pc + a_2}$$

Parameter	**Ne-CO_2 mixtures**
a1	0.55802 ± 0.06527
a2	0.00514 ± 0.00536
a3	0.00206 ± 0.00238
a4	0.55385 ± 0.08641
a5	0.01153 ± 0.03412
a6	0.02073 ± 0.06184
a7	**Constant 0.01**

- **a_7:** $Ne^* + N_2 + CO_2 \rightarrow Ne + N_2^+ + e^- + N_2$
- Parameter a_7 favours to take a constant value
  - $a_7 > 0.07$ does not fit the point 20 % N_2 at 0.06 atm
- Much lower efficiency $a_7/a_4 \approx 1.8$ % (35% in Ne-CO_2)

ATLAS Mixtures (Ar-CO_2-iC_4H_{10})

- **Paolo Iengo** asked data for ATLAS mixtures (Ar-CO_2-iC_4H_{10})
  - *In ATLAS Ar:CO_2 93:7 is the baseline gas mixture for Micromegas, however we are now considering to add a small fraction of iC_4H_{10} and have started test with Ar:CO_2:iC_4H_{10} 93:5:2 (October 2020).*

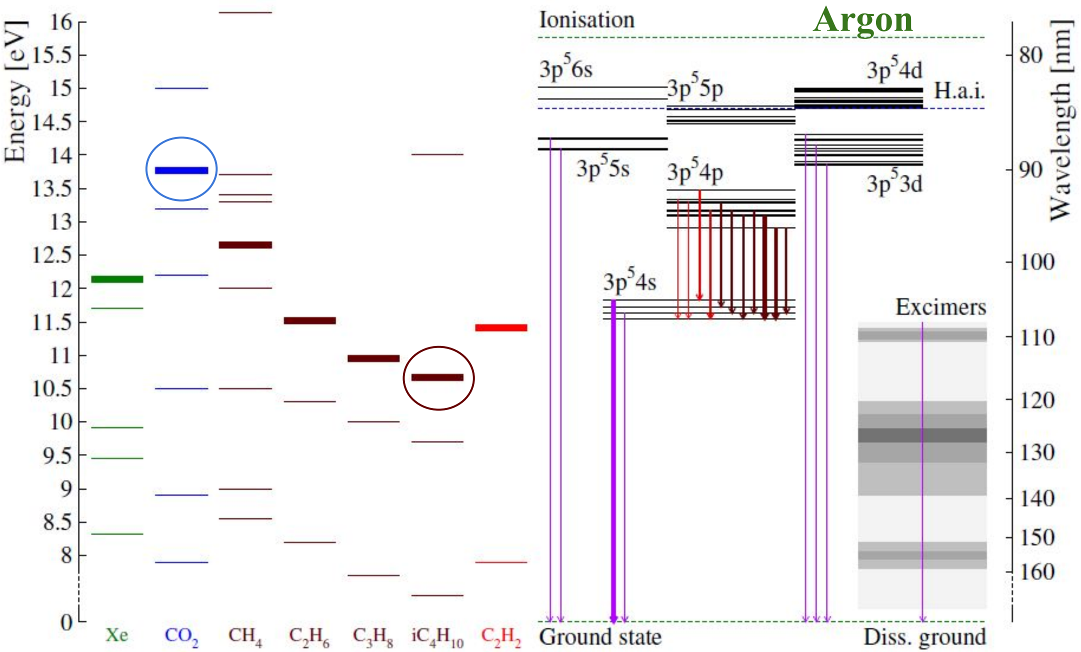
- **Tadeusz Kowalski** made the first systematic gas gain measurements with a single wire proportional counter (November 2020)

- Preliminary calculation results were shared at the weekly CERN GDD meeting (December 2020)
  - **Recalculated** with more sensible Penning adjustment method

- New measurements will be useful:
  - better understand the physical processes involved in the transfer of energy and,
  - estimate the maximum achievable gas gains in these mixtures.

Penning Correction in Ar-CO_2-iC_4H_{10} mixtures

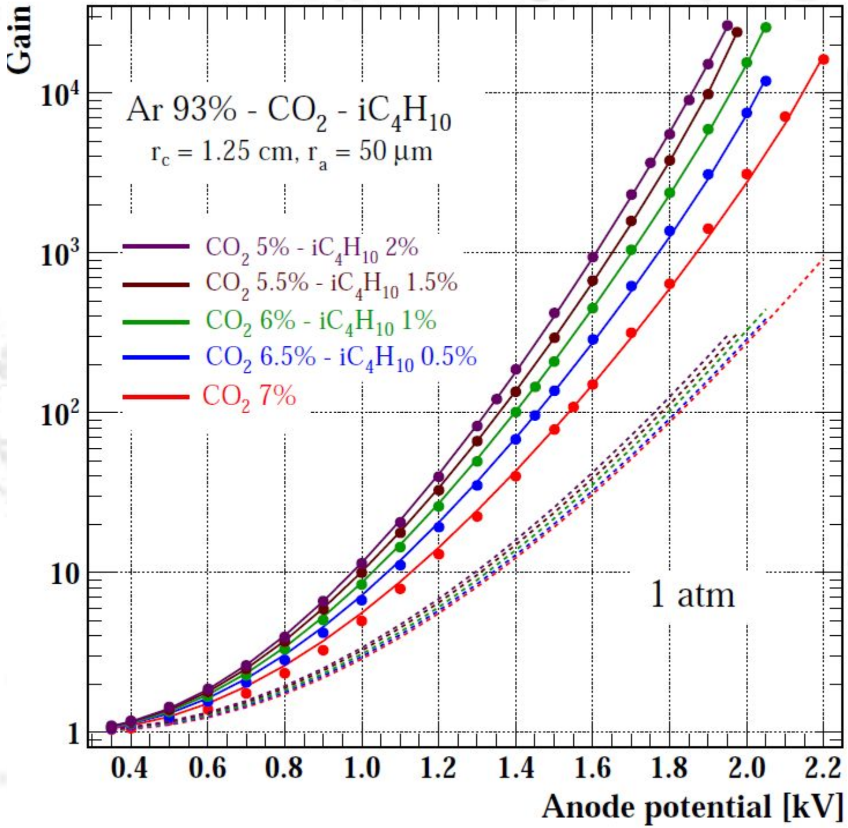
- **$Ar^* + CO_2 \rightarrow Ar + CO_2^+ + e^-$**
  - ➢ Ar^* $3p^53d$ (13.8 eV) and higher excitations can ionise CO_2 (IP: 13.77 eV)
- **$Ar^* + iC_4H_{10} \rightarrow Ar + iC_4H_{10}^+ + e^-$**
  - ➢ All excited Argon atoms can ionise iC_4H_{10} (IP: 10.67 eV)
  - ➢ The lowest excited Argon 11.55 eV
- **Concentration of the admixtures should be taken account while Penning calculation**



$$\alpha_{Pen} = \alpha\left(1 + r_{Pen}\,\frac{c_1 \cdot \nu_{3d}^{exc} + c_2 \cdot \nu_{all}^{exc}}{\nu^{ion}}\right)$$

- ❖ c_1: fraction of CO_2
- ❖ c_2: fraction of iC_4H_{10}

Gas Gains in Ar-CO_2-iC_4H_{10} mixtures

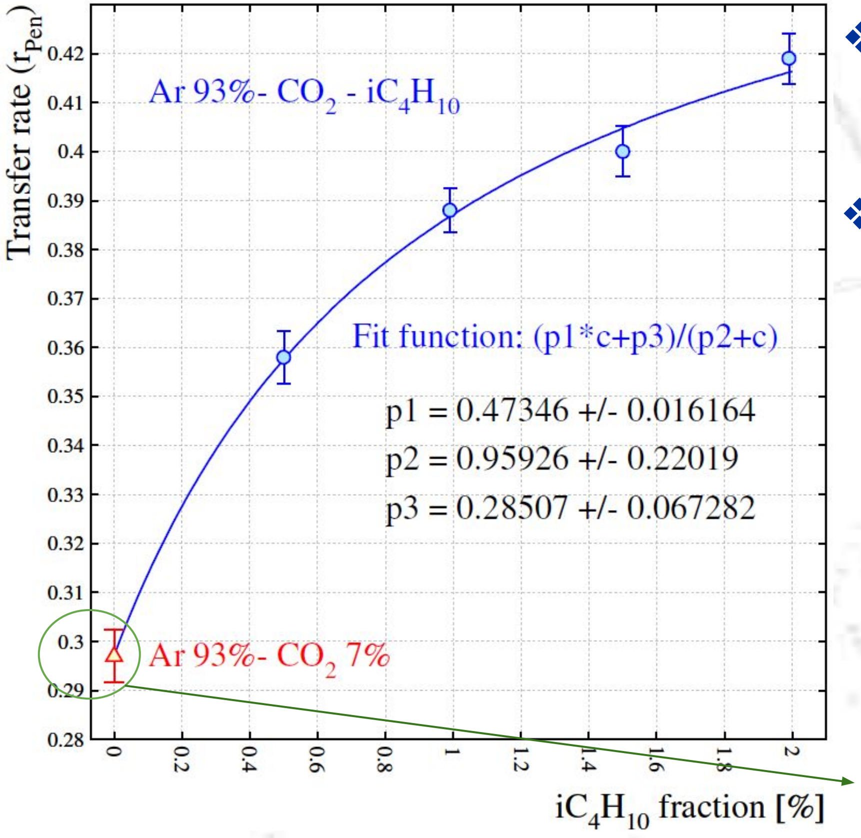


- Points are the measurements
- Dashed lines without any correction
- Full lines with Penning and feedback corrections
  - Feedback correction for the over-exponential increases in gas gain

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

- Higher gains are reached with more iC_4H_{10} at the same anode potential
- We are planning to proceed with the new gas gain measurements and their fits
  - Ar 93 % - iC_4H_{10} 7 % can be first
    - Other binary mixtures may also be useful
  - **Any suggestion will be welcome !**

Energy Transfer Model Ar-CO_2-iC_4H_{10} mixtures



- ❖ Concentration dependence of the energy transfers
  - ➢ c: fraction of the iC_4H_{10}
- ❖ Clear evidence of the rise with the increase of iC_4H_{10} concentration

$$r_{Pen}(c) = \frac{p1 \cdot c + p3}{c + p2}$$

1) Collosional ionizations (p1 ≈ 47 %)

- ➢ $Ar^* + B \rightarrow Ar + B^+ + e-$
  - ■ B: CO_2 or $CO_2 + iC_4H_{10}$

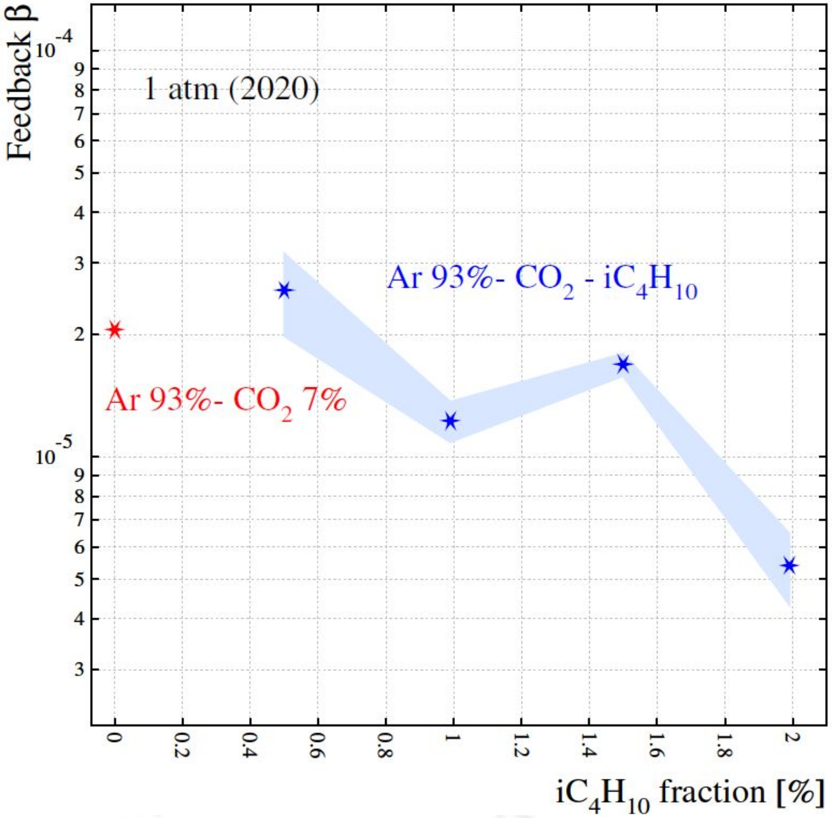
2) c = 0 refers to transfer rate in Ar 93 %-CO_2 7 %

p3/p2 ≈ 30 % is comparable with earlier data

Feedback Parameters

- Feedbacks terms tend to decrease with the increase of iC_4H_{10} concentration
  - iC_4H_{10} is better quencher than CO_2 molecules
  - The maximum obtainable gas gain increase
  - Measurements in Ar 93 % - iC_4H_{10} 7 % mixtures would be beneficial in providing better understanding
  - The feedback parameter in Ar 93% - CO_2 7% (red star) is quite consistent with our previously published data

  Özkan Şahin, TadeuszZ.Kowalski, RobVeenhof, *High-precision gas gain and energy transfer measurements in Ar–CO_2 mixtures*, Nucl. Instrum. Meth. **A 768** (2014) 104 (see plot 12).



Summary

- ❖ Energy transfer drops in Ne-CO_2 and Ne-N_2 are modelled successfully for the first time
  - ➢ Adding a **new parameter** to our original fit function (constructed in 2010 paper)
    - ■ Scales with the square of admixture concentration
    - ■ No pressure dependence
    - ■ Indicates a new kind of ionisation mechanism **$(Ne^* + B + B \rightarrow Ne + B^+ + e^- + B)$**
    - ■ Special thanks to **Rob Veenhof** for the useful discussions
  - ➢ The manuscript is under preparation (almost finished)
- ❖ Surveys of the ATLAS mixtures (Ar-CO_2-iC_4H_{10}) continue
  - ➢ The very promising initial results encourage us to expand our research on this topic
  - ➢ New gas gain measurements (thanks to Tadeusz Kowalski) with the single wire counter will give important ideas for the additional ionisations involved
  - ➢ These works seem useful for MMs applications, too

Thanks and ???