Modeling Impurity Concentration in Liquid Argon Detectors

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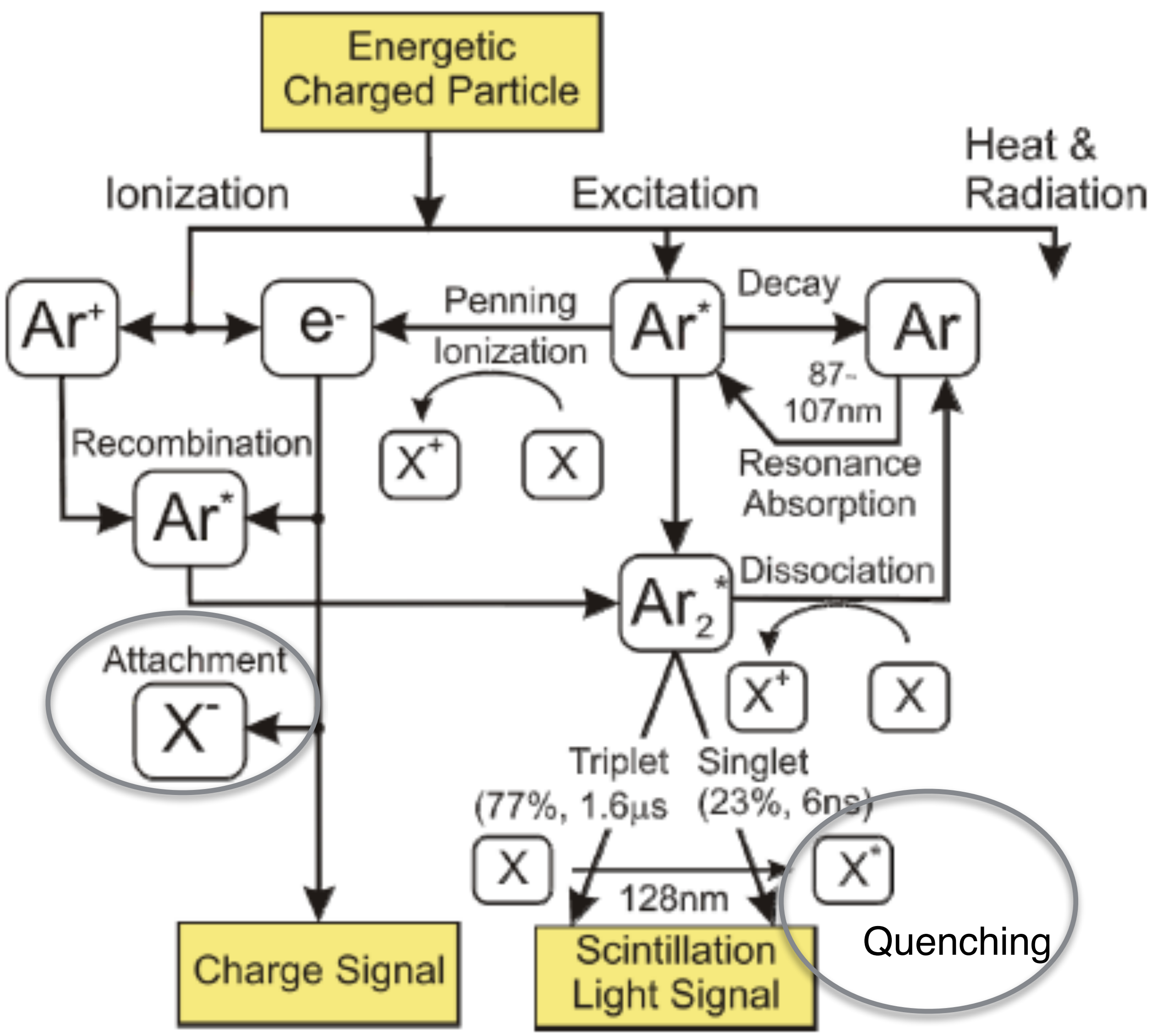
Outline

- Motivation
- Model description
- Measurement of Henry's coefficient for oxygen
- Determination of impurity leak rate
- Summary

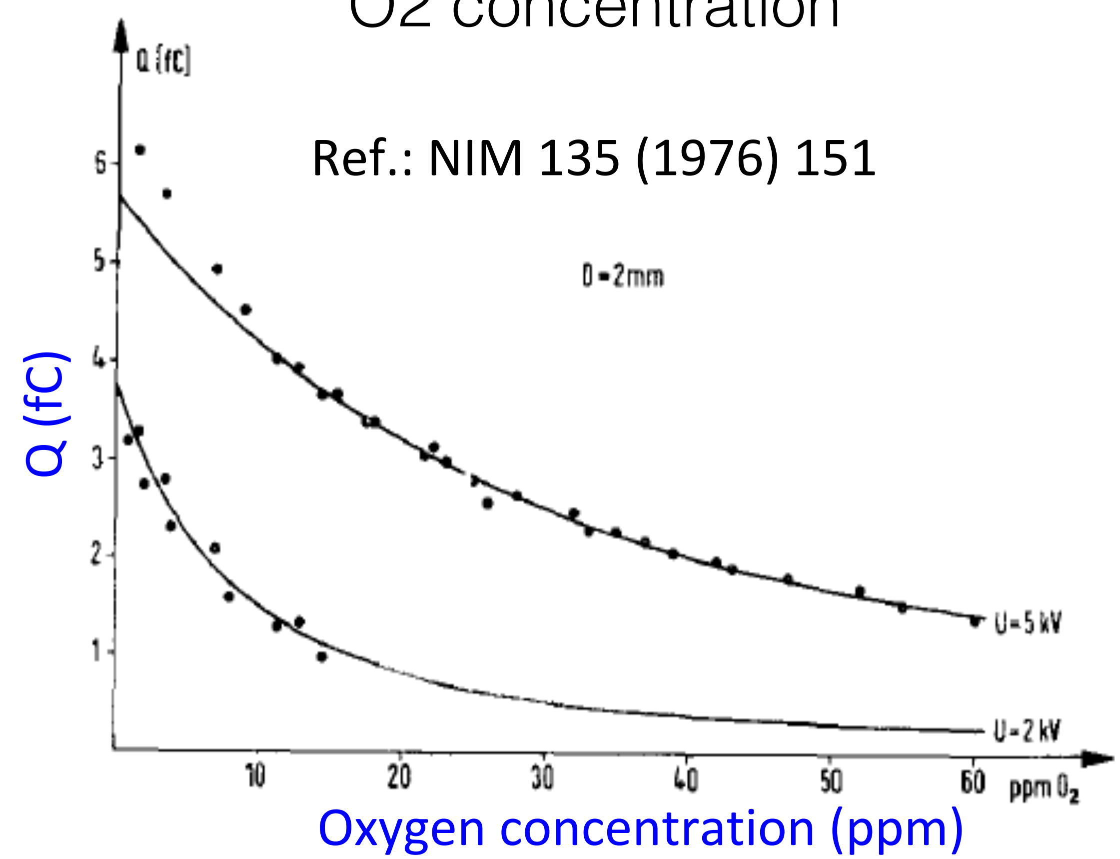
Motivation

- Impurities in LAr (O2, H2O, etc.) significantly reduce charge and light signals
- Ultra-high purity LAr (<1 ppb) is required for long drift distances (> 3.6 m)
- A mathematical model is important to understand the dynamics of LAr impurities
- Useful for detector design, optimization, and operation



Charge after 2 mm drift
vs.
O2 concentration

Ref.: NIM 135 (1976) 151



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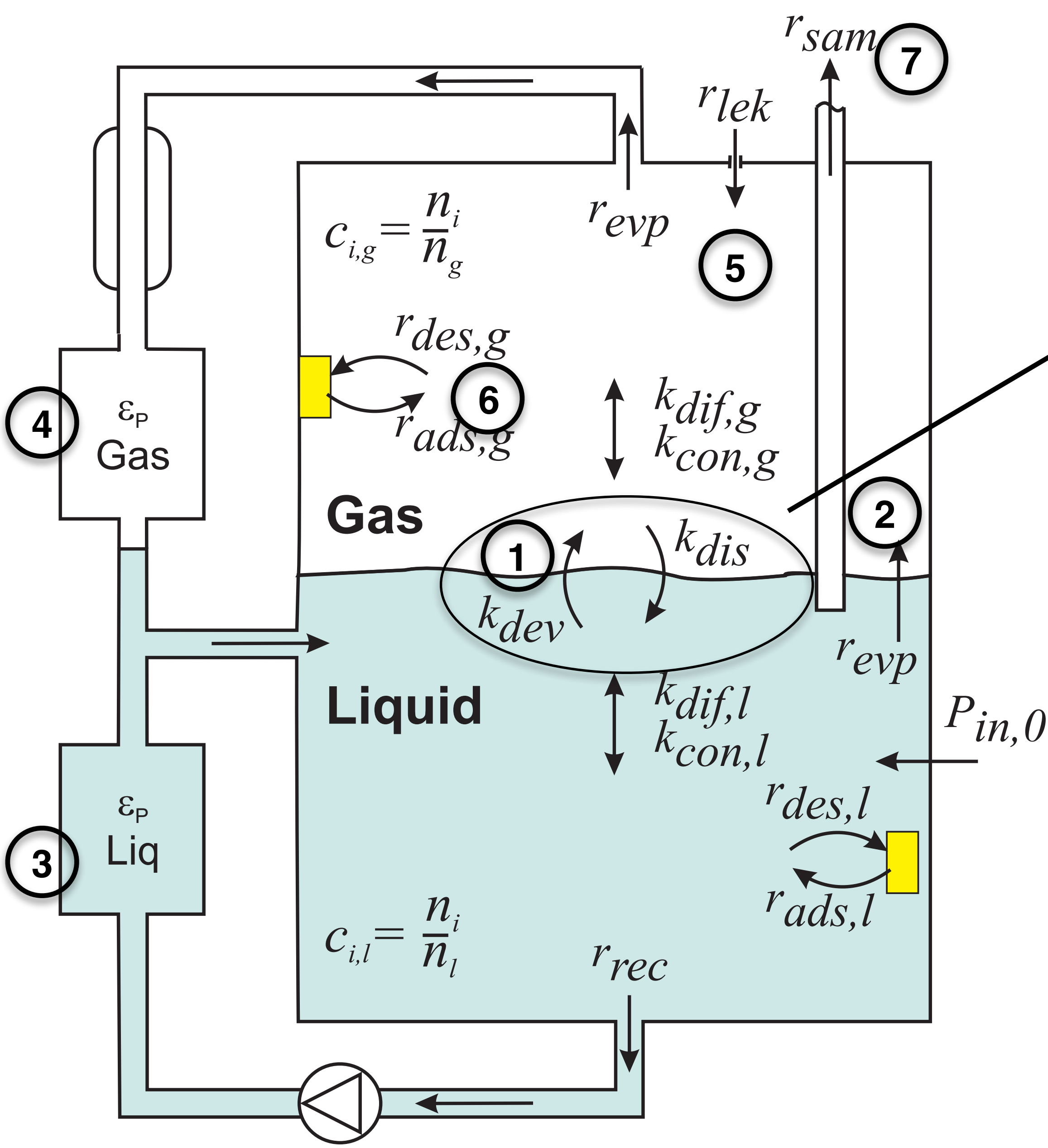
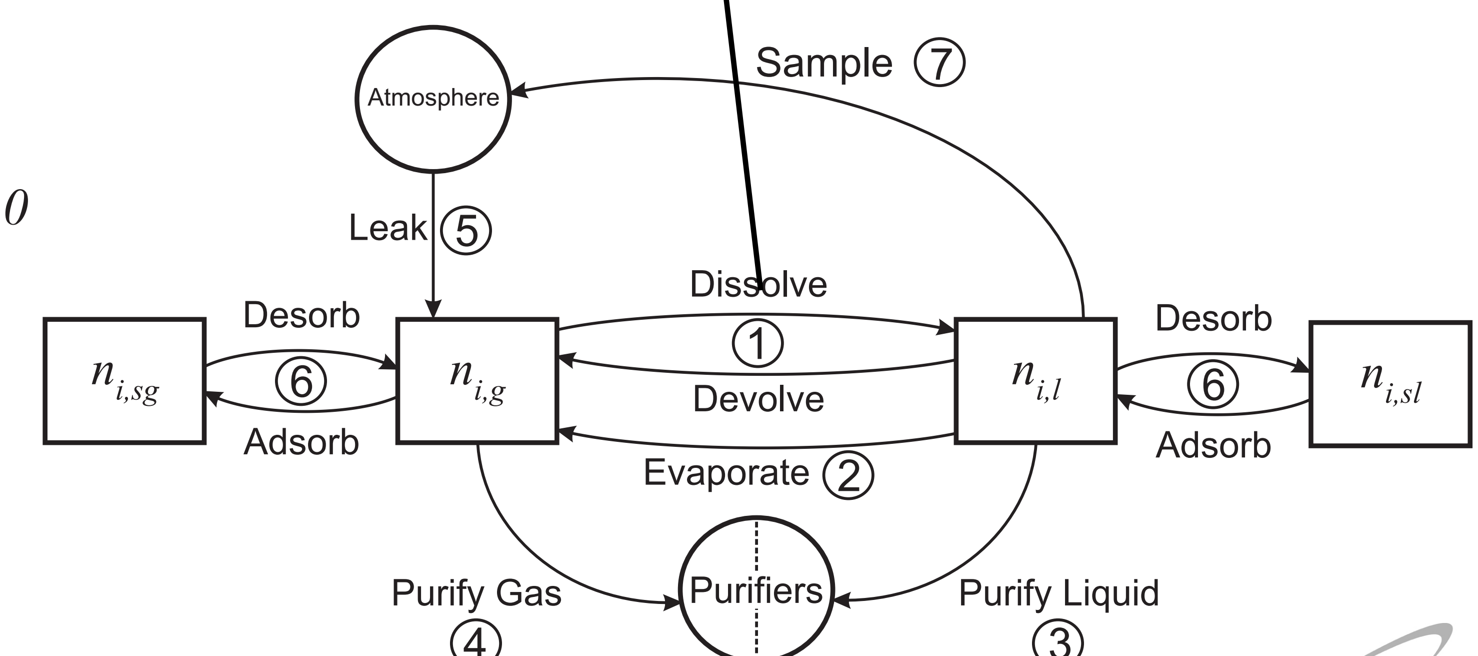
Model Description

- A quantitative kinetic model of impurity distribution is constructed
- Two species (Ar and impurity) in four places (gas, liquid, contact surfaces with gas/liquid)
- Each process is described by an ordinary differential equation
- The entire model is the sum of 7 processes



$$\left(\frac{dn_{i,g}}{dt}\right)_1 = n_g(-c_{i,g}\cdot k_{dis} + c_{i,l}\cdot k_{dev}),$$

$$\left(\frac{dn_{i,l}}{dt}\right)_1 = -\left(\frac{dn_{i,g}}{dt}\right)_1,$$



Determine Henry's Coefficient

- Full model is a non-linear 4th order ODE
- Full derivation can be found in the paper: arXiv:2009.10906
- Solutions without outgassing (#6) and sampling (#7):

$$c_{i,l}(t) = c_{i,l}^{ss} + C_1 \cdot e^{-k_F t} + C_2 \cdot e^{-k_S t},$$
$$c_{i,g}(t) = c_{i,g}^{ss} + C_3 \cdot e^{-k_F t} + C_4 \cdot e^{-k_S t}.$$

Ultimate concentration

Fast Components (~secs)

Slow concentration (~hrs)

- Henry's coefficient is the partition of an impurity between gas and liquid phases in equilibrium
- The model predicts a way to measure Henry's Coefficient
- Cleaning rate is defined as $r_s = k_s \times n_{i,l}$

$$H_{xx}(T) \equiv \frac{c_{i,g(as)}}{c_{i,l(iquid)}} = \frac{k_s \cdot n_{i,l}}{r_{evp}}$$

$$k_s = \frac{1}{\tau_{clean}}$$

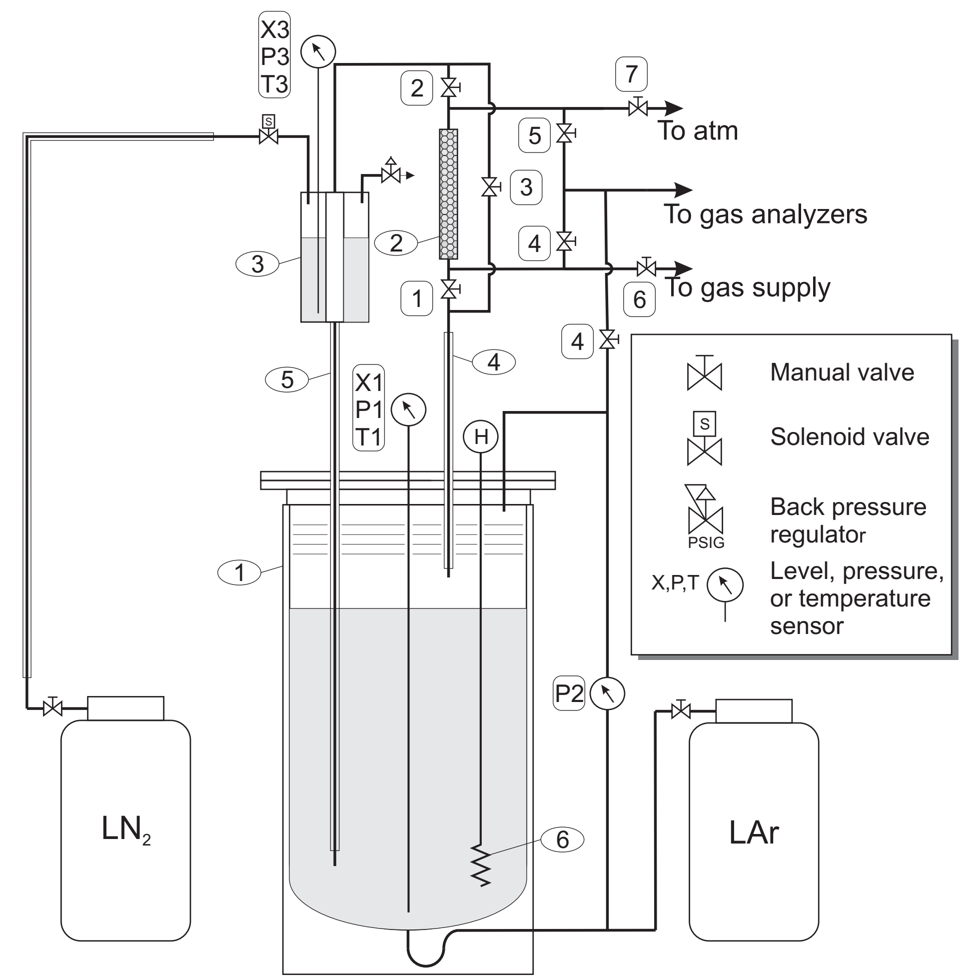
Amount of the Liquid in the system

Evaporation rate of the system determined by the heat input

Time constant of the impurity concentration

BNL 20-L LAr Test Stand

- For studying basic properties of LAr: measured longitudinal diffusion of electrons (NIMA 816 (2016) 160)
- Gas purification only
- Additional heating power can be varied 0-150 W
- Oxygen and water concentrations measured by sampling LAr into gas analyzers (0.2 ppb precision)



System Details: JINST 16 06 t06001

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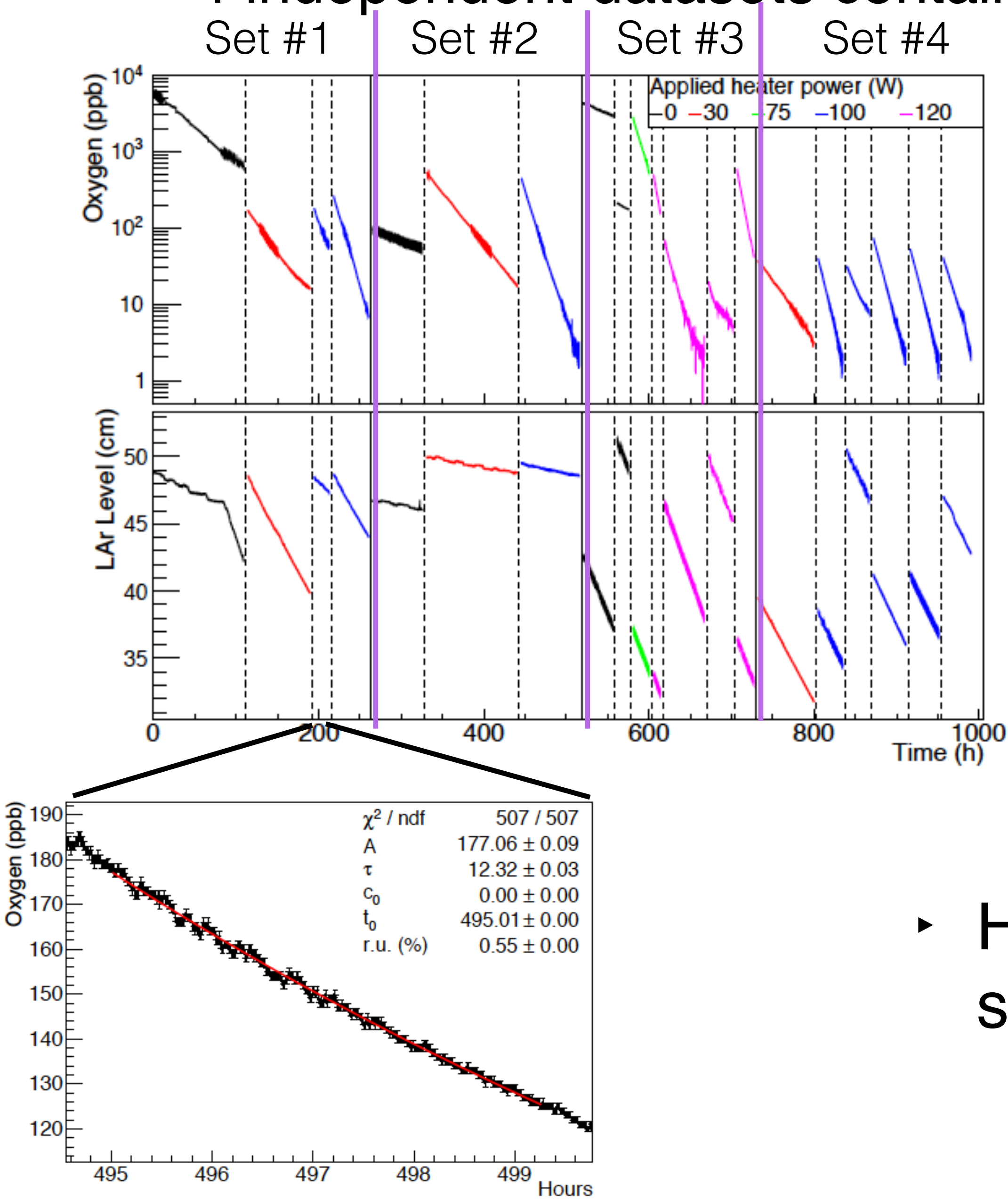
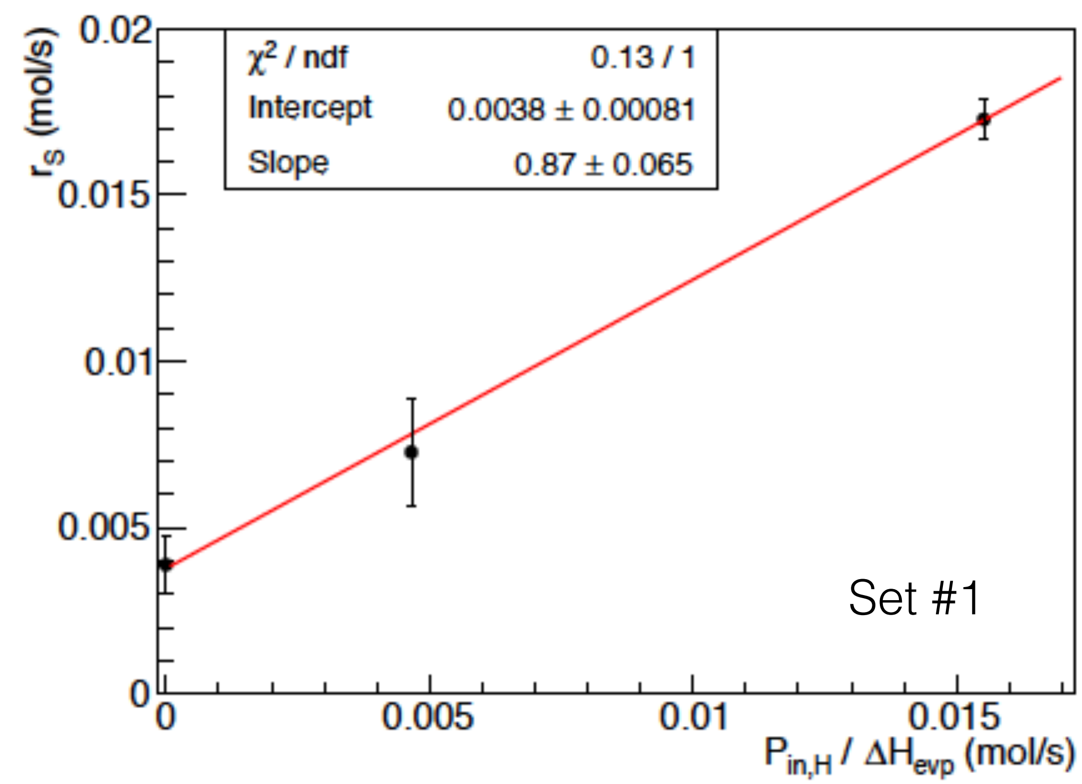
Henry's Coefficient for Oxygen

- Oxygen concentration record with other operating parameters (Temp, Press, Level…)
- Time evolution of concentrations measured under many different controlled conditions (heating power, level….)
- 4 independent datasets contained in the analysis



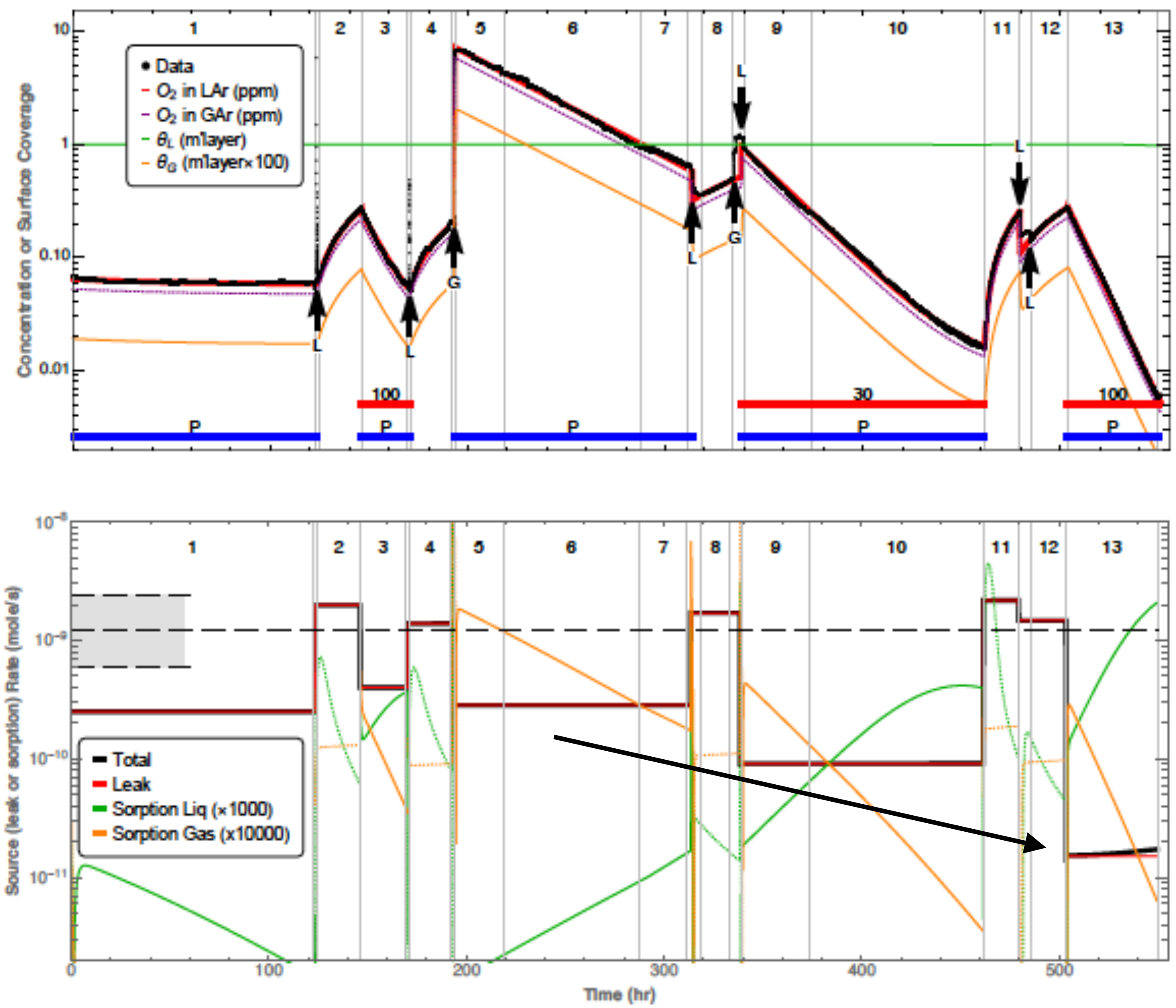


- Henry's coefficient by the model including systematics is consistent with literature value 0.91

$$H_{xx} = 0.84^{+0.09}_{-0.05}$$

Full model: Numerical fit to the data

- The full model is numerically fitted to all the data
- The Henry's coefficient is determined
- The "purification off" regions also fitted



- Effective leak is the impurity rate entering the liquid
- Effective leak rate is less than the total leak from atmosphere
- A fraction of the total leak rate enters the gas purification system before the impurity can reach the liquid
- Leak rate deduced from the model fit to liquid concentration therefore is the effective leak rate
- The total leak rate can be determined:
  - ~10^{-9} mol/s
- The ratio of effective leak to total leak decreases as the heating power (evaporation rate) increases

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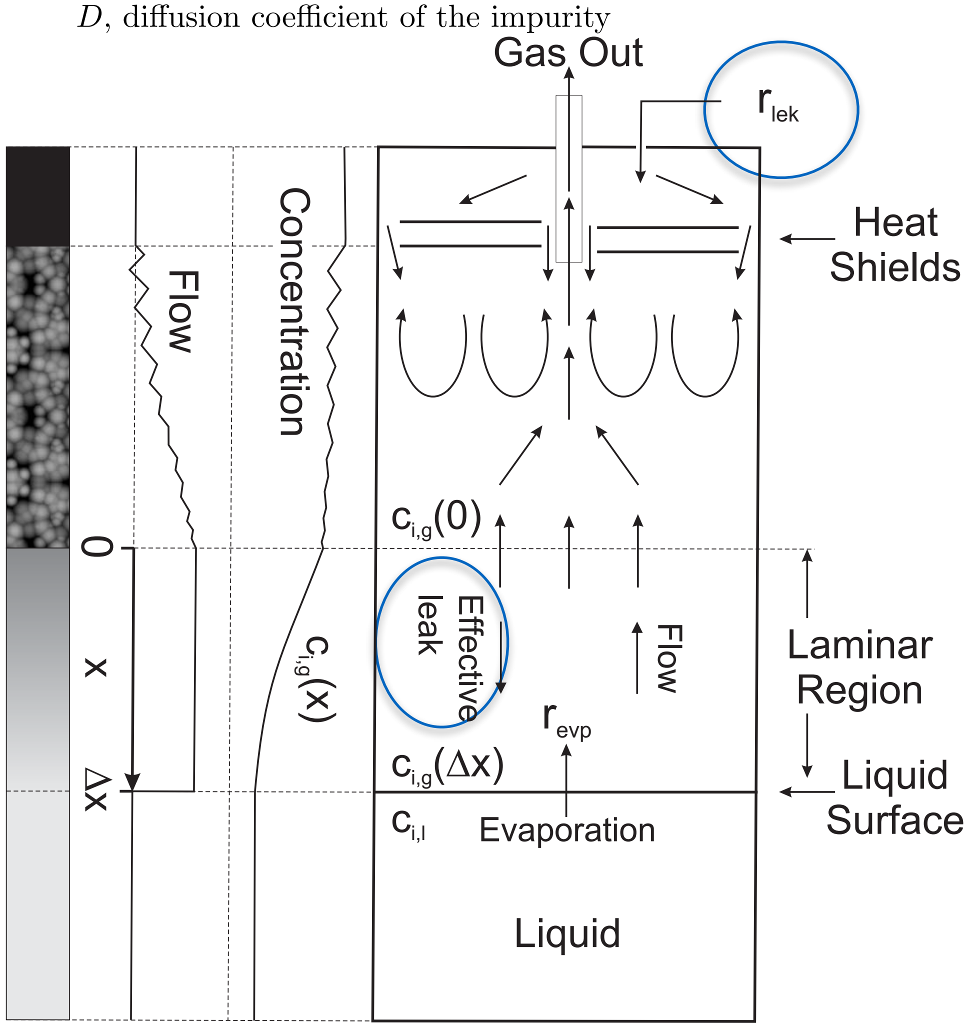
Keep Impurity Away from LAr- Necked Baffle

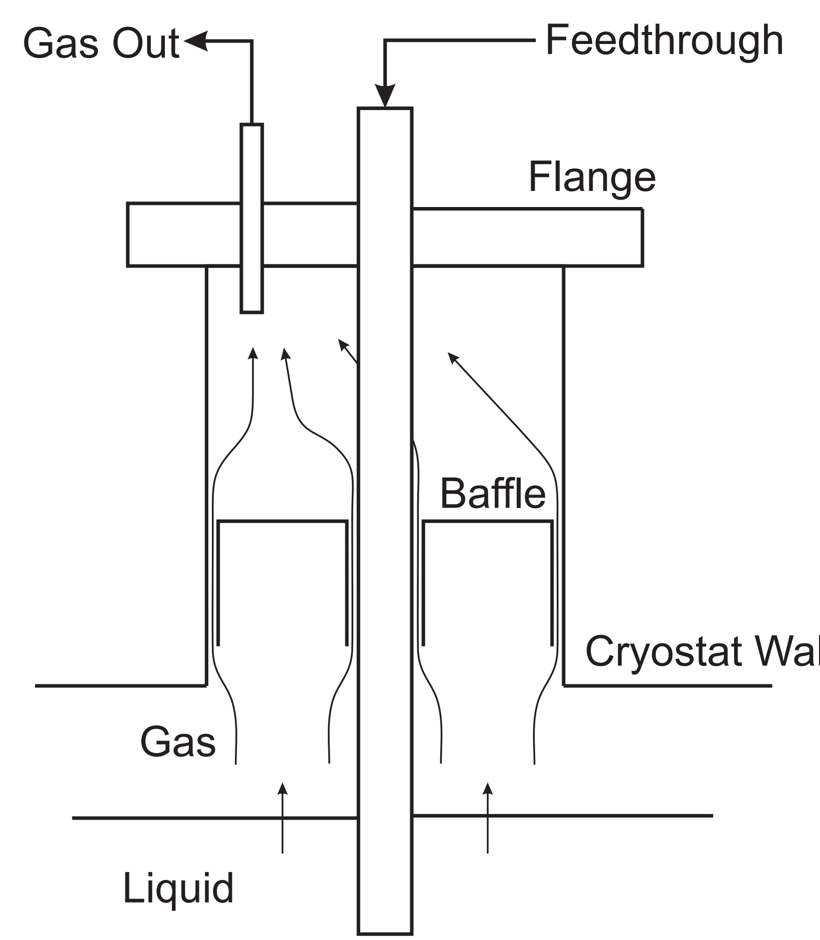
- The dependence of effective leak rate on the input heating power can be explained by a simple back diffusion model:
  - The larger r_{evp} (higher heating power) or smaller cross section area(A_c)
  - The lower concentration in the gas

$$c_{i,g}(x) = c_{i,g}(0) \cdot e^{-\frac{r_{evp} \cdot V_m \cdot x}{D \cdot A_c}}$$

r_{evp}, evaporation rate
V_m, mole volume of GAr
A_c, cross sectional area perpendicular to the flow direction
D, diffusion coefficient of the impurity



- Adding a necked baffle near the top region is expected to prevent impurities from reaching the LAr surface
- The idea will be tested in a new system



The new 260-L system

- Design for LArTPC field response measurement
- 260 Liter LAr Volume
    - 22” ID + 40” depth
    - Sufficient for small LArTPC
- Quick turn-round time of <1 week with ultra-high purity (<1 ppb) by gas purification
- Cryogenic operation studies last year
- Ideal system for future impurity studies, instrumentation testing, and other LArTPC measurements

Summary

- A mathematical model for impurity distribution and time evolution in a noble liquid cryogenic system is constructed and validated with data
(submitted to NIM, arXiv:2009.10906)
- The model provides a way of measuring Henry’s coefficient for an impurity in argon
  - The measured Henry’s coefficient for Oxygen is consistent with literature
- The model can be used to improve the performance of the existing detectors and to design future detectors
- The model suggests adding a necked baffle will help in reducing impurity concentrations in the detector
- More results are expected with the new 260-L system