Krypton Concentration Monitoring in Cryogenic Distillation for XENON1T with a ^{83m}Kr Tracer

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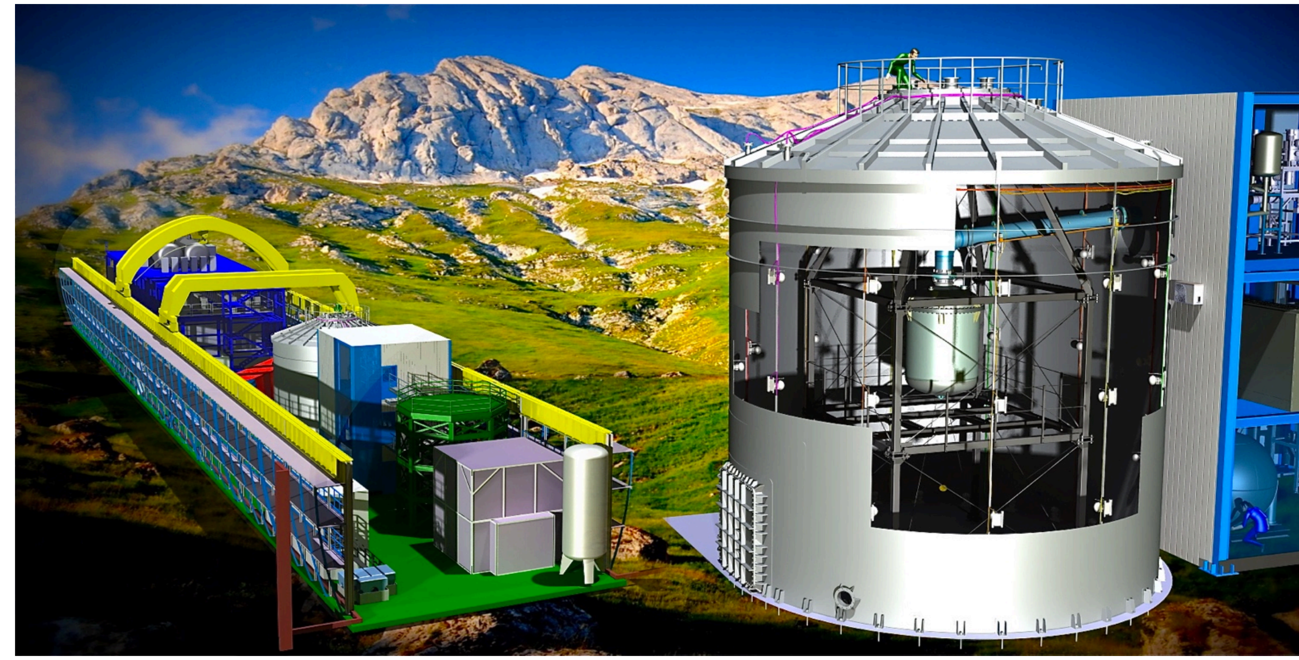
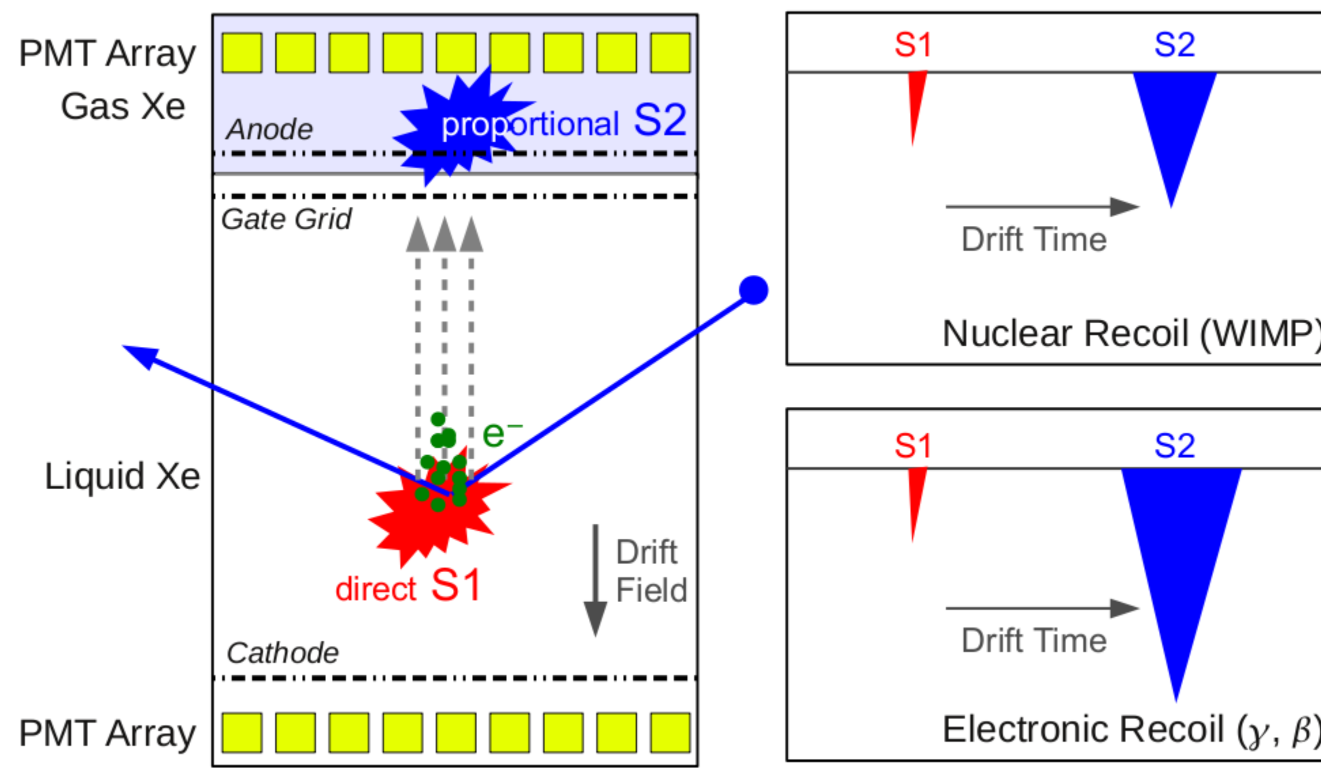
1. The XENON1T Experiment

cf. talk by A. Buß

- Direct dark matter search
- Located underground at LNGS
- Dual-phase Xe-TPC yields two signals:
  - Primary scintillation in LXe (**S1**)
  - Electroluminescence in GXe (**S2**)

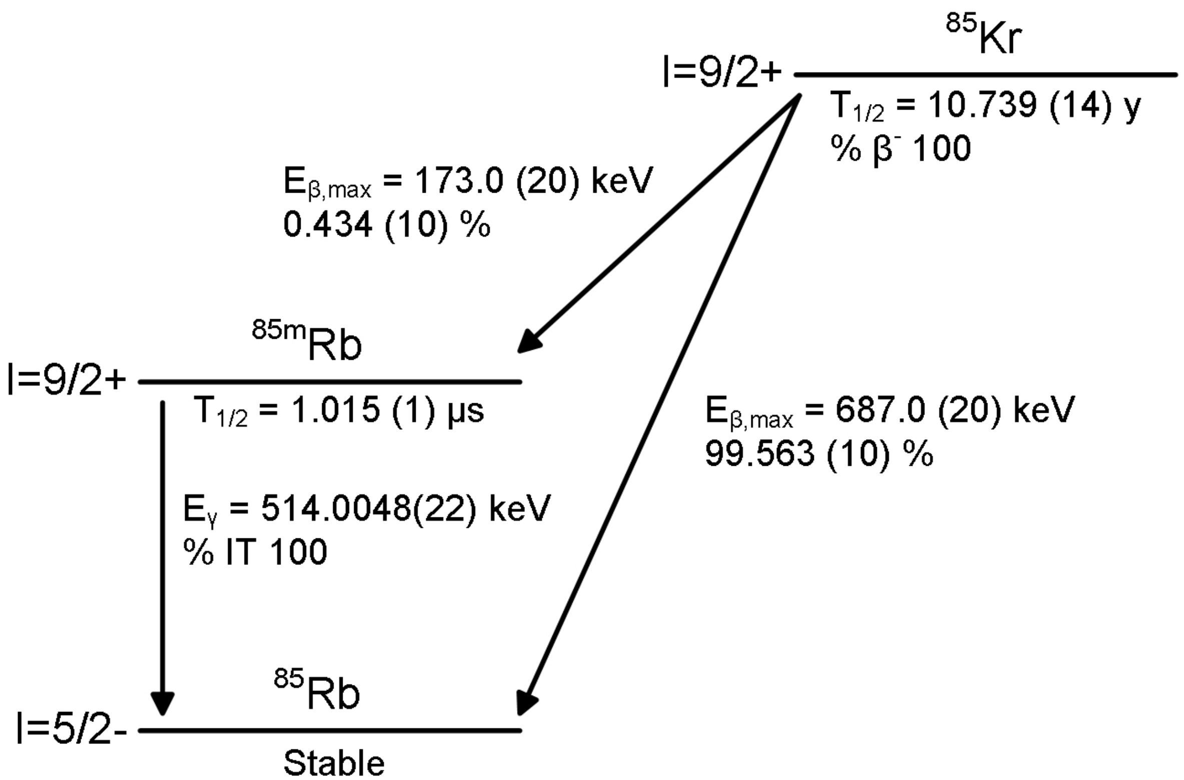




→ **99.5 % ER/NR discrimination from S1/S2 ratio**

2. ^{85}Kr Electronic Recoil Background

- Intrinsic contaminations of Xe with atmospheric Kr (~ 10^{-6})
- ^{85}Kr/^{nat}Kr ≈ 2 • 10^{-11} from man-made nuclear fission
- XENON1T purity requirement:
  - **^{nat}Kr/Xe < 0.5 ppt**
  - Reduction factor $\boldsymbol{F_{Red}} \approx \mathbf{10^5}$



$$R_{\text{background}} = \frac{N_{\text{Xe}} \cdot c_{^{85}\text{Kr}}}{\tau} \cdot 0.005 \cdot 0.03 = 0.47 \text{ events/ton/year}$$

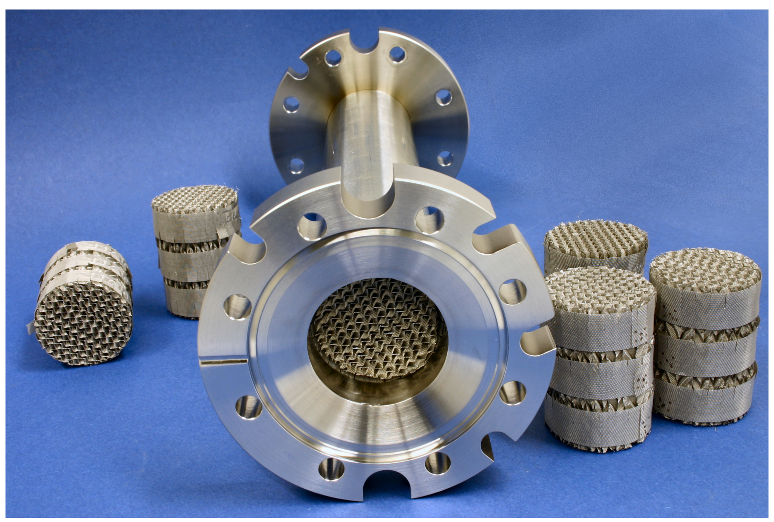
$A_{^{85}\text{Kr}}$

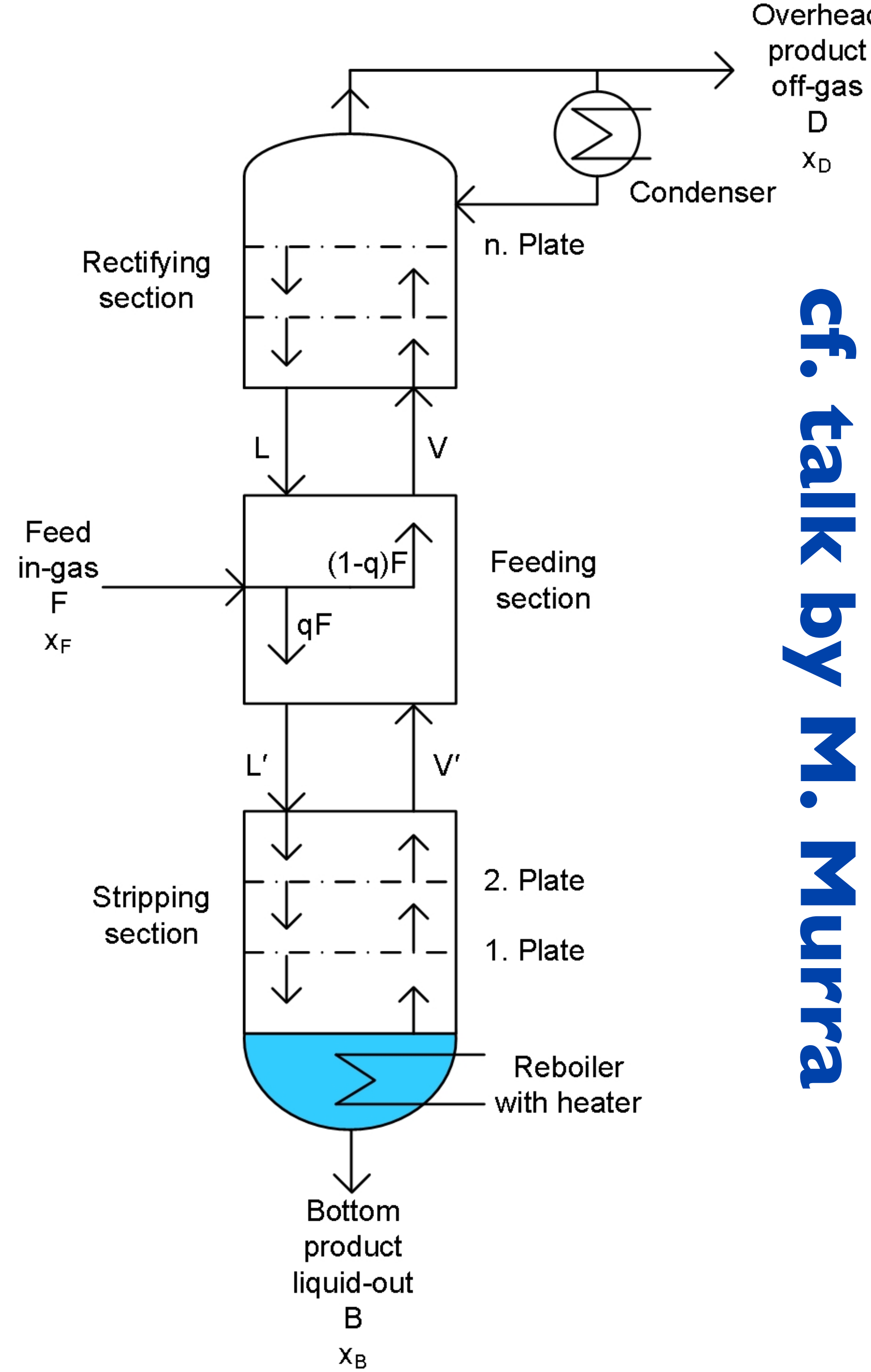
99.5 % ER/NR discrimination

β-spectrum ROI

2.1 Cryogenic Distillation

- Utilize higher Kr vapor pressure
- Connection of multiple distillation stages for desired purity (McCabe-Thiele method)
- Reflux along the column with bottom reboiler and top condenser
- Realized as package column





cf. talk by M. Murra

Achieved concentration of **0.026 ppt** (10^{-12}) $^{nat}Kr/Xe$ with phase-1 column in Münster

→ **Offline:** Far below the sensitivity of commercially available measurement systems. Measured with custom RGMS setup from MPIK Heidelberg.

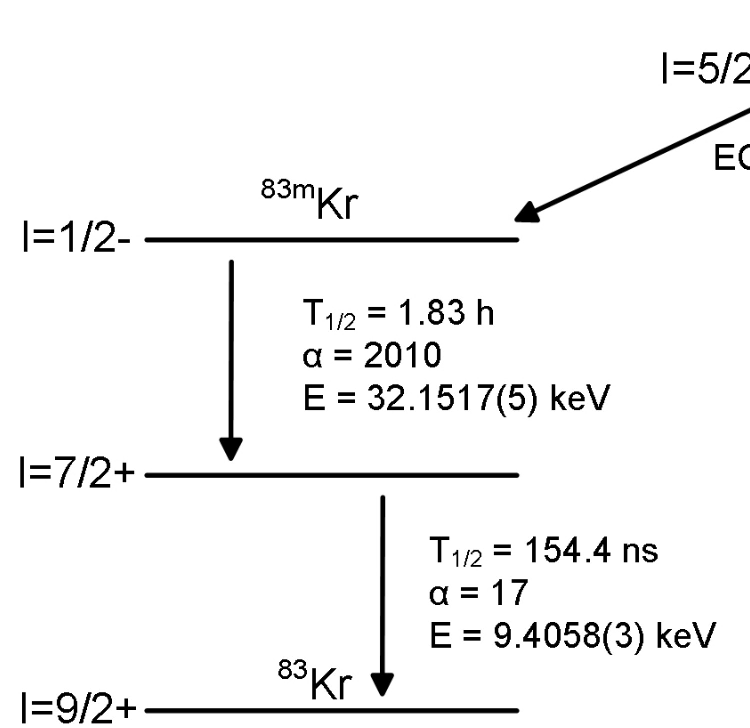
→ **Online:** Use a radioactive tracer, measure decays.

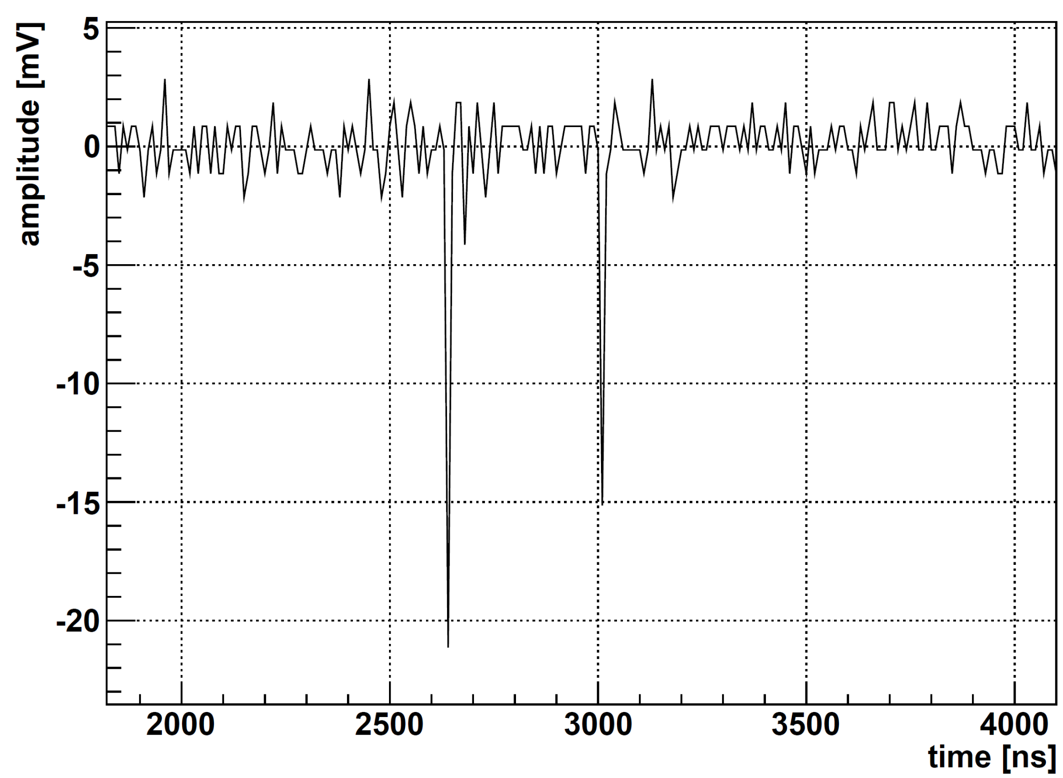
Rosendahl et al., JINST 9 (2014) P100 10

3. A Radioactive ^{83m}Kr Tracer

- Isomer with **$T_{1/2}$ = 1.83 h** and two highly converted transitions
  - No long-term contamination
  - Sufficient signal rate and distribution time
  - Background reduction by coincidence measurement
- Test Kr distillation at sub-ppt concentrations in Xe

→ Show that cryogenic distillation actually works in this regime!

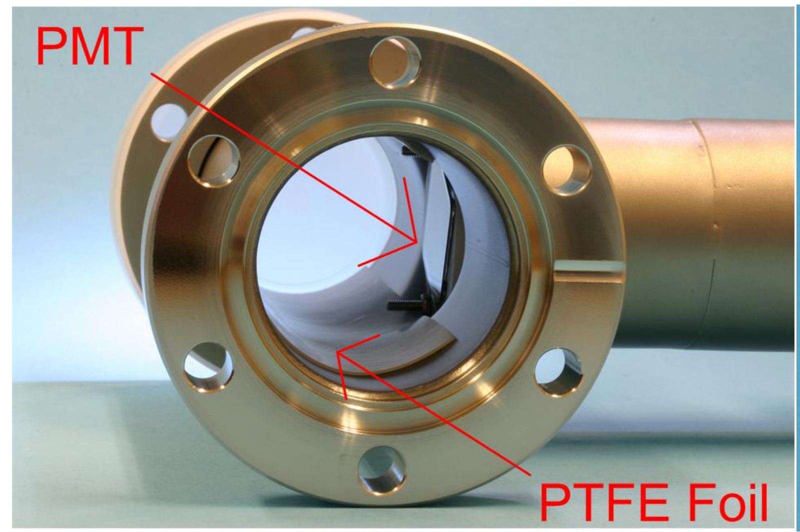


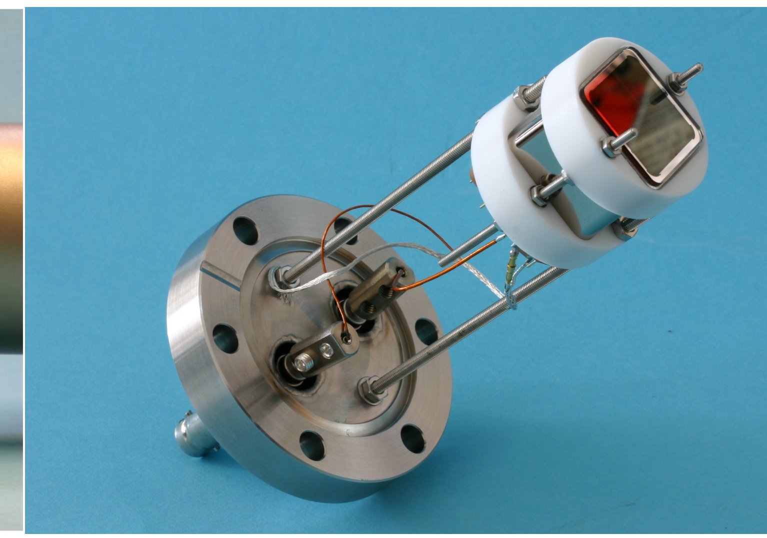


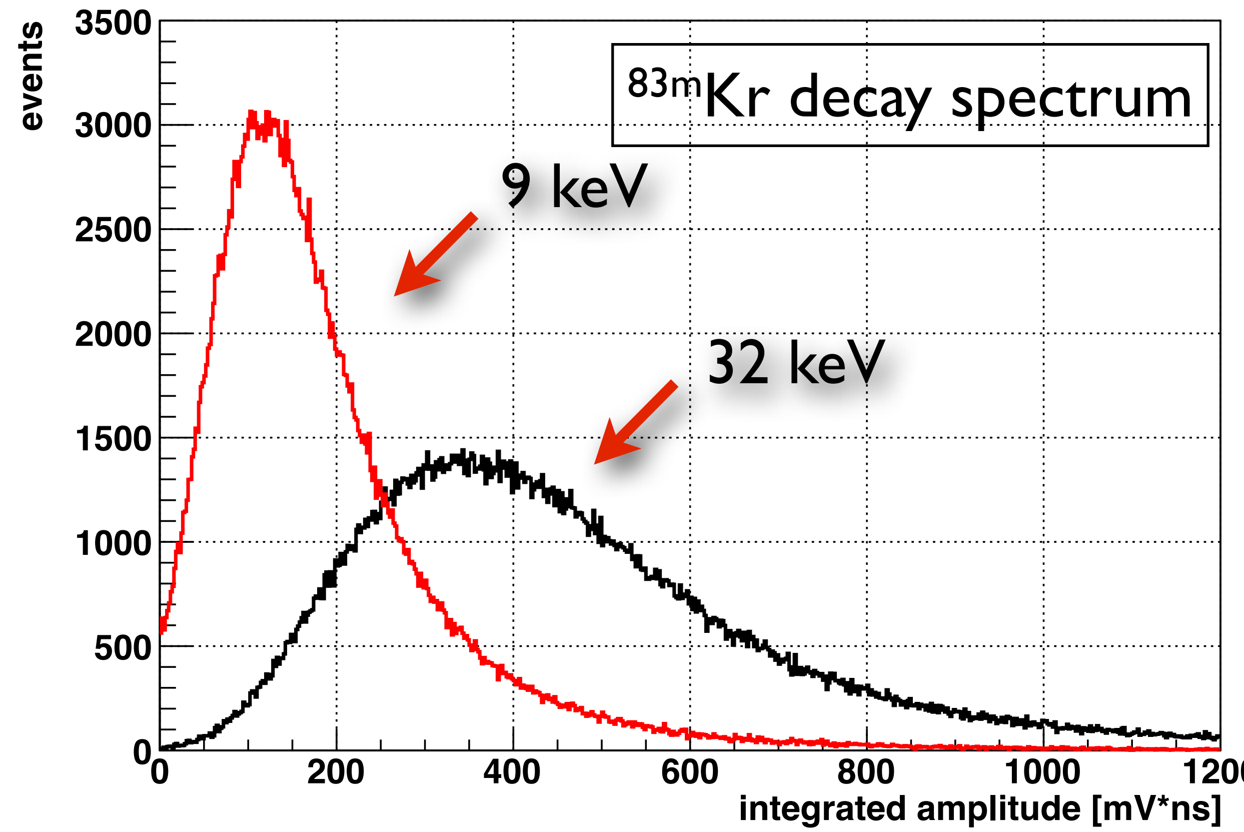
V. Hannen et al., JINST 6 (2011) P10013

3.1 Detector Design

- Interaction of decay products with GXe
- 30 keV e⁻ range ~ 1 cm
- **λ =178 nm** scintillation by de-excitation of Xe-dimers
- Custom-made detectors
  - Hamamatsu® R8520-06-Al photomultipliers
  - PTFE reflector for VUV

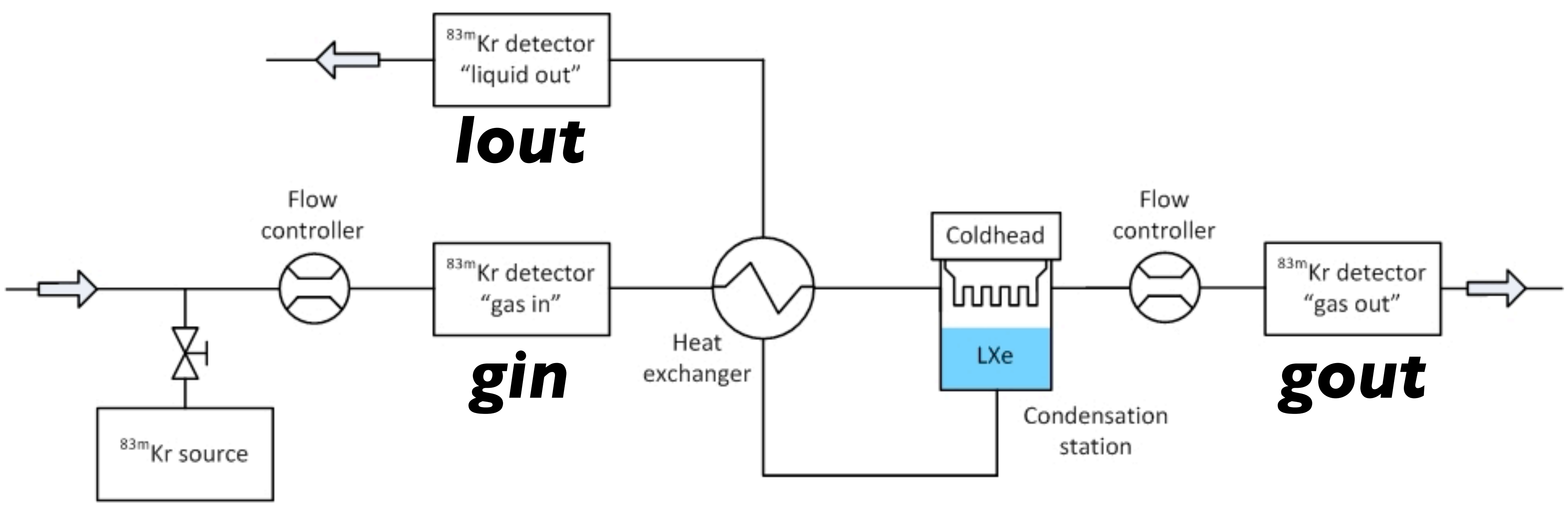




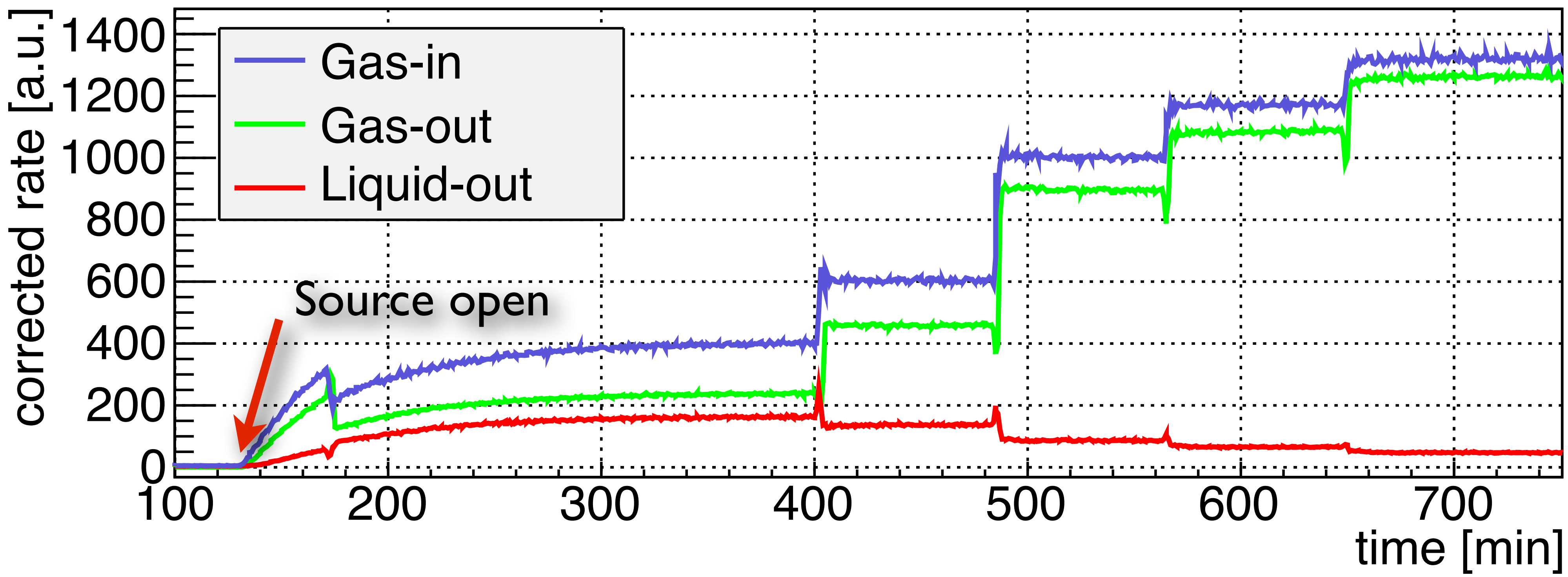


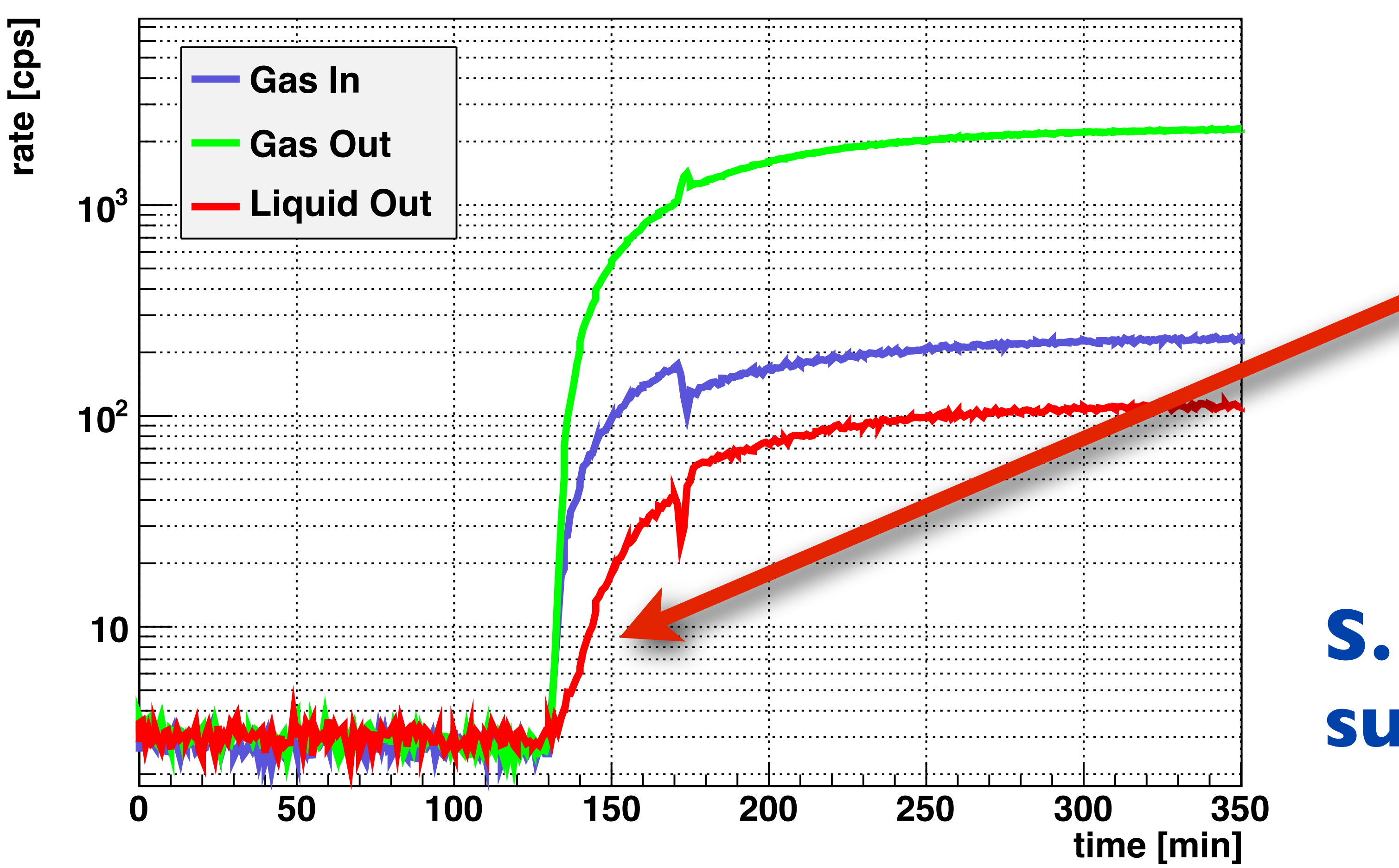
4. Modeling Signal Rate and Particle Flux for a Single Stage Setup

- Liquefaction at coldhead
- Expected enrichment of Kr in off-gas
- 3 detectors (i): ***gin***, ***gout***, ***lout***
- **3 ppq** (10-15) ^{83m}Kr/Xe with **1 MBq** source and **5 slpm flow**



4.1 Measured Decay Rates





Residence time of Kr in liquid phase (~ minutes)!

S. Rosendahl et al., submitted to Rev. Sci. Instr.

4.2 Flows, Separation Factor and Residence Time

S given by total particle flows at the detectors:

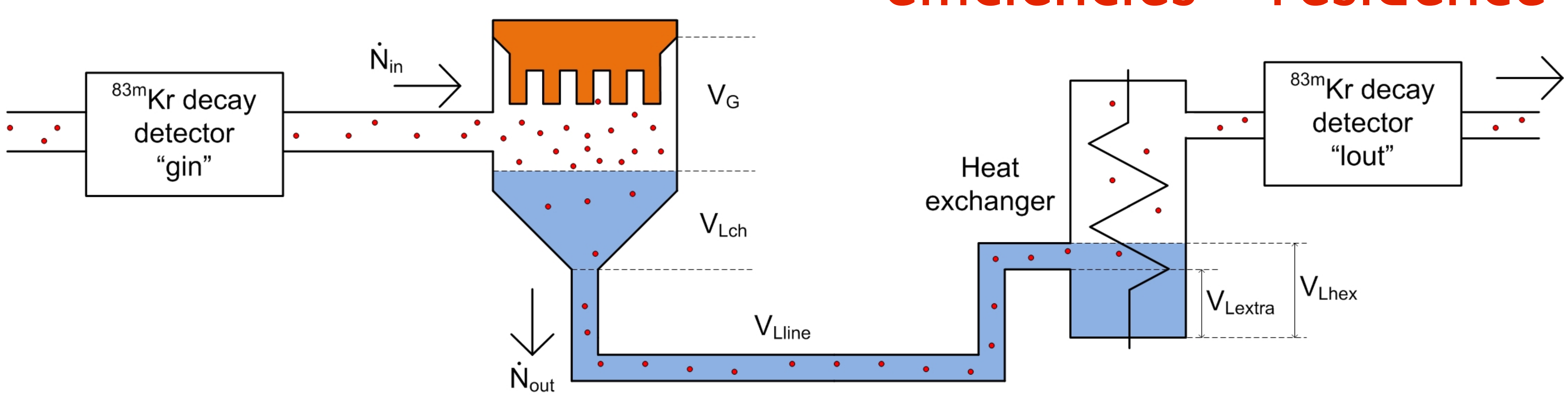
$$S = \frac{(c\dot{N})_{\text{gin}}}{(c\dot{N})_{\text{lout}}} = \frac{r_{\text{gout}} q_{\text{gout}} p_{\text{lout}}}{r_{\text{lout}} q_{\text{lout}} p_{\text{gout}}} \cdot \frac{\nu_{\text{liquid}}}{\nu_{\text{gas}}} \cdot e^{\frac{\tau_{\text{lout}}}{\tau}}$$

$$q_{\text{i}} = \frac{p_{\text{i}} V_{\text{det,i}}}{t}$$

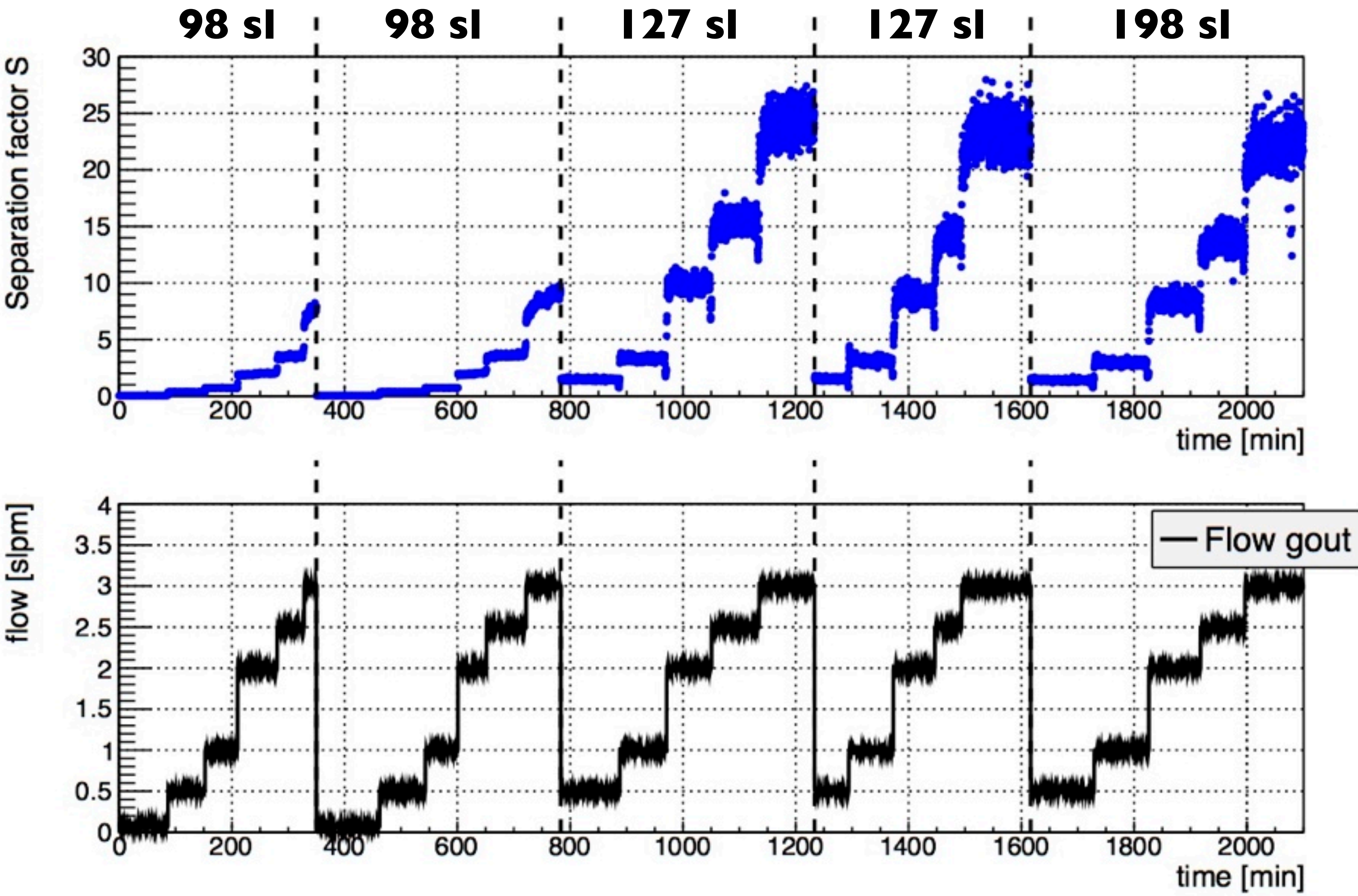
Measured

Relative detector efficiencies

Decay correction for residence time



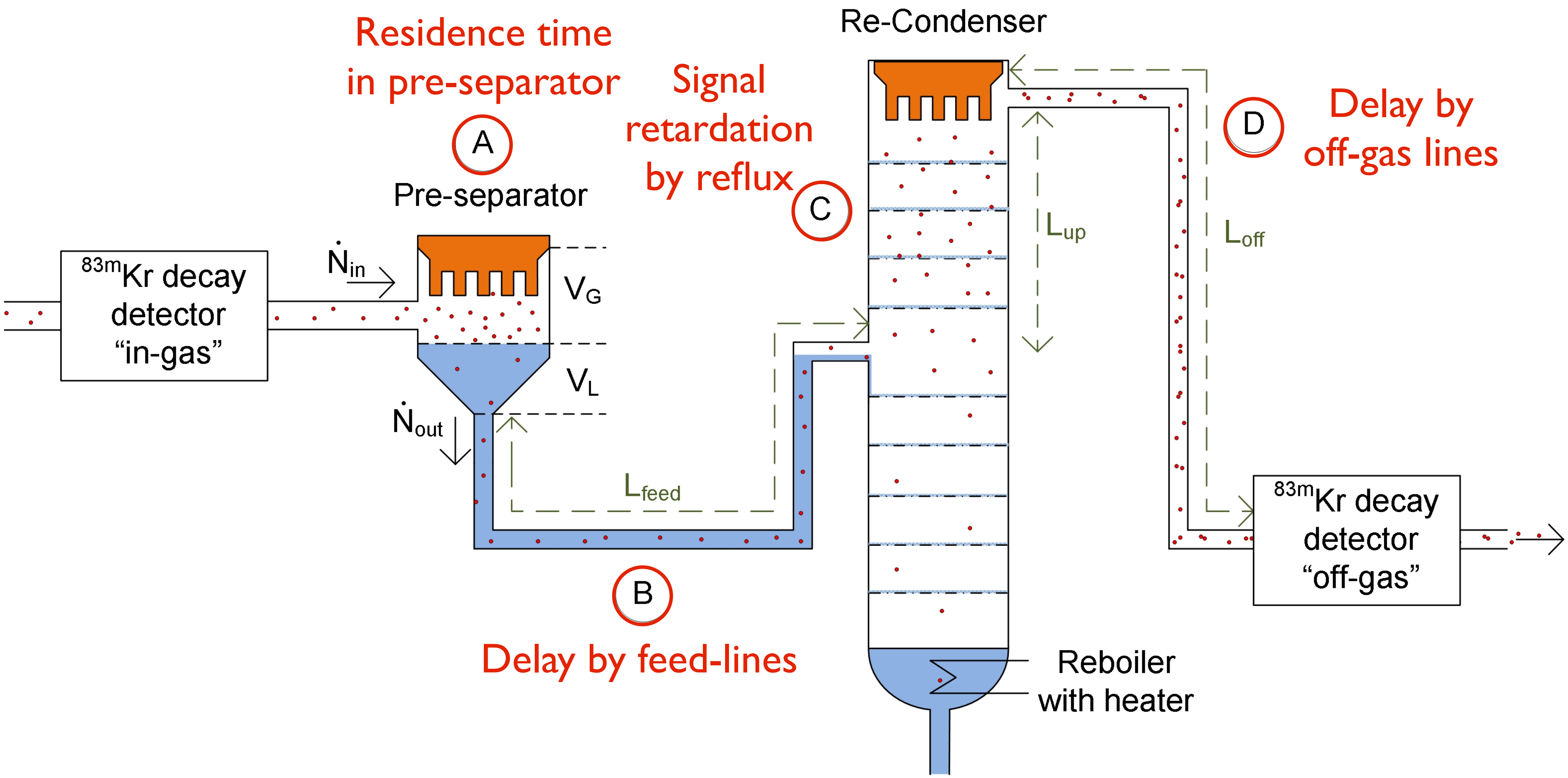
4.3 Separation Factors



- Residence time by fit of flow model (~ **min**)
- ***S*** **~ 10**

→ **Kr distillation works at sub-ppt concentrations!**

5. Particle Flux in the Phase-1 Column

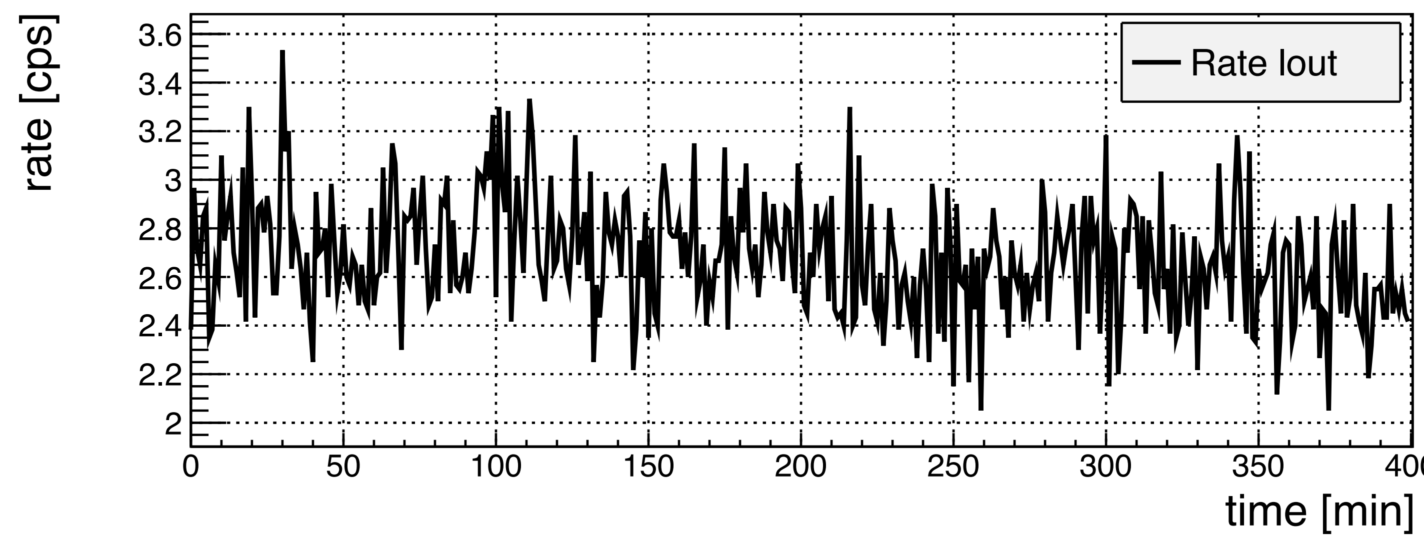


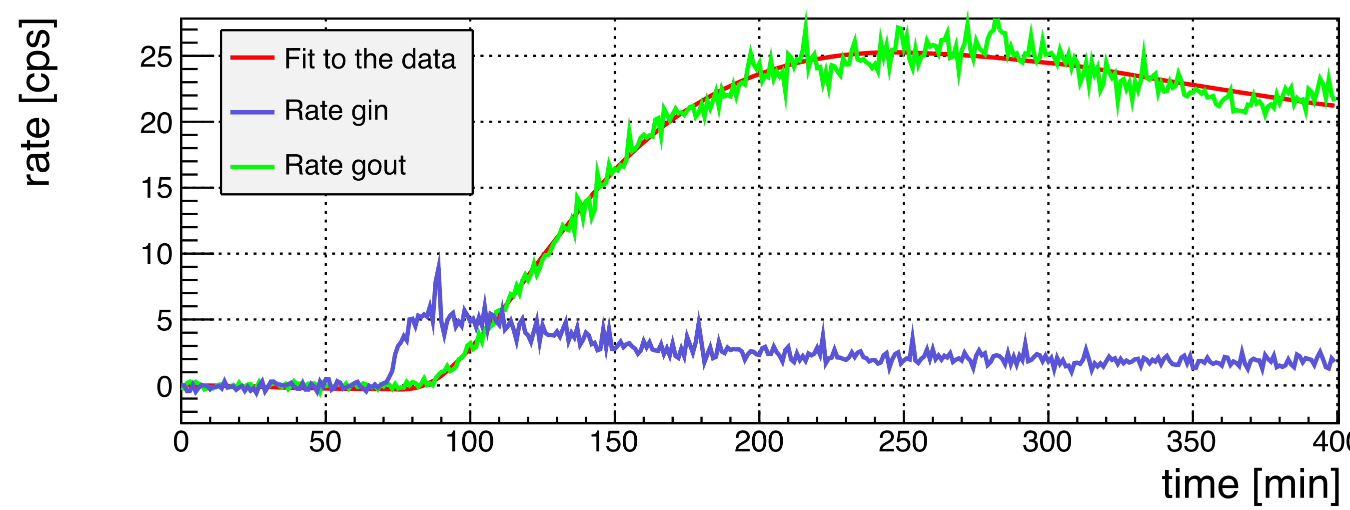
Rate fit function:

$$r_{\text{off-gas}} = \underbrace{r_{\text{out column}}}_{\text{Pressures + flow}} \cdot B_{\text{qp}} \cdot \exp\left(-\frac{\overset{\mathbf{A}}{\tau_1} + \overset{\mathbf{C}}{\tau_2} + \overset{\mathbf{B+D}}{\Delta t_{\text{tot}}}}{\tau}\right)$$

5.1 Tracer Applications for the Phase-1 Column

- Rate at ***liquid out*** dominated by background
- Model ***off-gas*** for Kr particle flow
- Determination of **residence time** & **HETP** value by fit of flow model





	15.01.14 LF2, 8.5 slpm	17.01.14 LF2, 12.0 slpm	20.02.2014 LF1, 8.5 slpm	06.03.14 LF2+GF1, 8.5 slpm
HETP	15.28 ± 0.01	12.6 ± 0.3	24.3 ± 7.6	11.67 ± 0.01
τ_1	3185 ± 7	2364 ± 14	762.4 ± 0.1	1921 ± 3
$B_{q,p}$	48.1 ± 0.1	35.3 ± 0.3	119.2 ± 0.1	45.6 ± 0.1
χ^2_{Red}	1.13	1.3	0.8	0.82
N_{dof}	394	326	246	246

6. Conclusion

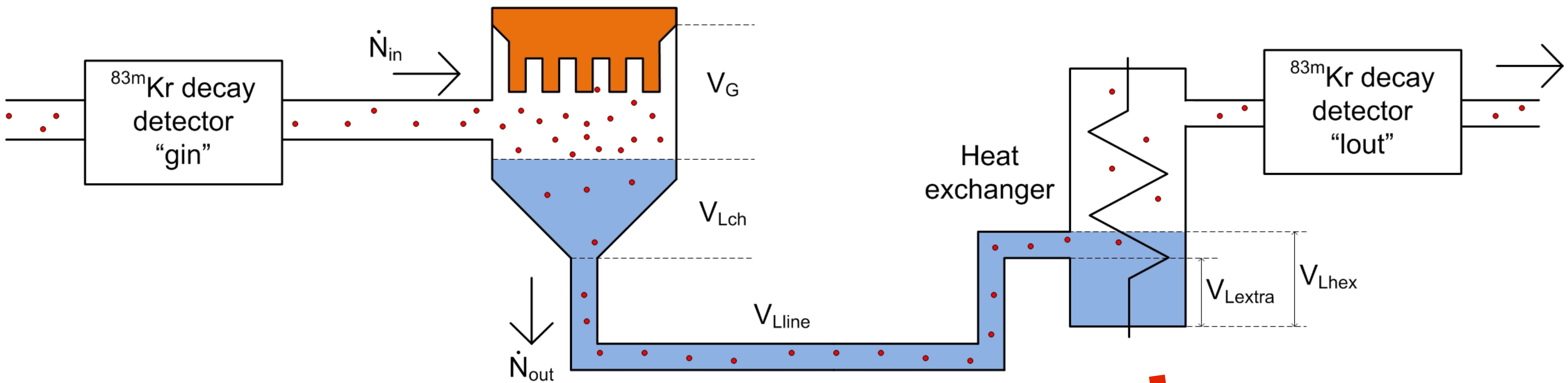
- ^{83m}**Kr** is an ideal tracer for cryogenic distillation (lifetime, two-fold decay).
- Concentration measurements are substituted with decay rate measurements.
- Separation factors $\boldsymbol{S \sim 10}$ for a single stage distillation setup prove that cryogenic distillation of Kr is possible at sub-ppt concentrations.
- Particle flow model in the phase-1 column can be used for calculating HETP value & residence time at different flows/pressures.

Thank you for your attention!

Bibliography

1. S. Rosendahl, *Gas Purification of the XENON Dark Matter Search, PhD Thesis*, Westfälische Wilhelms-Universität, Münster, 2015.
2. S. Rosendahl et al., *A novel ^{83m}Kr tracer method for characterizing xenon gas and cryogenic distillation systems*, JINST 9 P10010, 2014.
3. E. Aprile et al., *The XENON100 dark matter experiment*, Astroparticle Physics 35, 9, 2012.

Residence time



- Define relative fractions

$$f_{\mathrm{gas}} = \frac{(c\dot{N})_{\mathrm{gout}}}{(c\dot{N})_{\mathrm{gin}}} = \frac{r_{\mathrm{gout}} q_{\mathrm{gout}} p_{\mathrm{gin}}}{r_{\mathrm{gin}} q_{\mathrm{gin}} p_{\mathrm{gout}}} \cdot \frac{1}{\nu_{\mathrm{gas}}}$$

$$f_{\mathrm{liquid}} = \frac{(c\dot{N})_{\mathrm{lout}}}{(c\dot{N})_{\mathrm{gin}}} = \frac{r_{\mathrm{lout}} q_{\mathrm{lout}} p_{\mathrm{gin}}}{r_{\mathrm{gin}} q_{\mathrm{gin}} p_{\mathrm{lout}}} \cdot \frac{1}{\nu_{\mathrm{liquid}}} \cdot e^{\frac{V_{\mathrm{lout}}}{q_{\mathrm{lout}} \tau}}$$

$$f_{\mathrm{liquid}} + f_{\mathrm{gas}} = 1$$

Effective volume:

$$V_{\mathrm{lout}} = \tau_{\mathrm{lout}} \cdot q_{\mathrm{lout}}$$