AUSTRIAN ACADEMY OF SCIENCES

SMI – STEFAN MEYER INSTITUTE FOR SUBATOMIC PHYSICS

Studying the Strong Interaction with Kaonic Atoms at DAΦNE

Marlene Tüchler

Final Event of DK-PI

29.09.2023

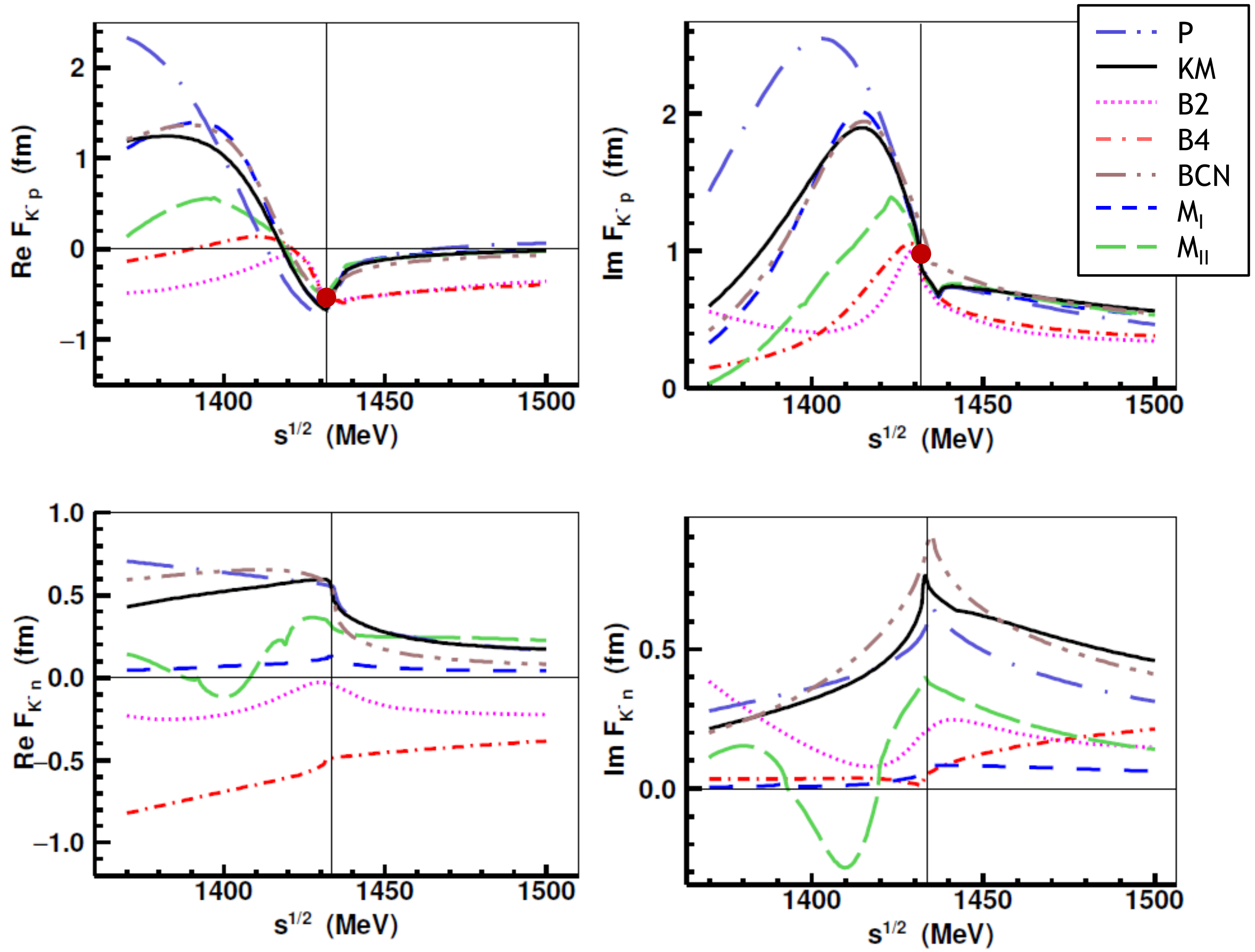
Overview

- Introduction
  - Kaonic Atoms
  - The SIDDHARTA-2 Experiment
- What I did during my time in the DK-PI
  - On-site operations
  - Characterisation and performance studies of the detector systems
  - Analysis of the first data
  - Outside of the lab
- What I am doing now & hope to achieve

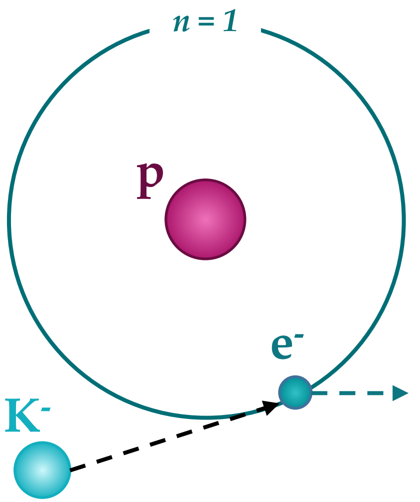
Introduction

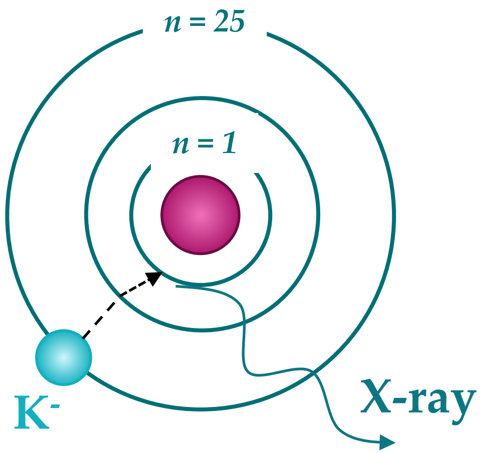
Motivation

- **X-ray spectroscopy of light kaonic atoms**
  - SIDDHARTA: K^-p
  - SIDDHARTA-2: K^-d
- Extraction of **isospin-dependent (*I* = 0, *I* = 1) $\bar{K}N$ scattering lengths a_0 and a_1**
- Interplay between **explicit & spontaneous chiral symmetry breaking**



Kaonic Atoms





- K^- substitutes electron in hydrogen atom

$$n \sim \sqrt{\frac{\mu}{m_e}} n_e$$

(μ ... reduced mass of kaonic atom;
n ... principal quantum number;
m_e … electron mass;
n_e … principal quantum number of electron)

- Quantum cascade process to ground state
- Kaonic atoms are sensitive probes for low-energy QCD including strangeness:

$$r_n = \frac{\hbar^2}{\mu e^2} \frac{n^2}{Z}$$

$$E_n = -\frac{\mu c^2}{2} \left(\frac{Z\alpha}{n}\right)^2$$

(Z ... atomic number;
e ... elementary charge;
α ... fine structure constant)

Antikaon-Nucleon Scattering Lengths

- Strong interaction between K⁻ and nucleons:
  Shift ε_{1s} and broadened width Γ_{1s} of 1*s* state

$$\varepsilon_{1s} = \mathrm{E}_{1s}^{\mathrm{measured}} - \mathrm{E}_{1s}^{\mathrm{QED}}$$

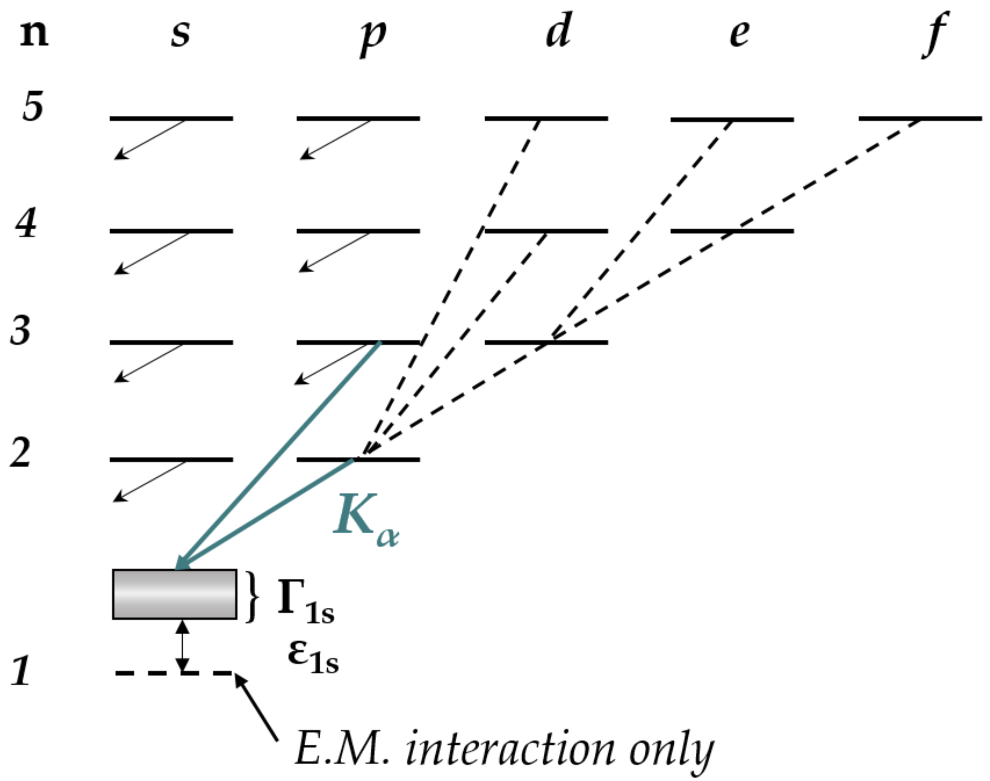
- **Improved Deser-Trueman formula**

$$\varepsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu^2 a_{\mathrm{K^-p}}[1 - 2\alpha\mu(\ln\alpha - 1)a_{\mathrm{K^-p}}]$$

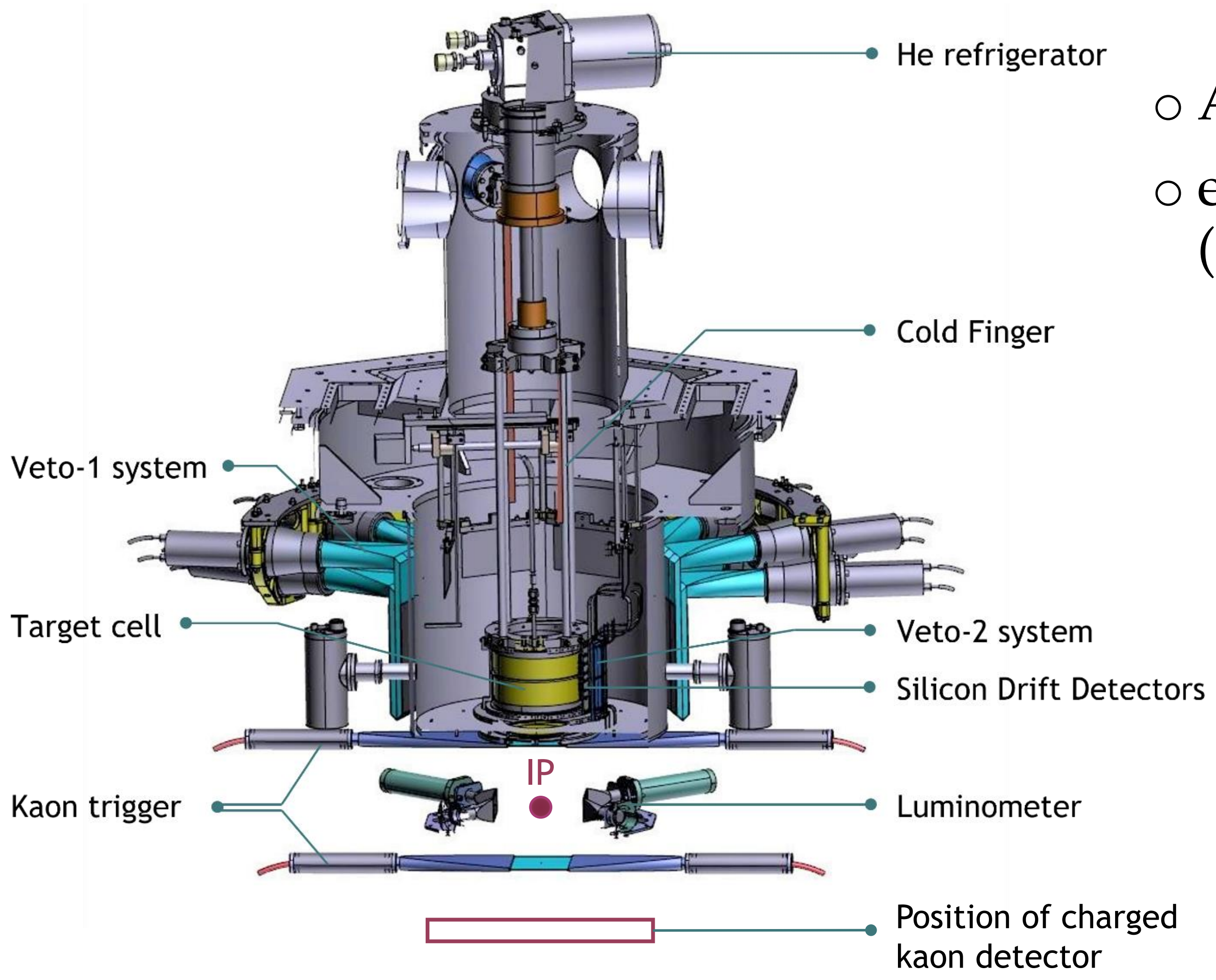
- **Isospin-dependent $\bar{\mathrm{K}}$N scattering lengths a_0 and a_1:**

$$a_{\mathrm{K^-p}} = \frac{1}{2}(a_0 + a_1) \qquad a_{\mathrm{K^-n}} = a_1$$

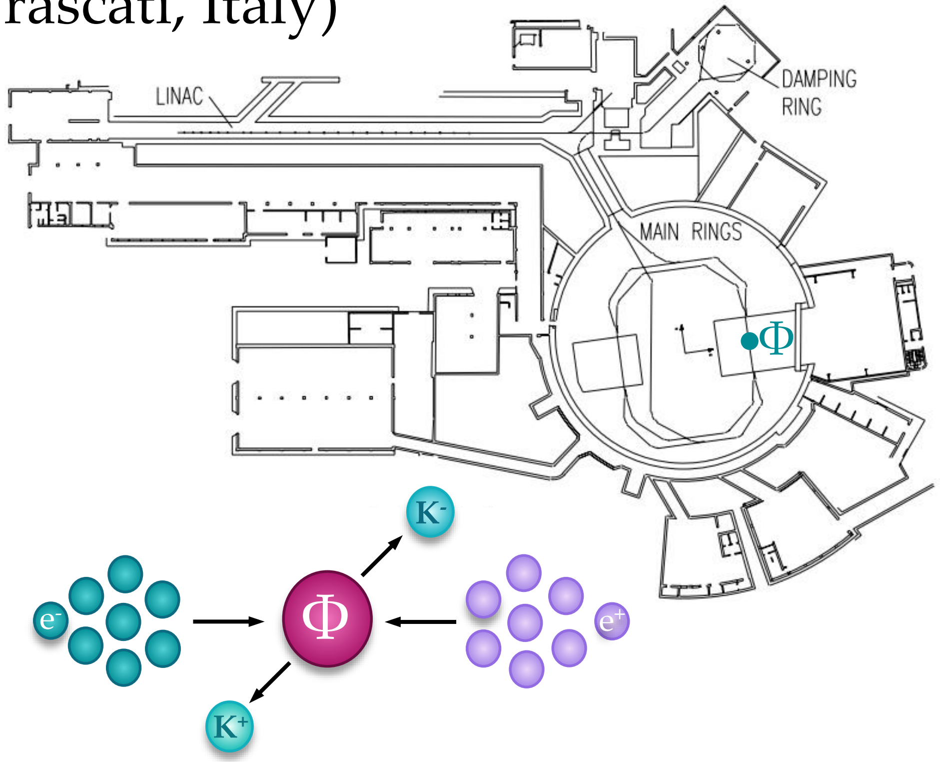
$$a_{\mathrm{K^-d}} = \frac{k}{2}(a_{\mathrm{K^-p}} + a_{\mathrm{K^-n}}) + C = \frac{k}{4}(a_0 + 3a_1) + C \qquad k = \frac{4(m_{\mathrm{N}} + m_{\mathrm{K}})}{2m_{\mathrm{N}} + m_{\mathrm{K}}}$$



The SIDDHARTA-2 Experiment at DAΦNE



- At interaction point (IP) of DAΦNE
- e^+e^- collider complex at INFN-LNF (Frascati, Italy)



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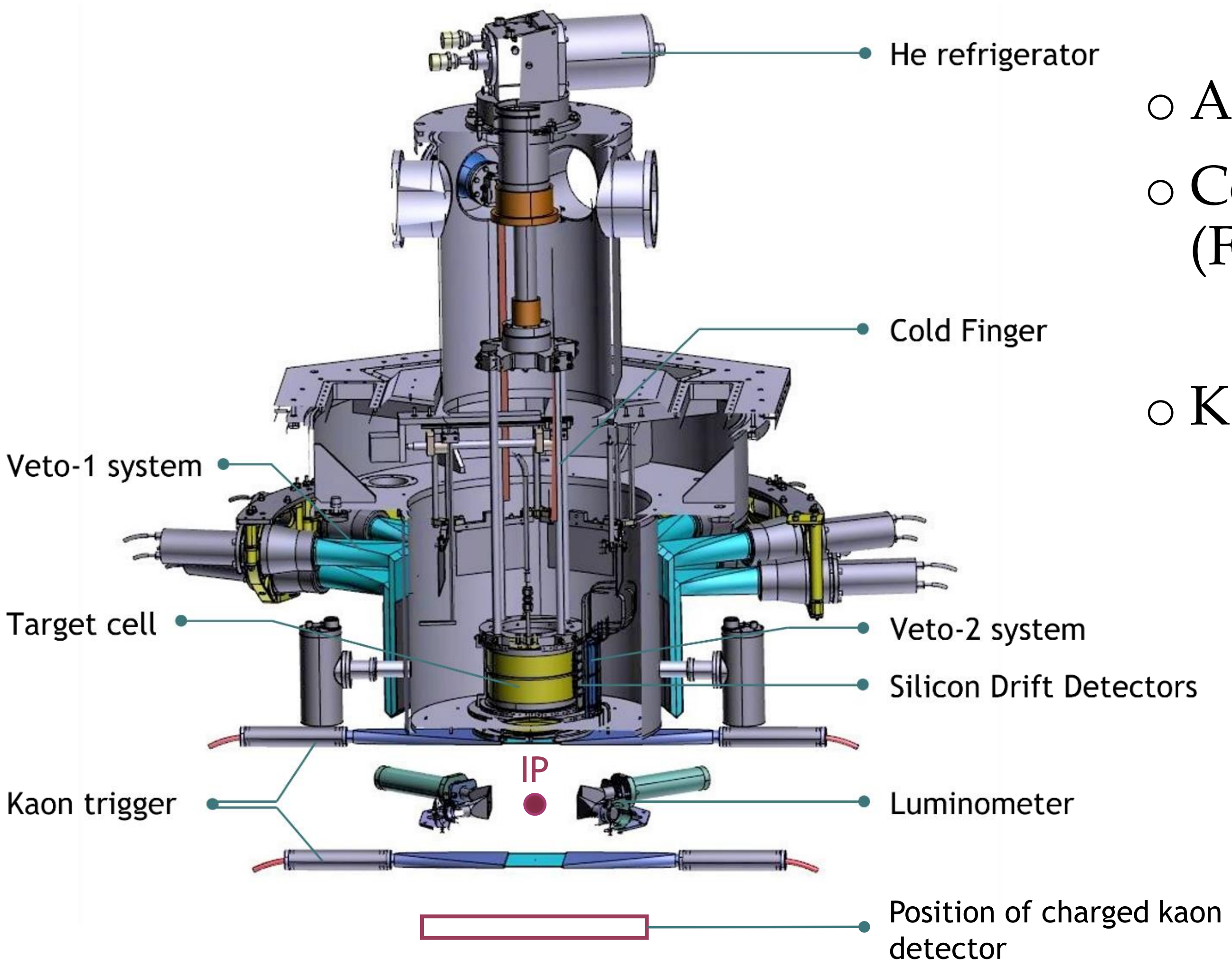


- At interaction point (IP) of DAΦNE
- Collider complex at INFN-LNF (Frascati, Italy)

- Kaonic deuterium is a challenge:
  - K_α X-ray yield for K^-p ~ 0.012
  - **Expected K^-d K_α X-ray yield ≤ 0.0039**
  - **Γ_{1s} (K^-d) ~ 800-1000 eV**

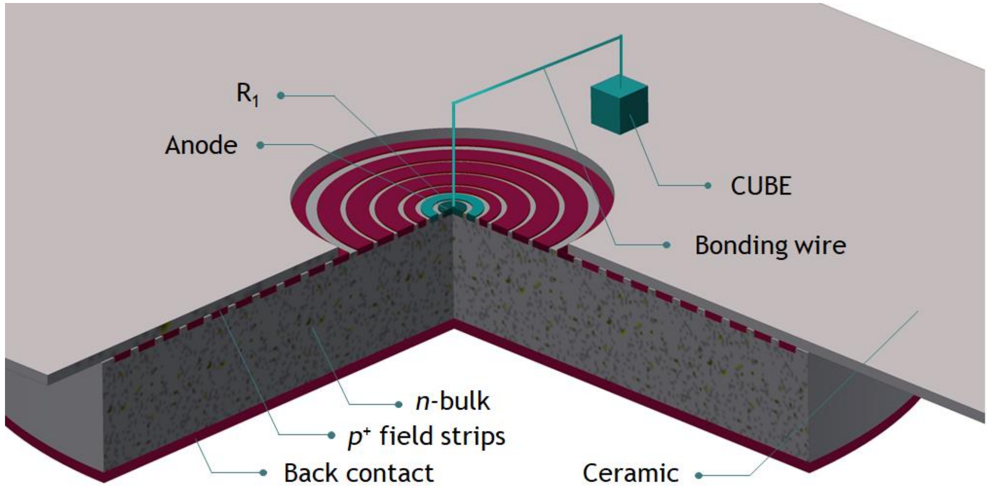
→ Multiple-stage veto system

What I did during my PhD studies

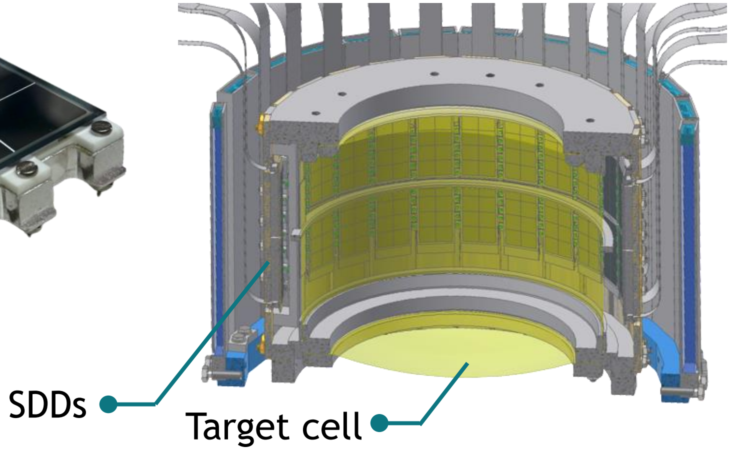
- Characterisation of the detector systems
- Analysis of first data
- Outside of the lab

X-Ray Detection System

- Newly developed arrays of monolithic **Silicon Drift Detectors (SDDs)**
    - 48 arrays of 8 read-out channels
    - 2π solid angle

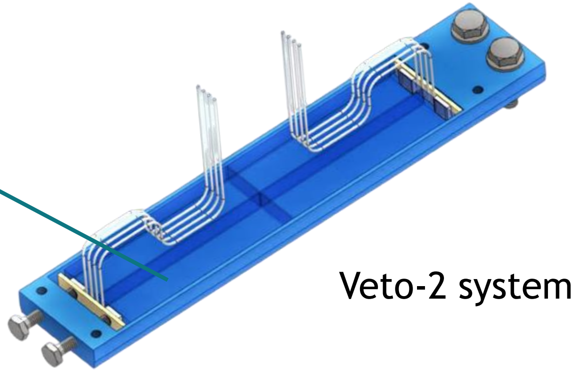


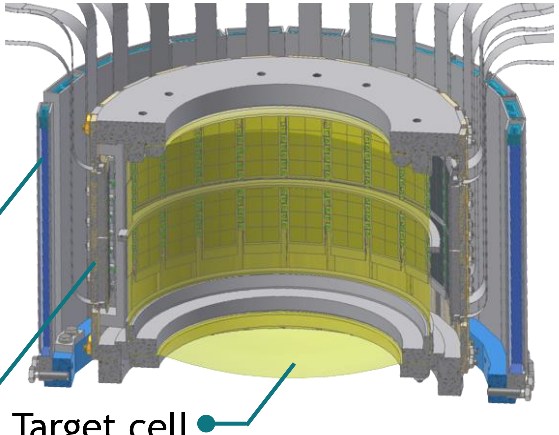
- Energy resolution at 6 keV:
  ~ 155 eV (FWHM)
- Stable energy response within 2 eV
- Non-linearity ≤ 3.8 eV for 8 keV X-rays



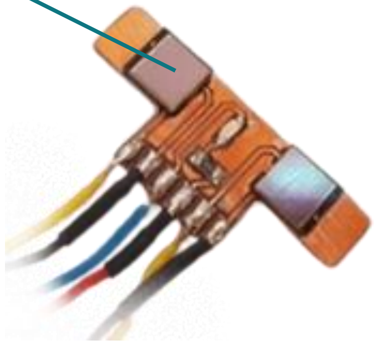
The Veto-2 System

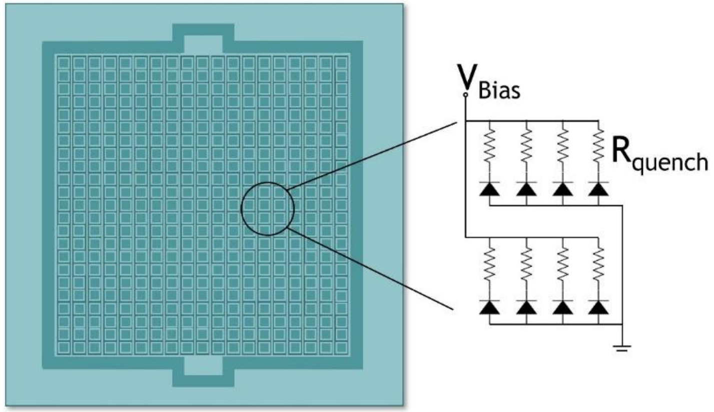
- Suppression of **synchronous hadronic background**
- Barrel of 24 detector units surrounding SDDs
  - One unit: Four plastic scintillators read out by **SiPMs**





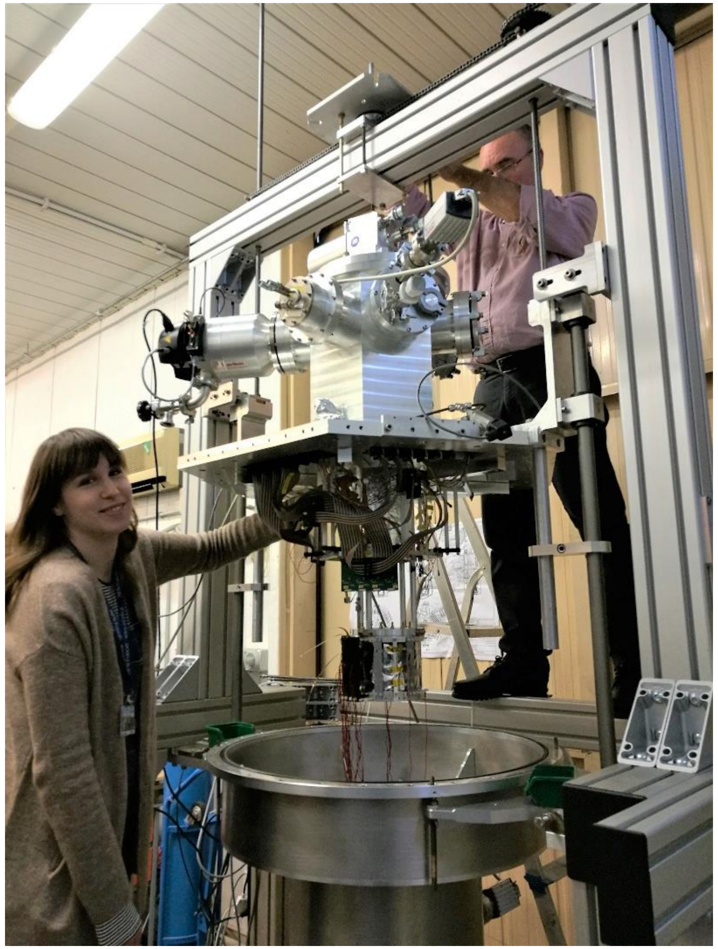
- Improvement of S/B by 16%
- Timing information to study kaon stopping distribution

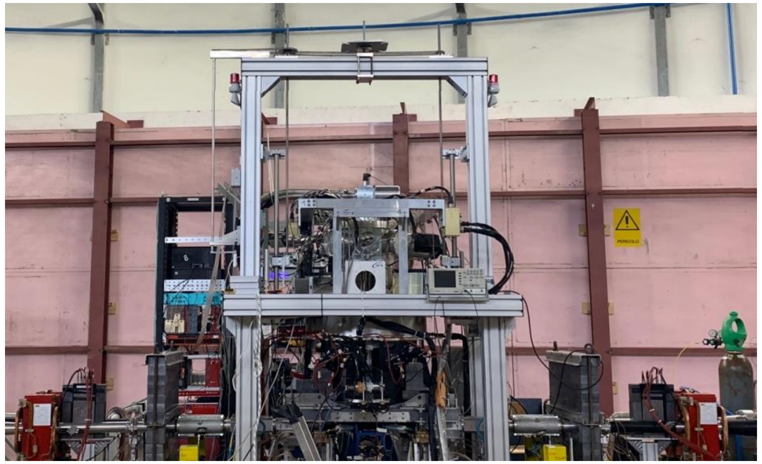




Paper submitted to JINST

Working On-site

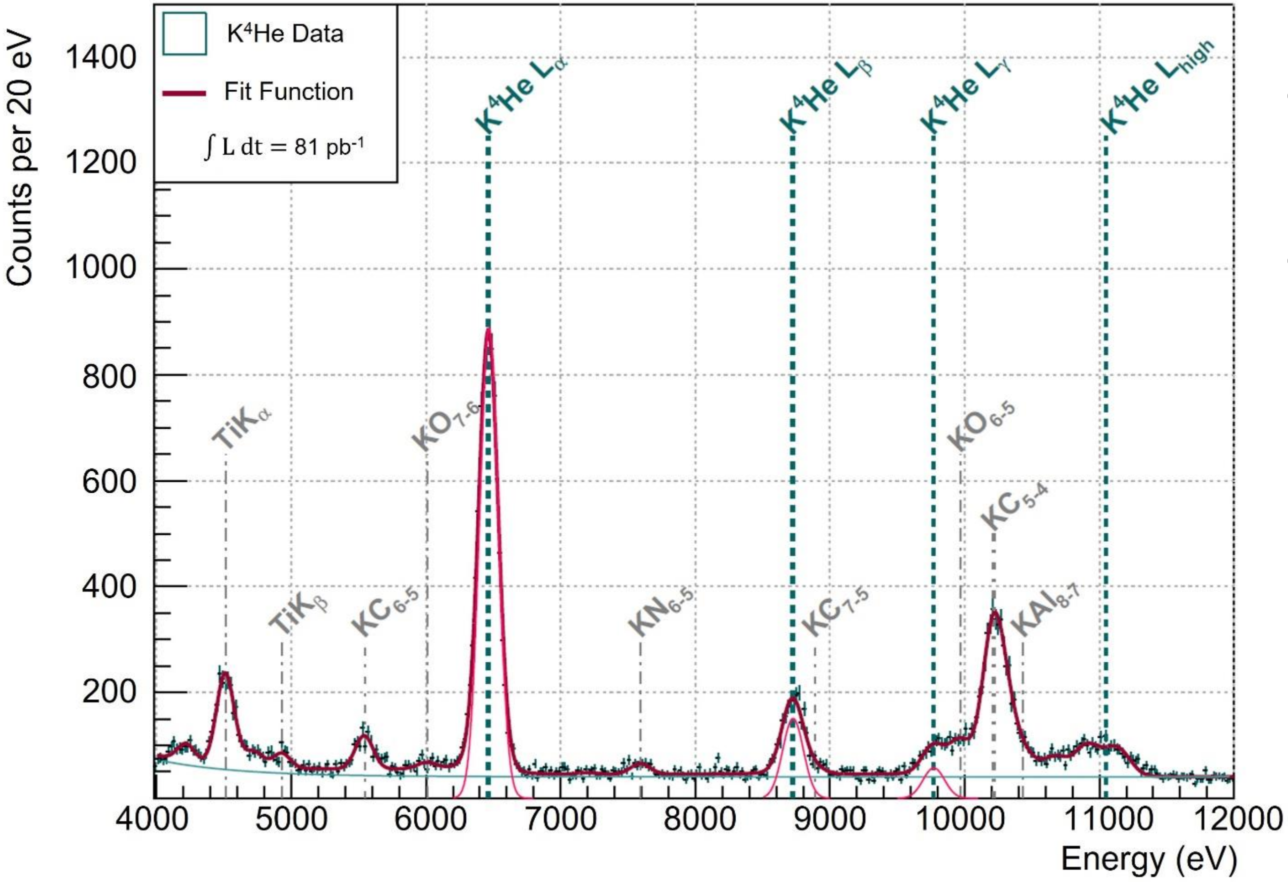




What I did during my PhD studies

- Characterisation of the detector systems
- Analysis of first data
- Outside of the lab

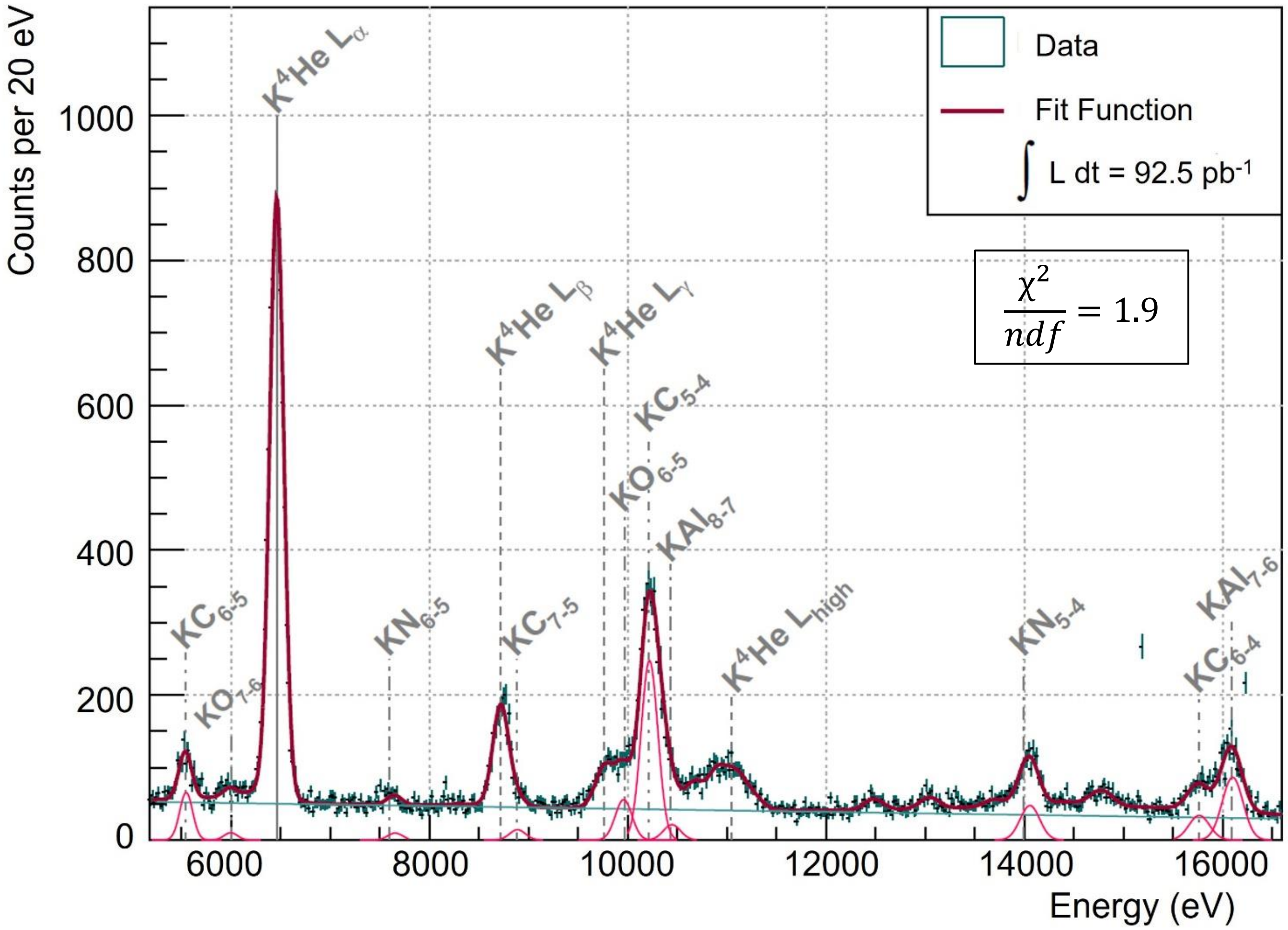
K^4He Measurement



- Most precise measurement of kaonic ^{4}He achieved with SDDs
- Integrated luminosity of 81 pb^{-1} (≅ 65 days)

K^4He L_α transition energy (eV)	$6463.44 \pm 0.95_{stat} \pm 2.00_{syst}$
2*p* shift (eV)	$0.44 \pm 0.95_{stat} \pm 2.00_{syst}$
2*p* width (eV)	$0.6 \pm 10.1_{stat}$

Kaonic Atom Transitions from Solid Targets



Transition	Transition energy (eV)
K^-C (7 → 5)	$8882.0 \pm 2.9_{stat} \pm 3.7_{syst}$
K^-C (6 → 5)	$5541.1 \pm 2.9_{stat} \pm 2.0_{syst}$
K^-C (6 → 4)	$15755.6 \pm 2.9_{stat} \pm 8.7_{syst}$
K^-C (5 → 4)	$10212.7 \pm 2.9_{stat} \pm 7.4_{syst}$
K^-O (7 → 6)	$5990.5 \pm 10.5_{stat} \pm 2.0_{syst}$
K^-O (6 → 5)	$9952.4 \pm 10.5_{stat} \pm 7.4_{syst}$
K^-N (6 → 5)	$7648.1 \pm 7.8_{stat} \pm 3.7_{syst}$
K^-N (5 → 4)	$14048.6 \pm 7.8_{stat} \pm 8.7_{syst}$
K^-Al (8 → 7)	$10439.1 \pm 6.7_{stat} \pm 7.4_{syst}$
K^-Al (7 → 6)	$16092.3 \pm 6.7_{stat} \pm 8.7_{syst}$

Sgaramella, F., Tüchler, M. et al.
Eur. Phys. J. A 59, 56 (2023)

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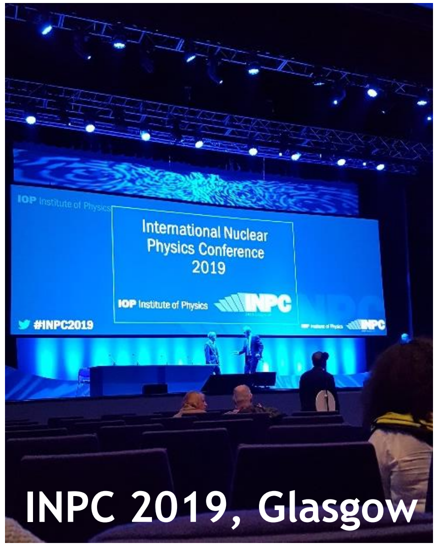
Outside of the lab



INPC 2019, Glasgow


ECT* Workshop 2019, Trento

European Researchers' Night 2019


DK-PI Summer School 2019, Zwettl

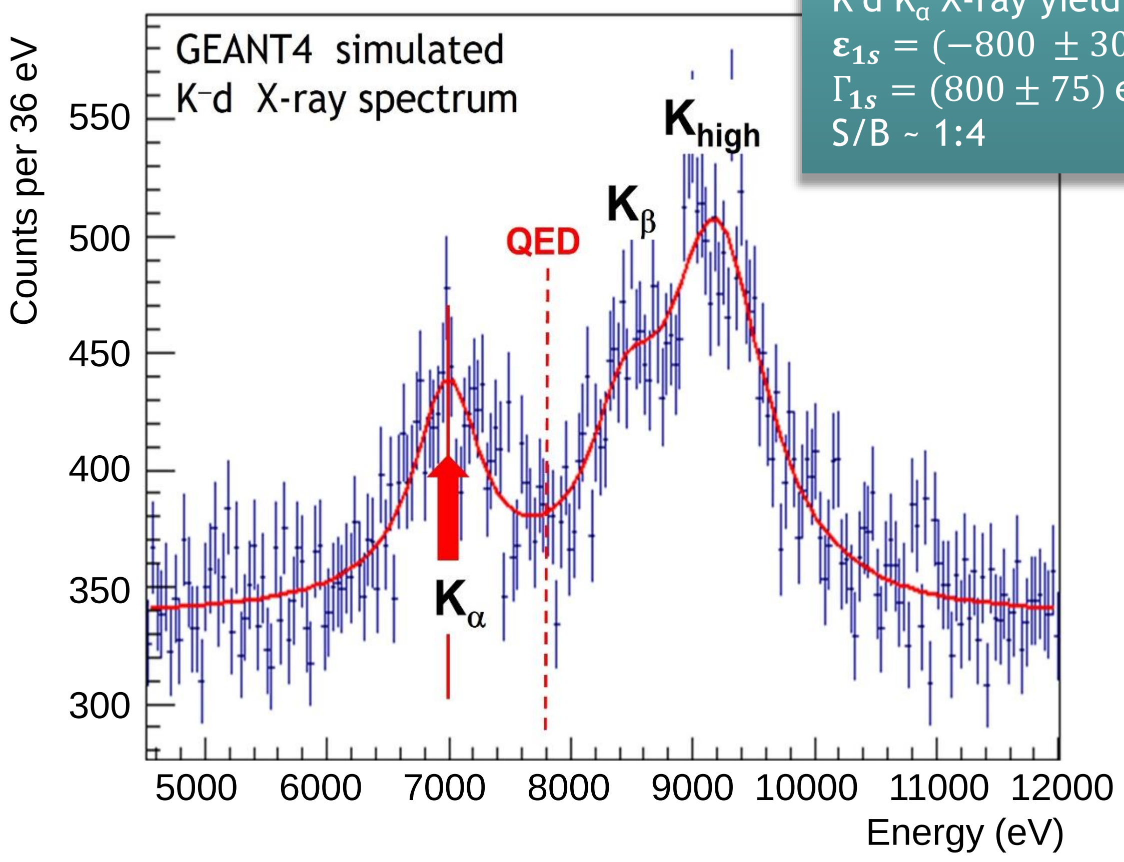

3rd Jagiellonian Symposium, Krakow, 2019

SSP 2022, Vienna

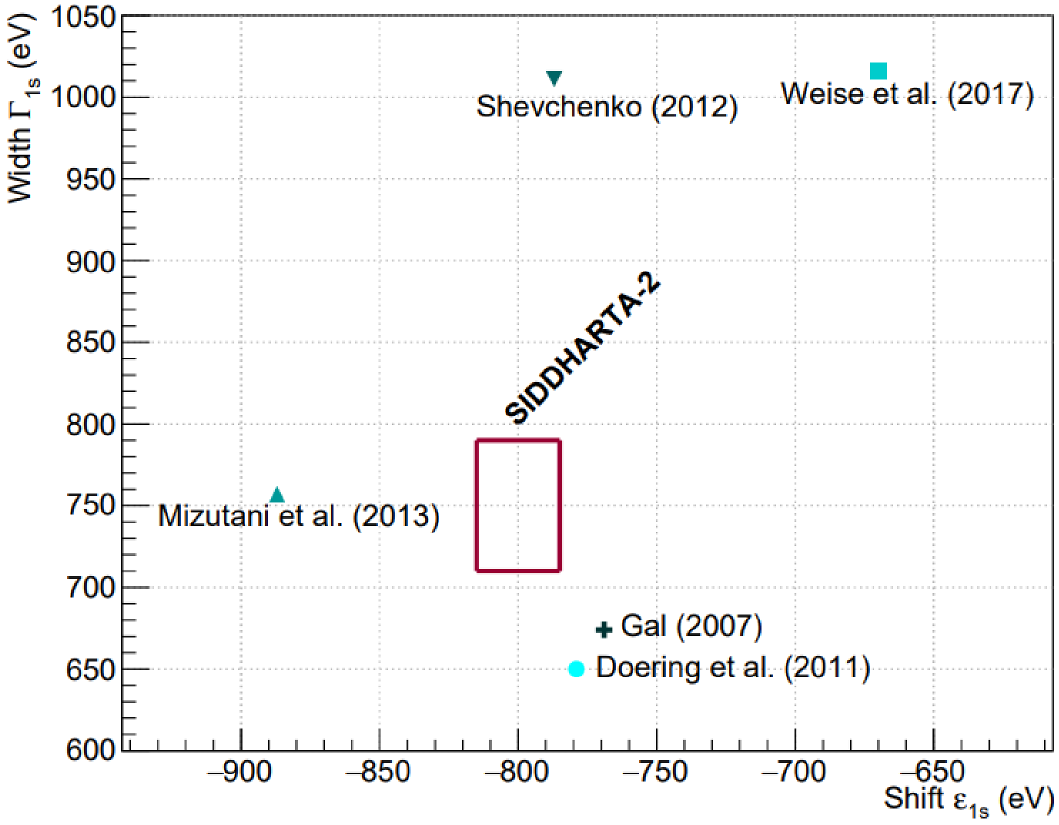

FFK 2023, Vienna

What I am doing now

The Grand Finale: Kaonic Deuterium



K^-d K_α X-ray yield: 0.1%
$\boldsymbol{\varepsilon_{1s}} = (-800 \pm 30)$ eV
$\Gamma_{1s} = (800 \pm 75)$ eV
S/B ~ 1:4

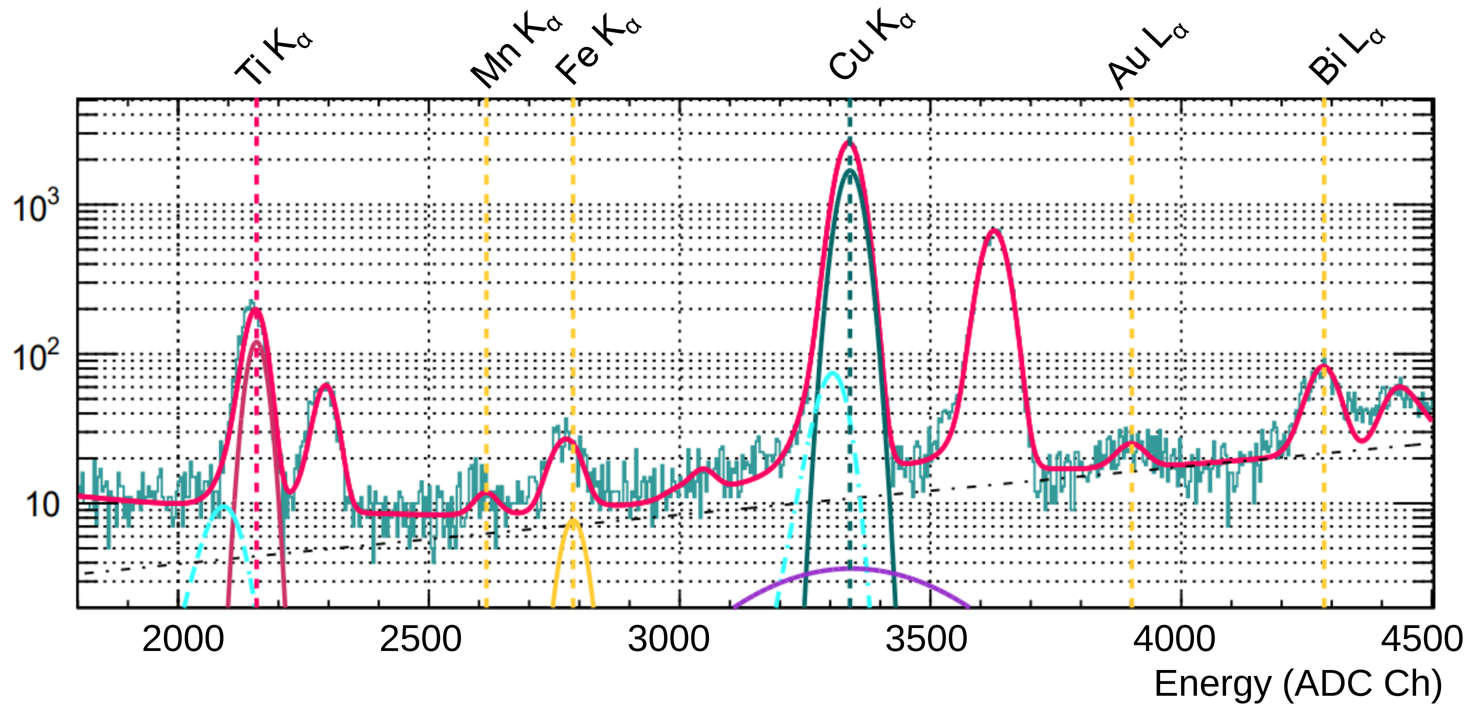


The Grand Finale: Kaonic Deuterium

- Our goal: 500 – 800 pb^{-1}
- Currently: ~200 pb^{-1}

- **To-do:**

Optimisation of SDD energy calibration



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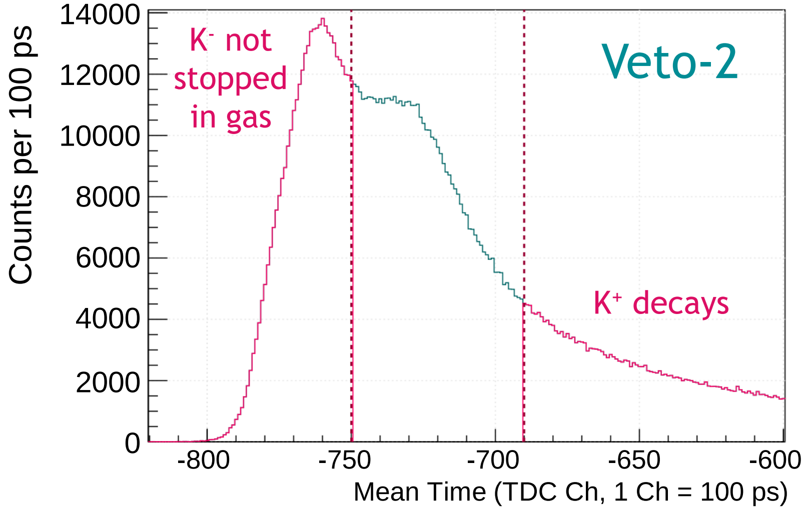

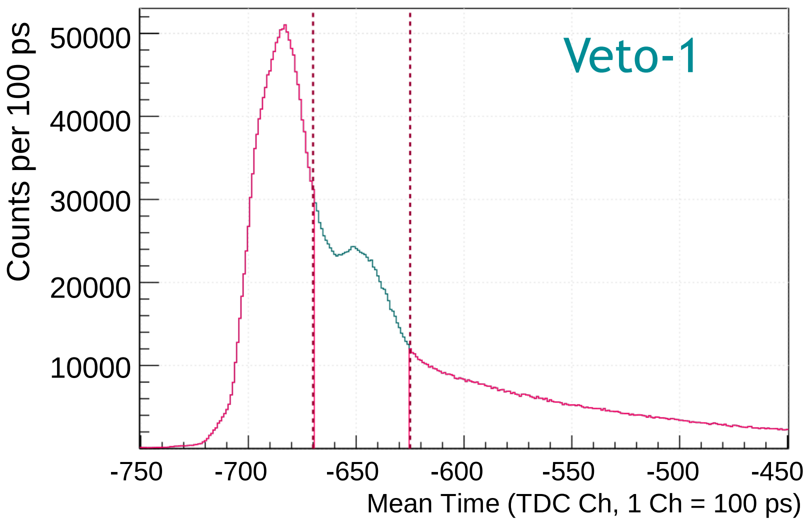

- **To-do:**

Optimisation of SDD energy calibration → Fine-tuning of veto systems and background reduction

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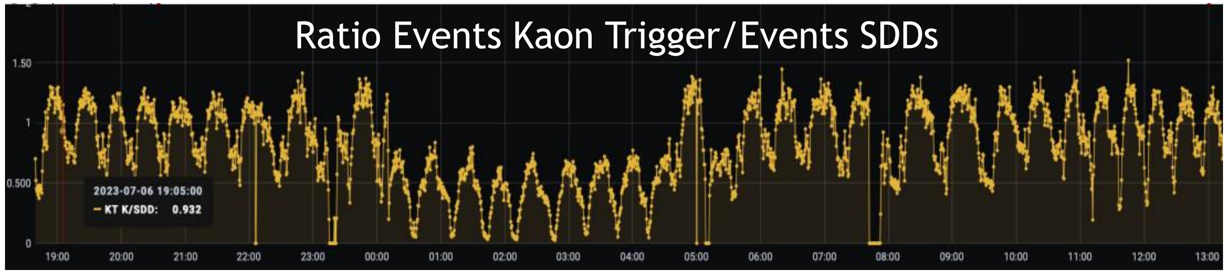
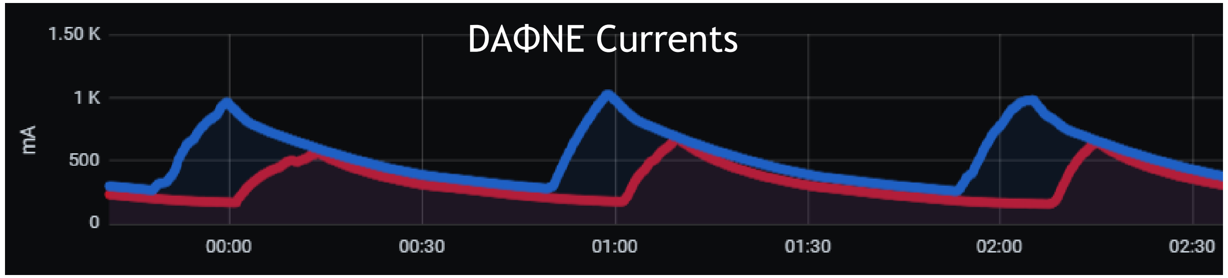




- **To-do:**

1. Optimisation of SDD energy calibration
2. Fine-tuning of veto systems and background reduction
3. Data selection based on quality criteria

The Grand Finale: Kaonic Deuterium

- Our goal: 500 – 800 pb^{-1}
- Currently: ~200 pb^{-1}

- **To-do:**

Optimisation of SDD energy calibration → Fine-tuning of veto systems and background reduction → Data selection based on quality criteria → Fitting of K^-d energy spectrum

Summary

Achievements

- Characterisation of SDDs and Veto-2 system
- Most precise measurement of ($3d \rightarrow 2p$) transition in kaonic helium-4 obtained with SDDs
- First report of higher-n transitions in intermediate-mass kaonic atoms

Ongoing work and future goals

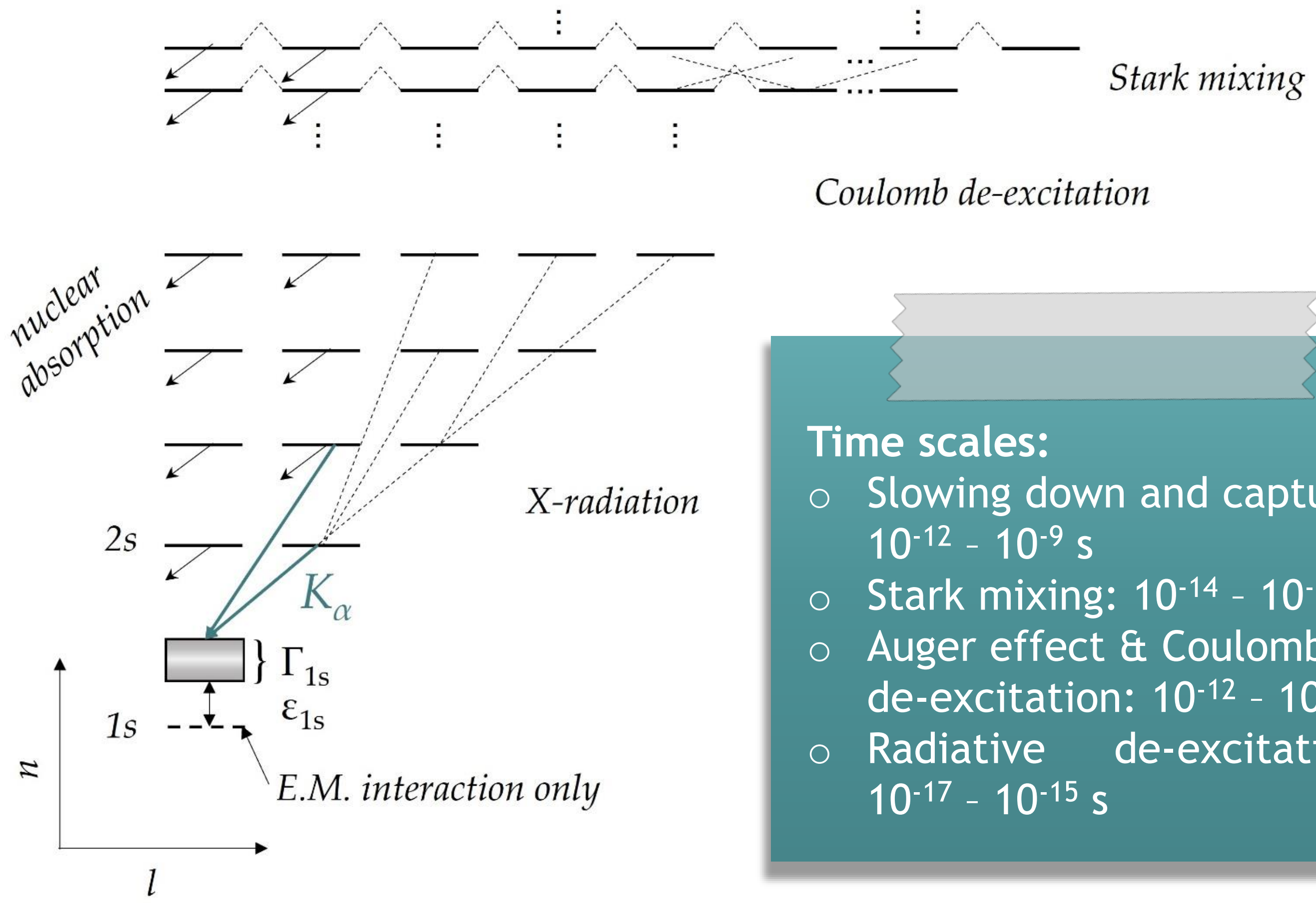
- Measurement of ($2p \rightarrow 1s$) transition in K^-d
  - Optimisation of SDD energy calibration
  - Optimisation of background reduction
  - Fitting of energy spectrum

Appendix

Atomic Cascade

- **Radiative mechanisms**
  1) Radiative decay

- **Non-radiative (collisional) mechanisms**
  2) Stark mixing
  3) External Auger effect
  4) Coulomb de-excitation
  5) (Elastic scattering)

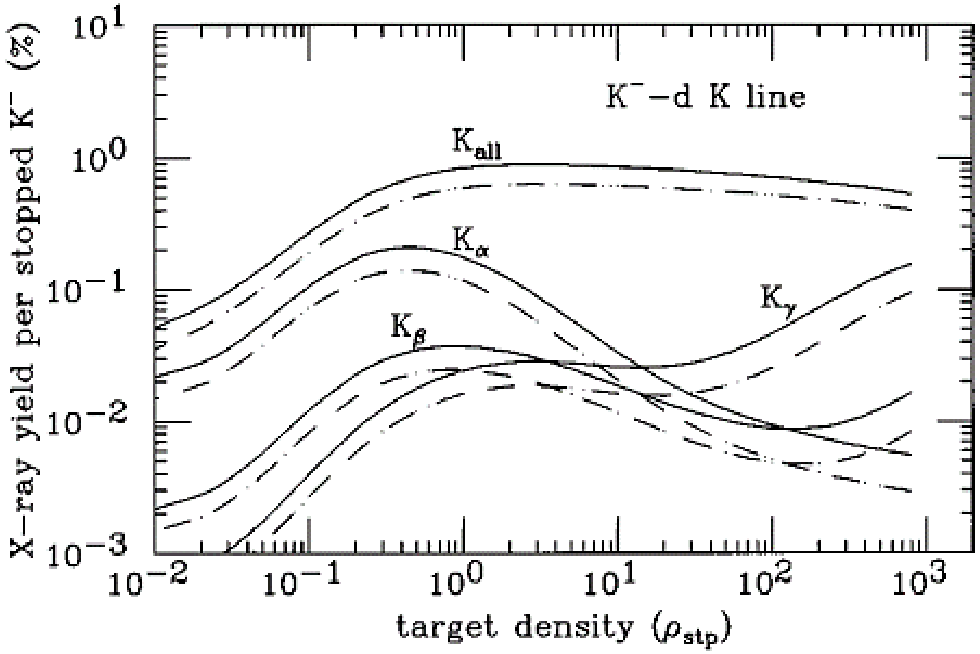


Time scales:
- Slowing down and capture: 10^{-12} – 10^{-9} s
- Stark mixing: 10^{-14} – 10^{-13} s
- Auger effect & Coulomb de-excitation: 10^{-12} – 10^{-9} s
- Radiative de-excitation: 10^{-17} – 10^{-15} s

Atomic Cascade

2) Stark Mixing

- Mixing of pure parity states $|nml\rangle$ in electric field
- Same n, $\Delta l = \pm 1, \Delta m = 0$
- For Z ≤ 2: main cause of reduction of X-ray yield
- Day-Snow-Sucher effect:
  - X-ray yield decreases with increasing target density

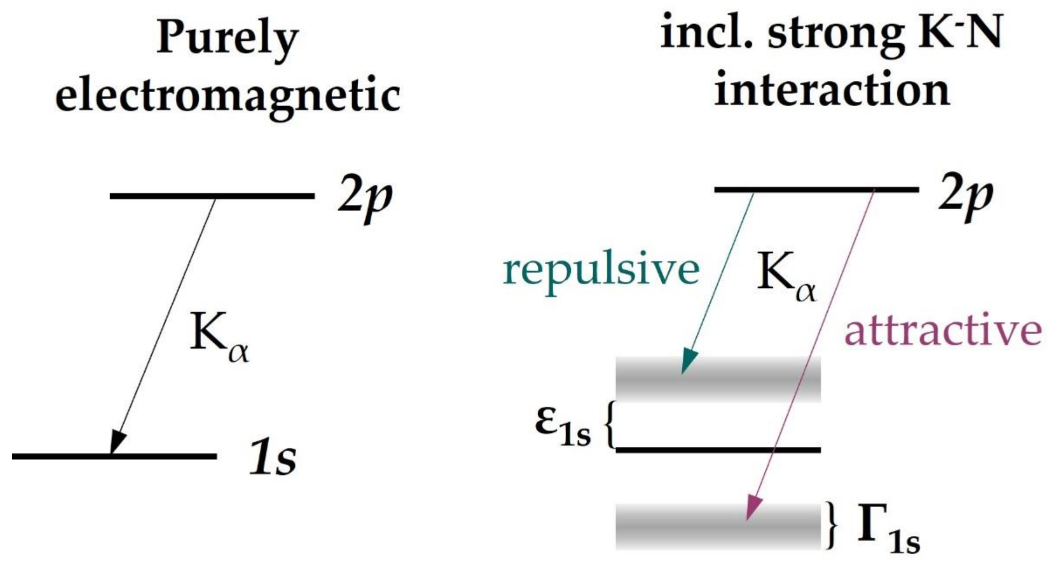


Koike et al. Phys. Rev. C **53**(1) (1996)

Hadronic effects

$$\varepsilon_{1s} = E_{1s}^{measured} - E_{1s}^{QED}$$

$$L(E) = \frac{1}{\pi} \frac{\frac{\Gamma}{2}}{(E - E_{\mu})^2 + \frac{\Gamma^2}{4}}$$



- $\bar{K}N$ interaction strongly attractive
- Repulsive shifts
- Nuclear dynamics: Λ(1405) resonance ~27 MeV below K^-p threshold
  - $I = 0$, $S = -1$ $\bar{K}N$ bound state
- Strong coupling to $\Sigma\pi$ channel

Deser-Trueman-Baumann-Thirring Formula

- Formulated for pionic hydrogen
- Kaonic hydrogen without isospin-breaking corrections:

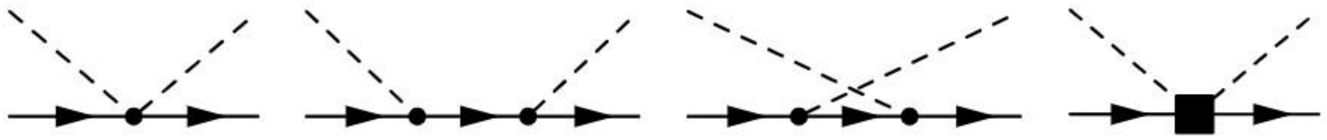
$$\varepsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu^2 a_{\mathrm{K^-p}}$$

- In kaonic atoms, isospin-breaking corrections $\delta \sim m_d - m_u$ are large: Improved formula of order $O(\delta^4)$

$$\varepsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu^2 a_{\mathrm{K^-p}}[1 - 2\alpha\mu(\ln\alpha - 1)a_{\mathrm{K^-p}}]$$

- Kaonic deuterium: complete three-body calculations necessary
  - Coupled-channels approach
  - Solution of Schrödinger equation with Coulomb potential and $\bar{\mathrm{K}}\mathrm{N}$ interaction potential

Chiral Unitary Approach with Coupled Channels



- Non-perturbative re-summation of scattering amplitude necessary
- Starting point: chiral $SU(3)_R \times SU(3)_L$ meson-baryon chiral effective Lagrangian

- Meson-baryon interaction kernel:
  - LO: Tomozawa-Weinberg terms (a)
  - Born terms (direct (b) and crossed (c))
  - NLO (d): includes low-energy constants

- T-matrix formalism: $\mathbf{T} = \mathbf{V} + \mathbf{V} \cdot \mathbf{G} \cdot \mathbf{T}$

$$f_{ij}(\sqrt{s}) = \frac{1}{8\pi\sqrt{s}} T_{ij}(\sqrt{s})$$

$$a_{K^-p} = f_{11}(\sqrt{s} = m_{K^-} + m_p)$$

Ikeda et al. Nucl. Phys. A. **881** pp. 98–114 (2012)

Optical Models

- Phenomenological optical potential to describe kaon-nucleus interaction

$$V^{opt}(r) = -\frac{2\pi}{\mu}\left(1+\frac{\mu}{m}\right)\rho(r)$$

$\bar{a}$ … average complex effective $\overline{\text{K}}$N scattering length
$\rho(r)$ … nucleon density distribution
V_C … Coulomb potential

$$[-\nabla^2 + 2mE_B + (2m(V_C + V^{opt}) - V_C^2)]\Psi = 0$$

$$2mV^{opt}(r) = -4\pi F_k f(0)\rho(r)$$

F_k … kinematical factor
$f(0)$ … forward scattering amplitude

- Density-dependent optical models:
  - Level shifts repulsive
  - $Re(V^{opt})$ attractive
  - Low-density limit: $Re(V^{opt})$ repulsive

$$2\mu V^{opt}(r) = -4\pi\left(1+\frac{\mu}{m}\right)\left[b + B\left(\frac{\rho(r)}{\rho(0)}\right)^{\alpha}\right]\rho(r)$$

b, B, α: determined in fits to data

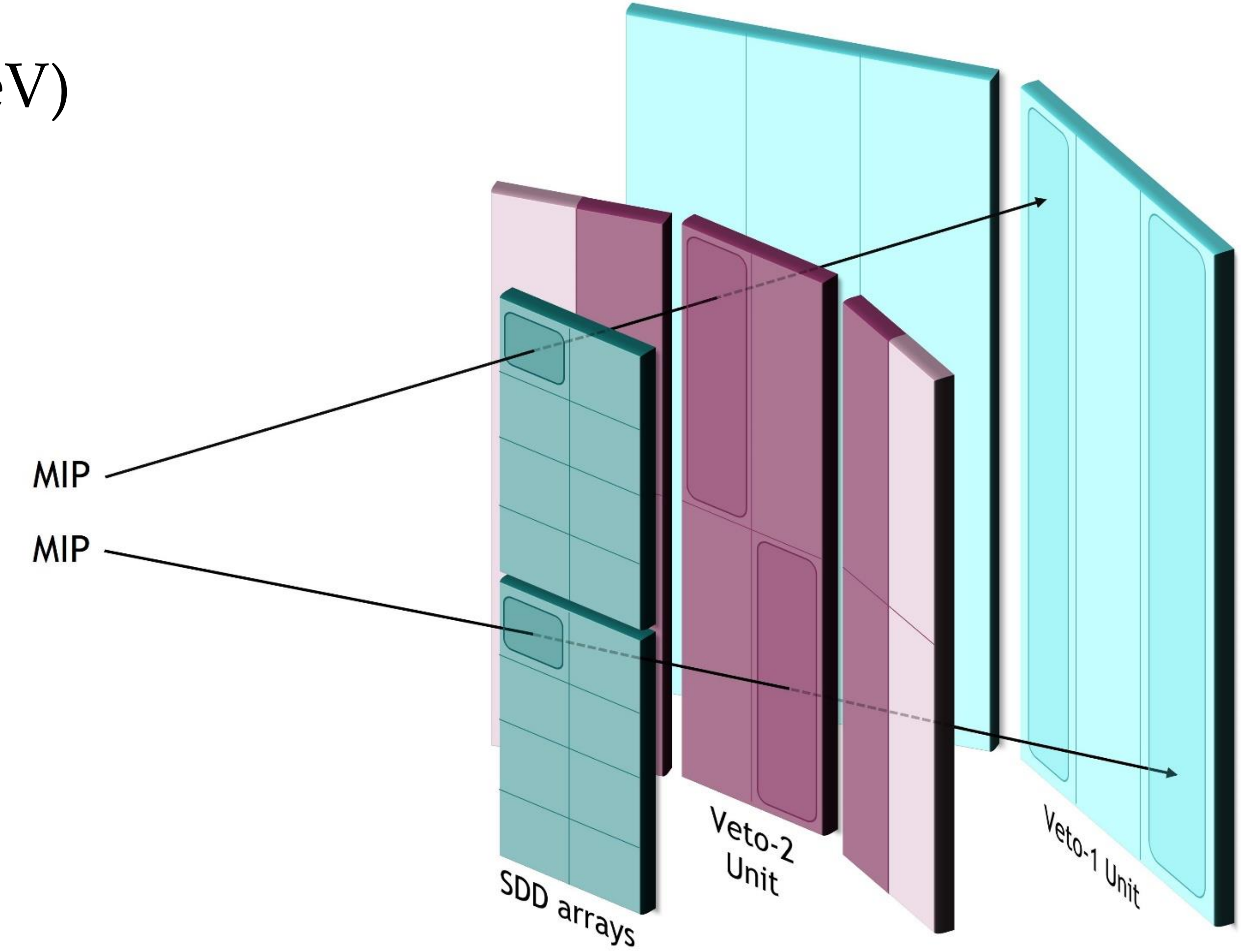
Veto-2 Performance: Efficiency

- Coincidence of SDD signal (≥ 20 keV) and signal in Veto-1 detectors to select hadronic events

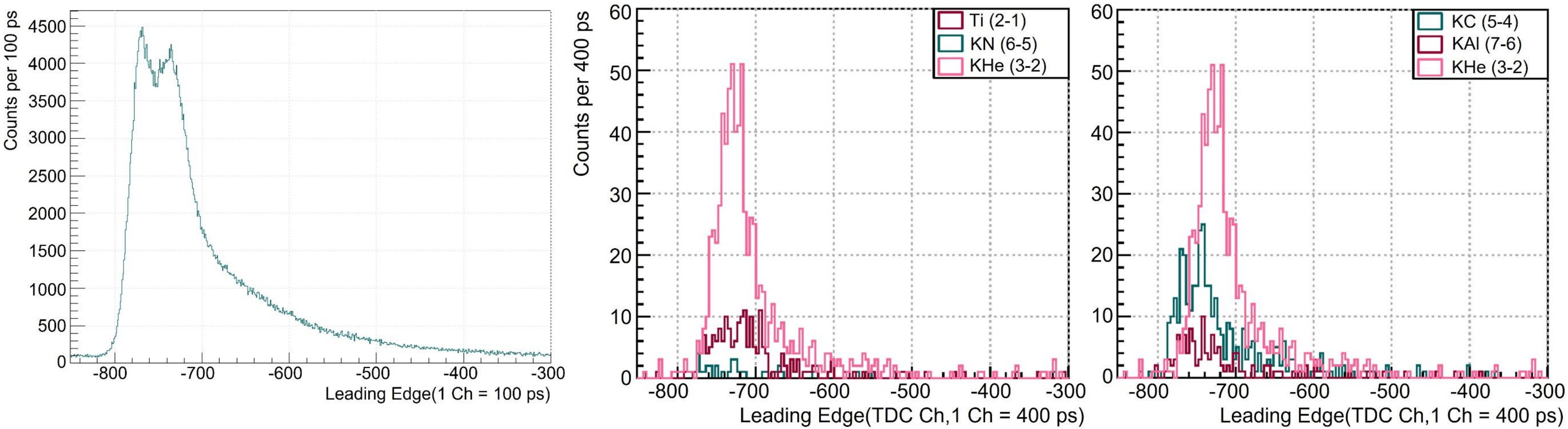
$$\varepsilon = \frac{\Sigma_{V2}}{\Sigma_{coinc}}$$

- 8 Veto-2 scintillators per SDD cell

Efficiency He = (62 ± 1)%
Efficiency D = (57 ± 1)%

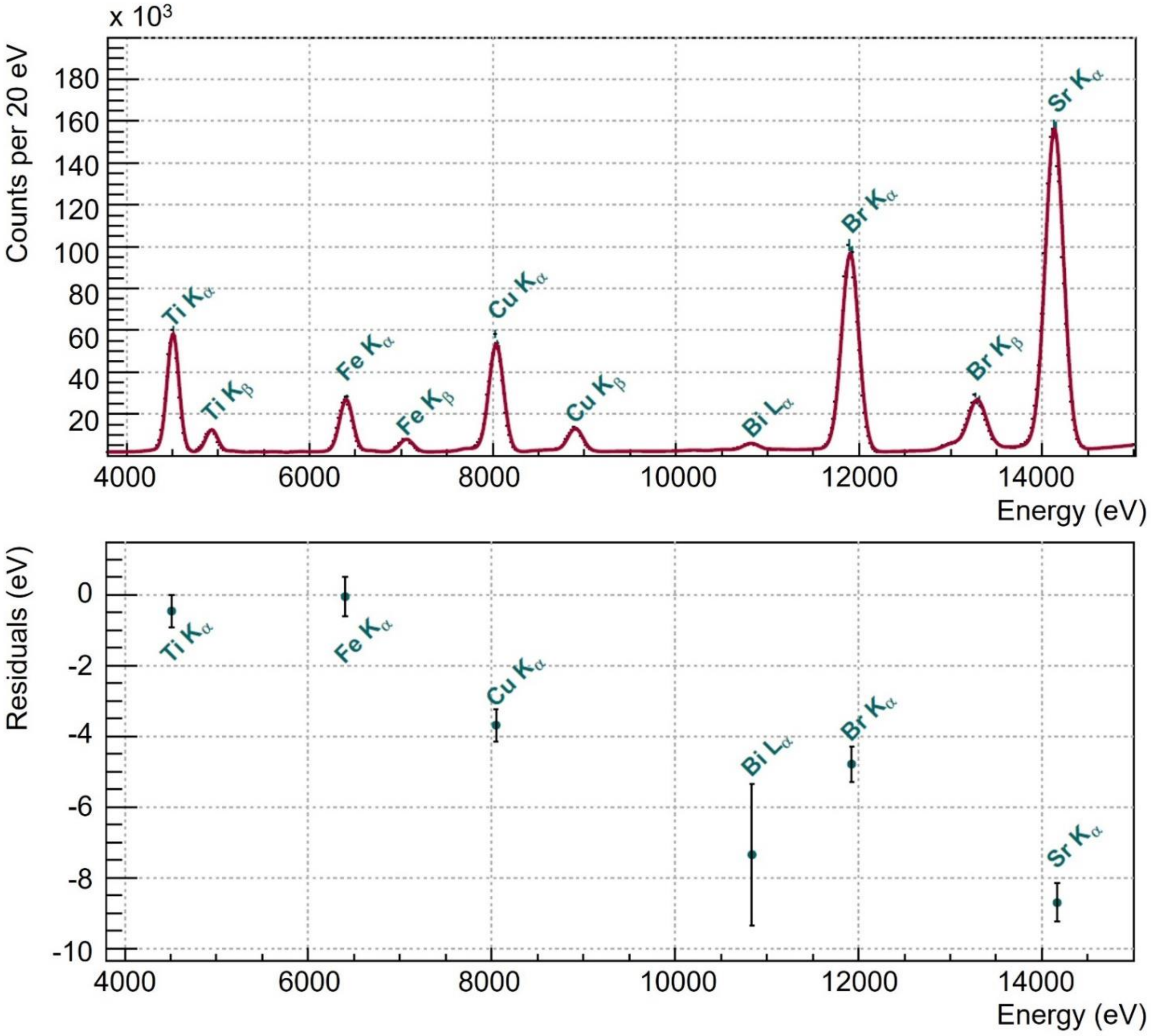


Veto-2 System Performance: Timing

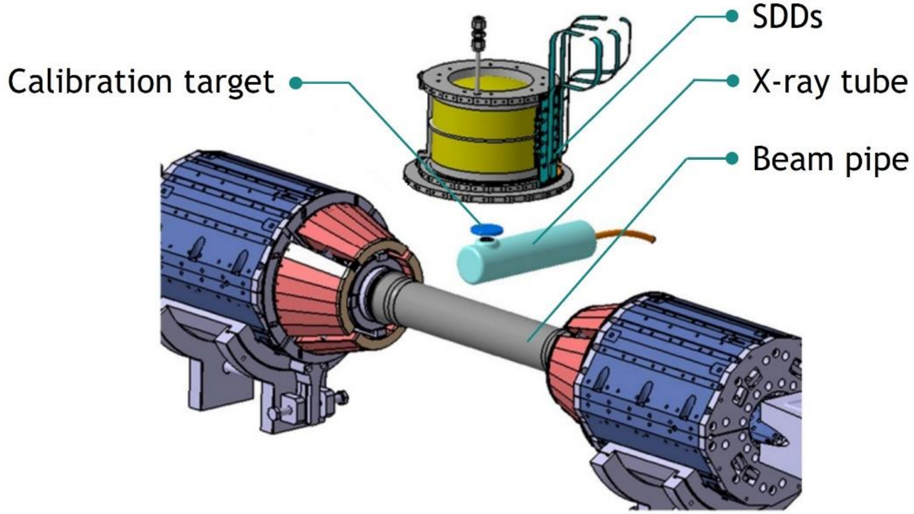


- Time resolution of < 1 ns required
- Veto-2 system tool to study kaon stopping distribution
- Optimisation of setup

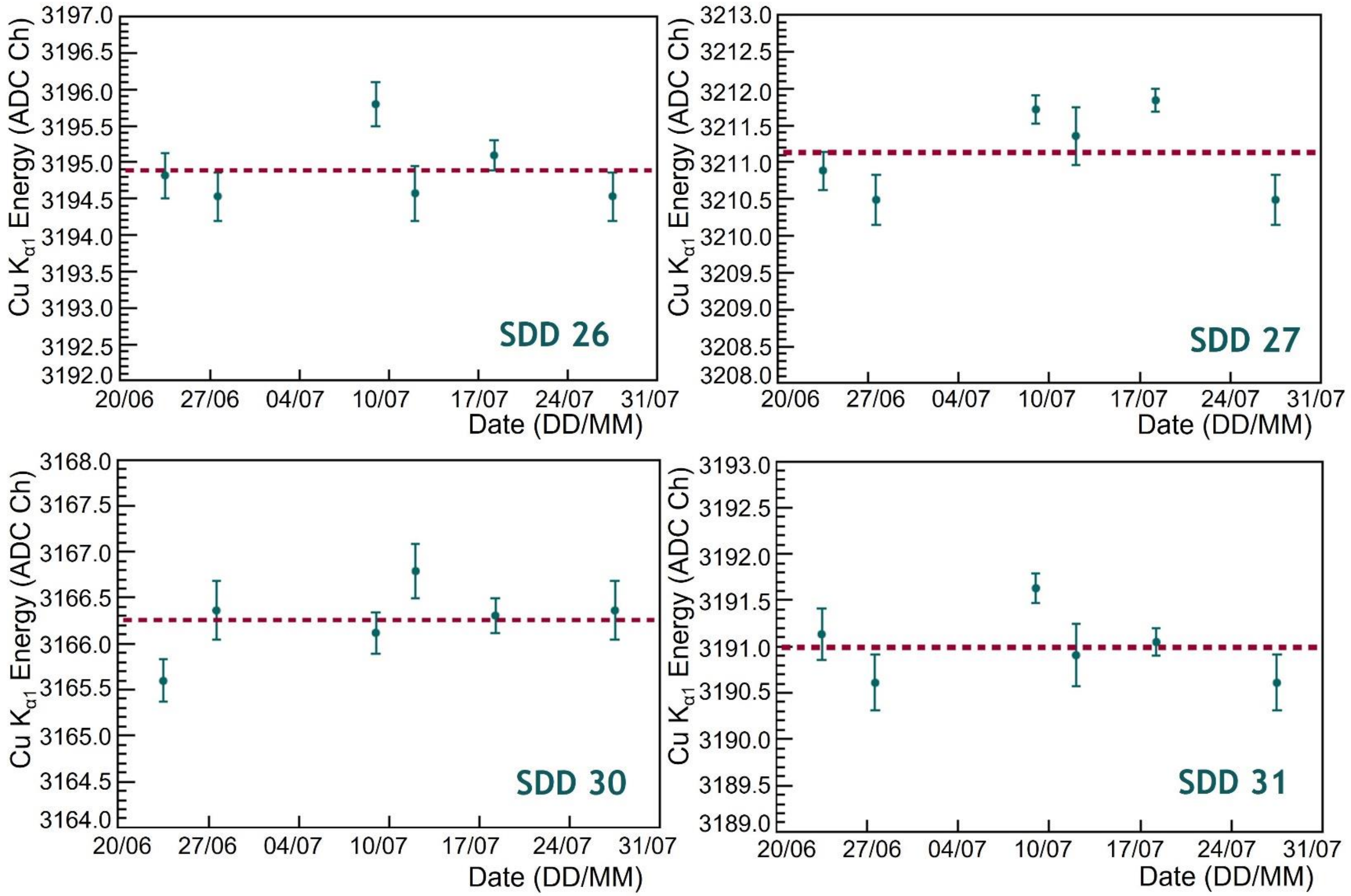
Linearity of the SDDs



- Spectrum obtained with X-ray tube shining on multi-element target (Ti, Fe, Cu, Br, Sr)
- Residual at Fe K_α (6.4 keV) from (Ti, Cu)-calibration of **(−0.05 ± 0.78) eV**



Stability of the SDD Energy Response



- Stability of Cu K_α calibration line over time
- Six calibration runs over period of 34 days
- Stability of SDD energy response over time within **0.55 ADC Ch ≈ 2.0 eV**