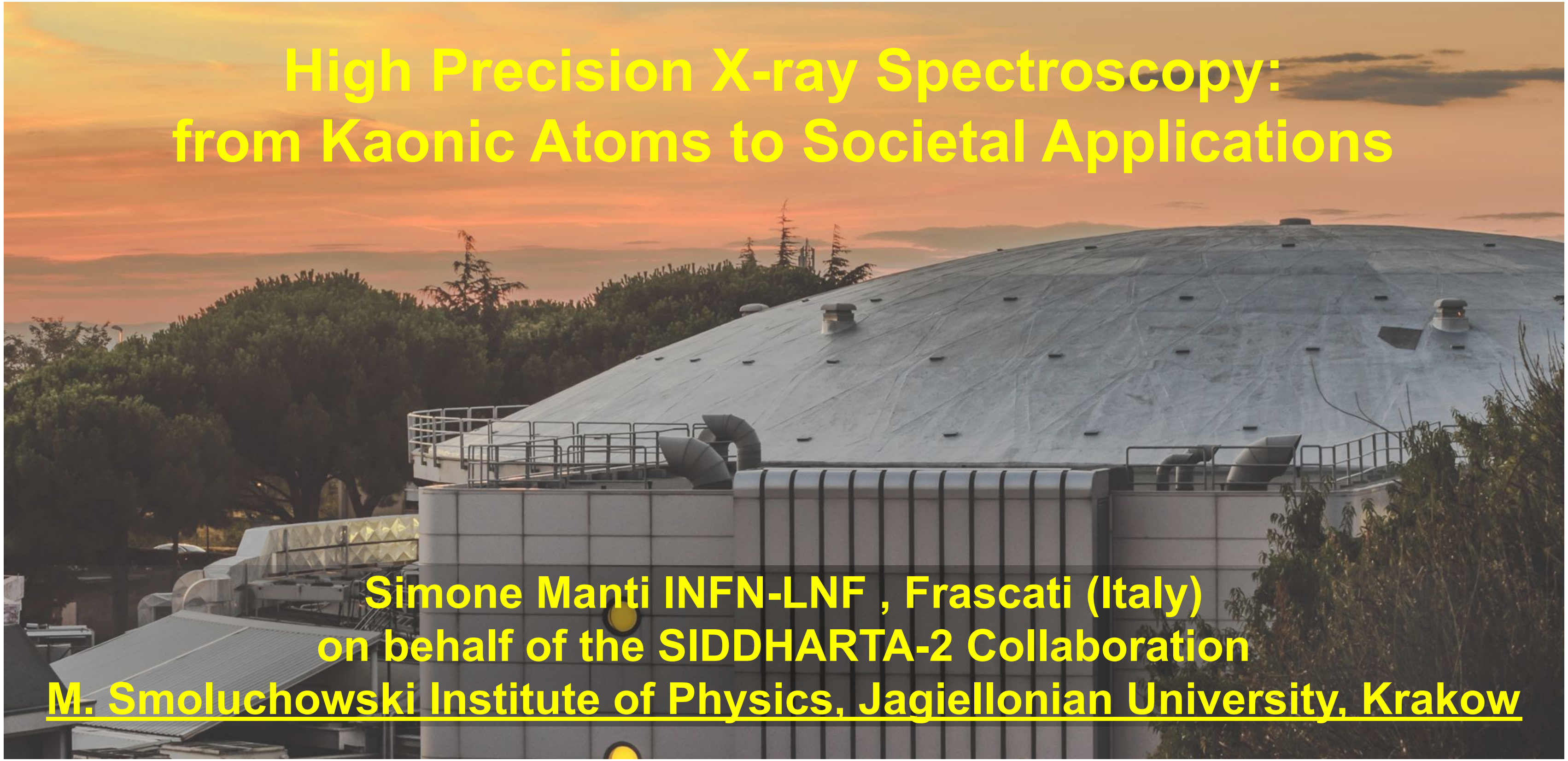

High Precision X-ray Spectroscopy: from Kaonic Atoms to Societal Applications

Simone Manti INFN-LNF , Frascati (Italy)
on behalf of the SIDDHARTA-2 Collaboration
M. Smoluchowski Institute of Physics, Jagiellonian University, Krakow

Content

- **High Precision X-ray Spectroscopy of Kaonic Atoms with SIDDHARTA**
- **Studying QCD, QED and BSM with Kaonic Atoms**
- **Beyond Kaonic Atoms: Impact of Crystal Spectrometers**

Content

- High Precision X-ray Spectroscopy of Kaonic Atoms with SIDDHARTA
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- Beyond Kaonic Atoms: Impact of Crystal Spectrometers

SIDDHARTA-2

SIlicon Drift Detector for Hadronic Atom Research by Timing Applications

HadronPhysics2 Study of Strongly Interacting Matter

HadronPhysics I3 Study of Strongly Interacting Matter

FWF Der Wissenschaftsfonds.

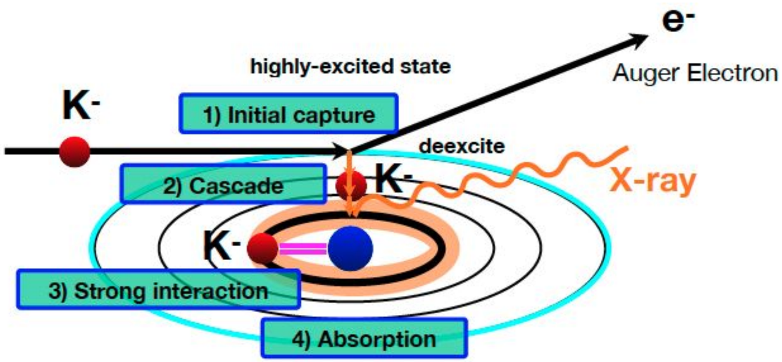
LNF-INFN, Frascati, Italy
SMI-ÖAW, Vienna, Austria
Politecnico di Milano, Italy
IFIN –HH, Bucharest, Romania
TUM, Munich, Germany
RIKEN, Japan
Univ. Tokyo, Japan
Victoria Univ., Canada
Univ. Zagreb, Croatia
Helmholtz Inst. Mainz, Germany
Univ. Jagiellonian Krakow, Poland
ELPH, Tohoku University

STRONG-2020

HrZZ Croatian Science Foundation

Farnesina Ministero degli Affari Esteri e della Cooperazione Internazionale

Kaonic Atoms X-ray Spectroscopy

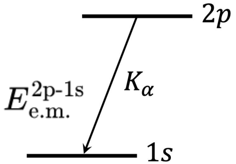


$$n_{\text{init}} \sim n_e \sqrt{\frac{\mu}{m_e}}$$

$n_{\text{init}} \sim 25$ for K-p

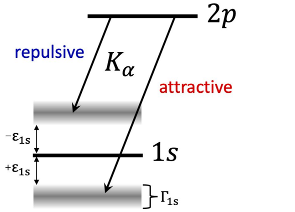
μ : K-p Reduced Mass

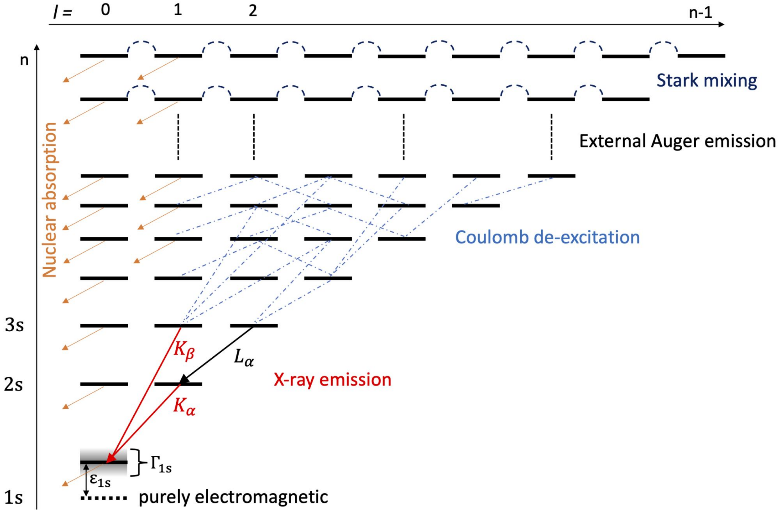
Purely electromagnetic



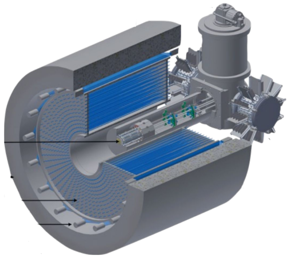
$$\varepsilon_{1s} = E^{\text{2p-1s}}_{\text{meas}} - E^{\text{2p-1s}}_{\text{e.m.}}$$

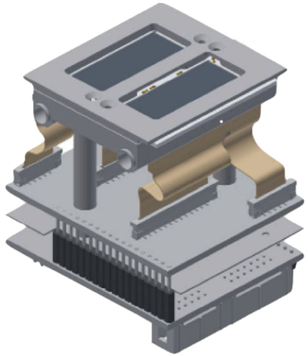
Electromagnetic + strong interaction





A long journey…



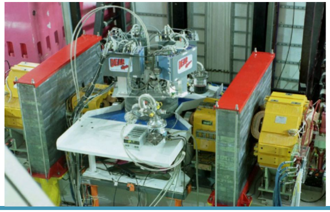


The modern era of light kaonic atom experiments

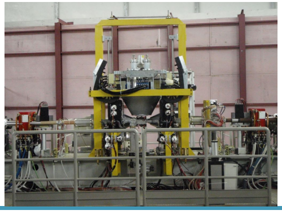
Catalina Curceanu, Carlo Guaraldo, Mihail Iliescu, Michael Cargnelli, Ryugo Hayano, Johann Marton, Johann Zmeskal, Tomoichi Ishiwatari, Masa Iwasaki, Shinji Okada, Diana Laura Sirghi, and Hideyuki Tatsuno

Rev. Mod. Phys. 91, 025006 – Published 20 June 2019

DEAR 2002



SIDDHARTA 2009



SIDDHARTA-2 2022

Fundamental physics New Physics
The modern era of light kaonic atom experiments
Rev.Mod.Phys. 91 (2019) 2, 025006

Part. and Nuclear physics QCD @ low-energy limit Chiral symmetry, Lattice
Kaonic Atoms to Investigate Global Symmetry Breaking
Symmetry 12 (2020) 4, 547

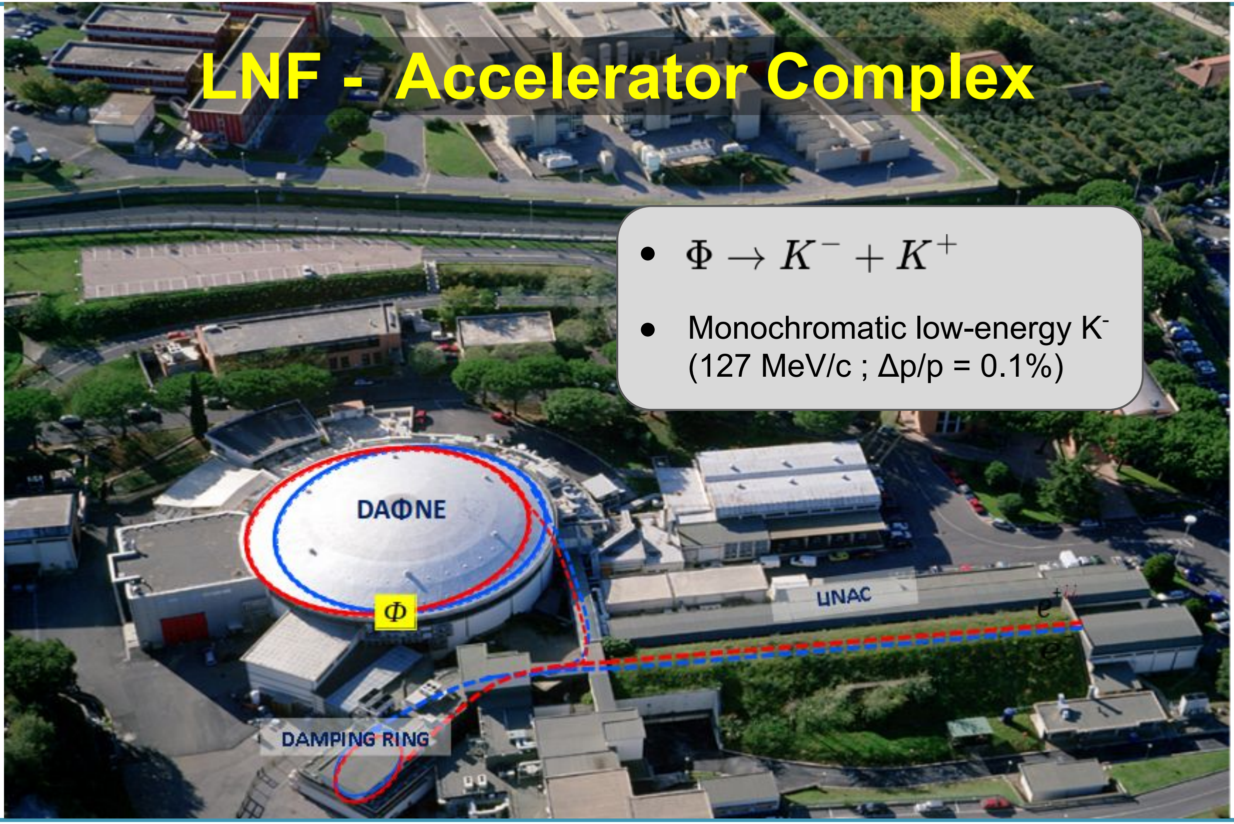
Kaonic Atoms Kaon-Nuclei Interactions (Scattering and Nuclear Interactions)

Astrophysics EOS Neutron Stars
The equation of state of dense matter: Stiff, soft, or both?
Astron.Nachr. 340 (2019) 1-3, 189

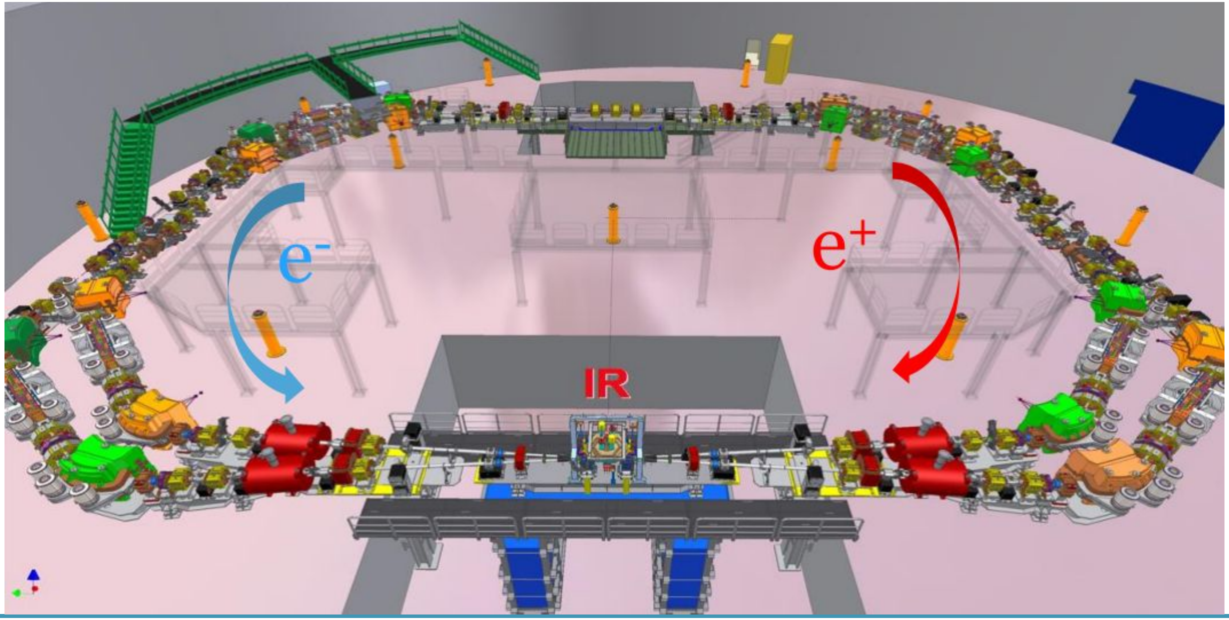
Dark Matter studies
On self-gravitating strange dark matter halos around galaxies
Phys.Rev.D 102 (2020) 8, 083015

LNF - Accelerator Complex

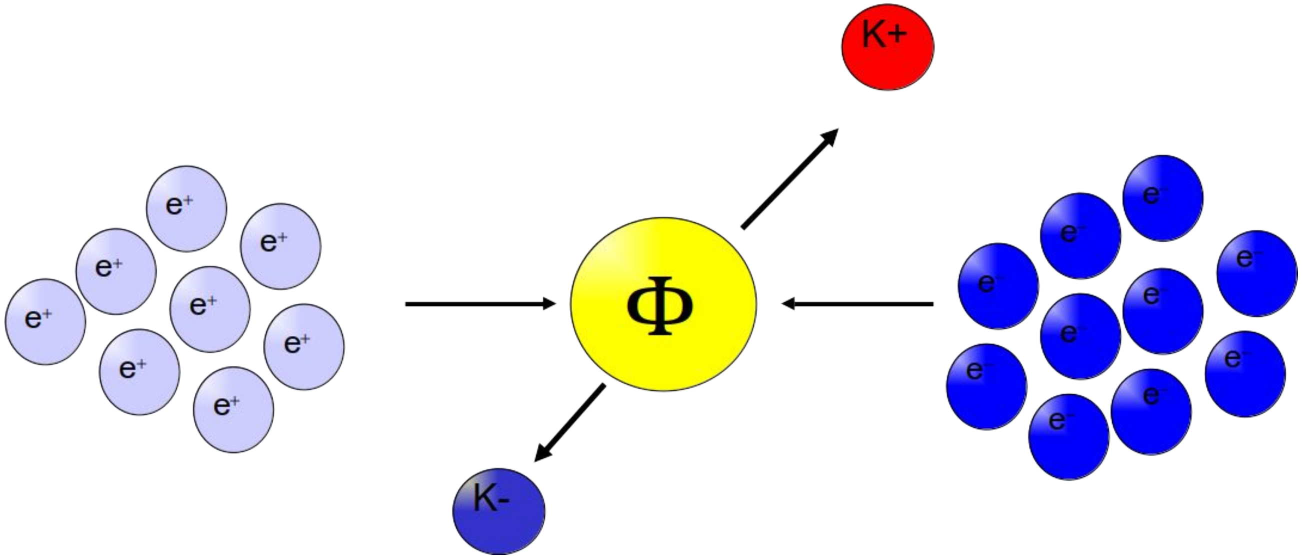
- $\Phi \rightarrow K^- + K^+$
- Monochromatic low-energy K^- (127 MeV/c ; $\Delta p/p$ = 0.1%)



Laboratori Nazionali di Frascati (INFN-LNF)

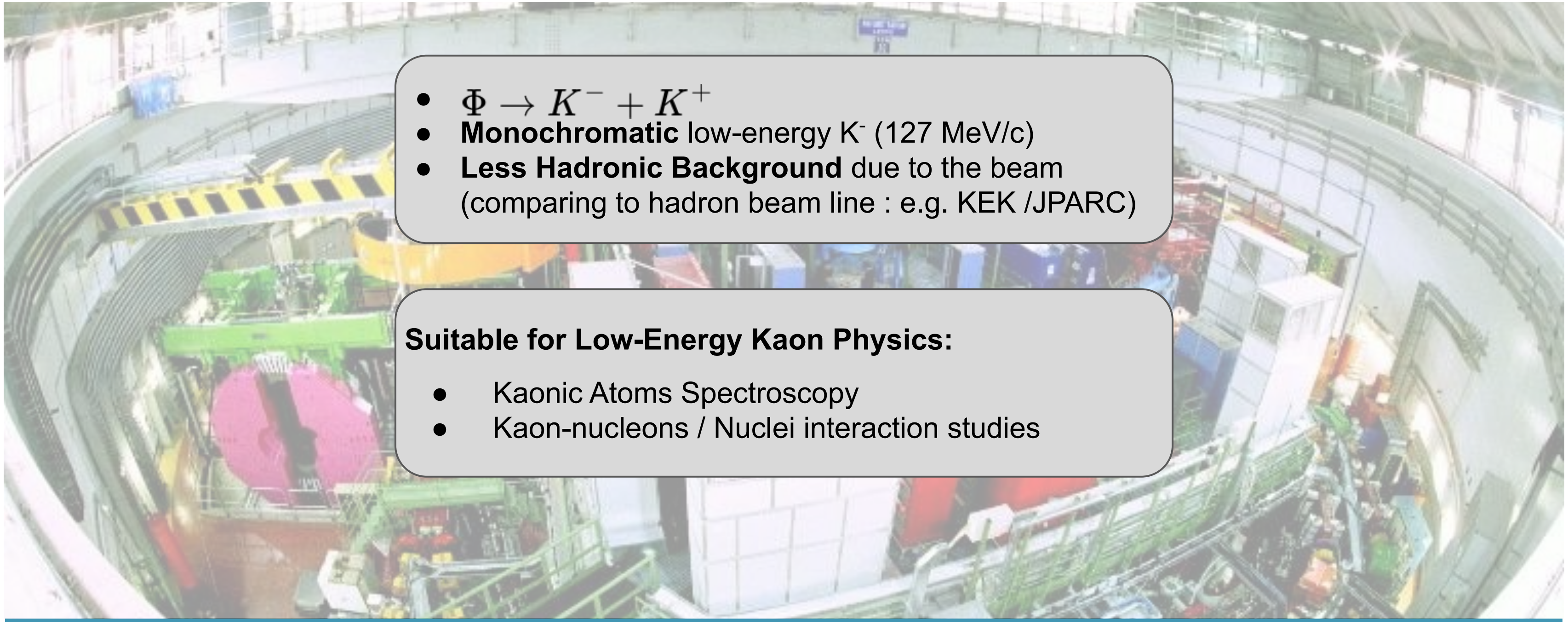


The DAΦNE Principle



Flux of produced Kaons: about 1000/second

The DAΦNE Principle

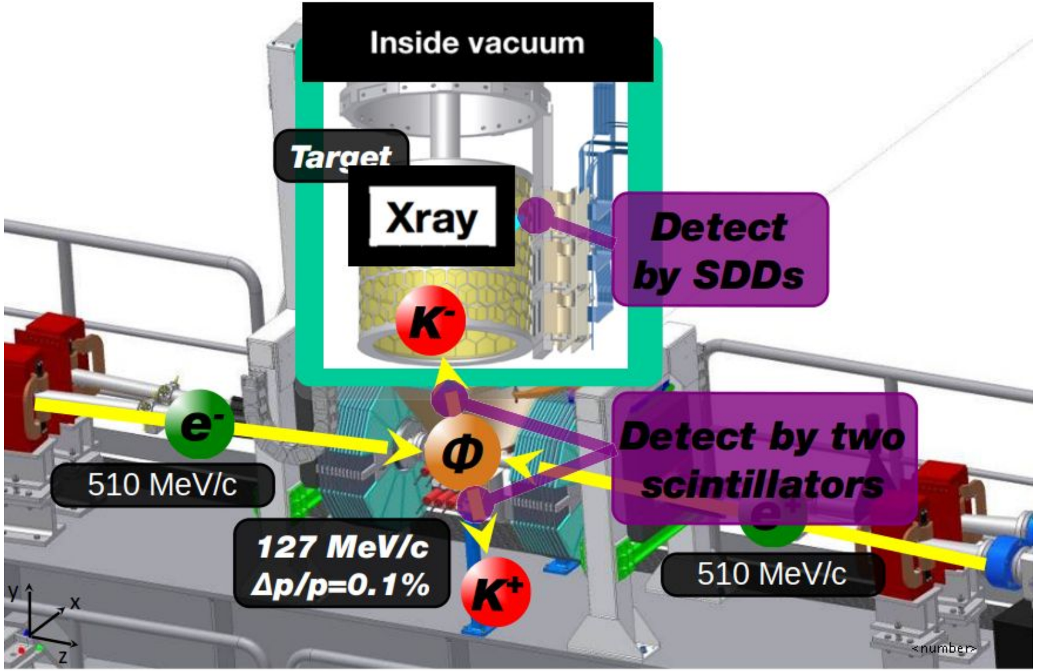


- $\Phi \rightarrow K^{-} + K^{+}$
- **Monochromatic** low-energy K^{-} (127 MeV/c)
- **Less Hadronic Background** due to the beam (comparing to hadron beam line : e.g. KEK /JPARC)

Suitable for Low-Energy Kaon Physics:

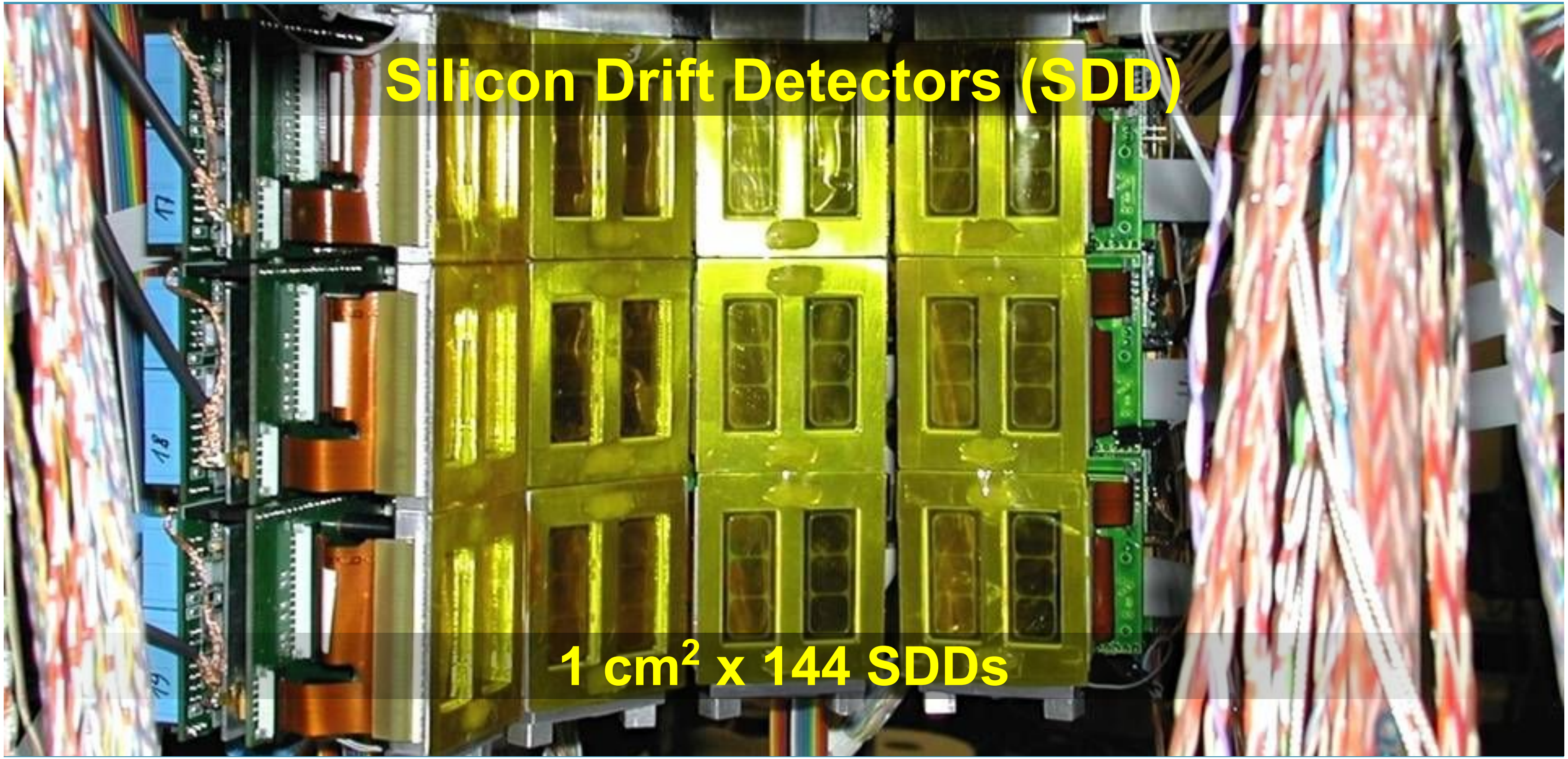
- Kaonic Atoms Spectroscopy
- Kaon-nucleons / Nuclei interaction studies

SIDDHARTA Setup Overview



Content

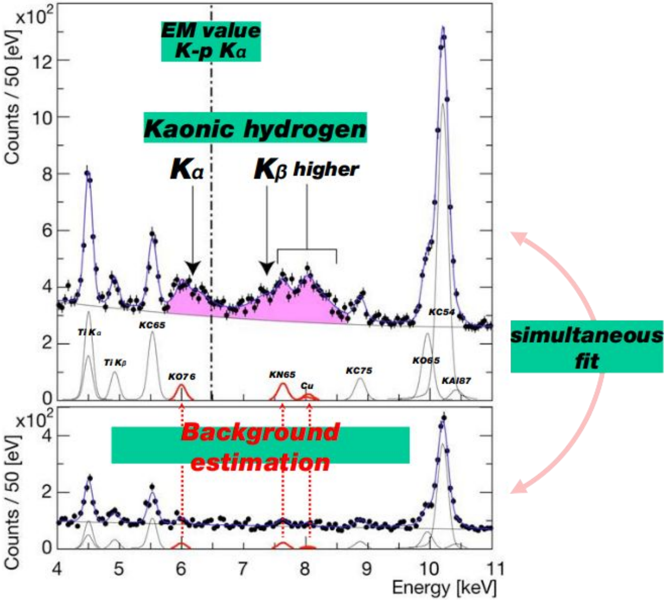
- High Precision X-ray Spectroscopy of Kaonic Atoms with SIDDHARTA
- Studying QCD, QED and BSM Physics with Kaonic Atoms
- **Beyond Kaonic Atoms: Impact of Crystal Spectrometers**

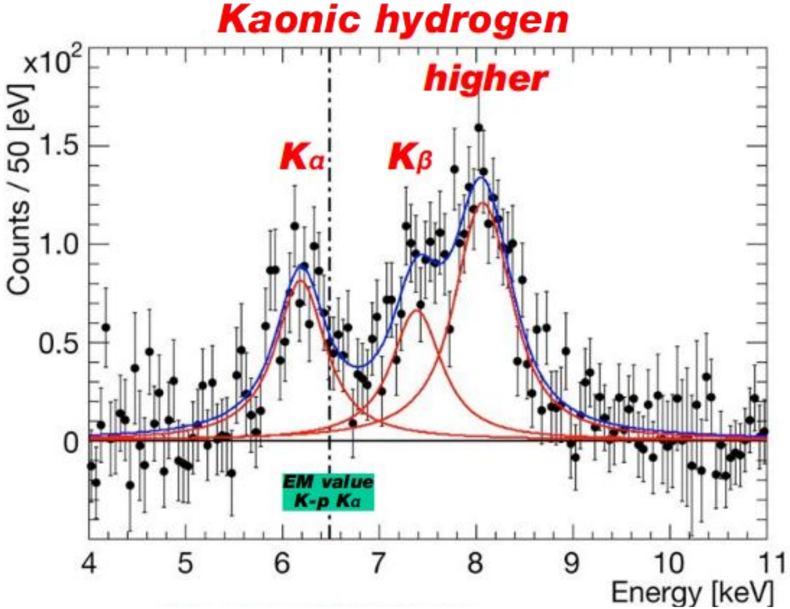

Silicon Drift Detectors (SDD)
1 cm² x 144 SDDs

The Kaonic Hydrogen Measurement of SIDDHARTA

Hydrogen spectrum

Deuterium spectrum





Physics Letters B 704.3 (2011): 113-117.

The SIDDHARTA-2 Scientific Goal: Kaonic Deuterium

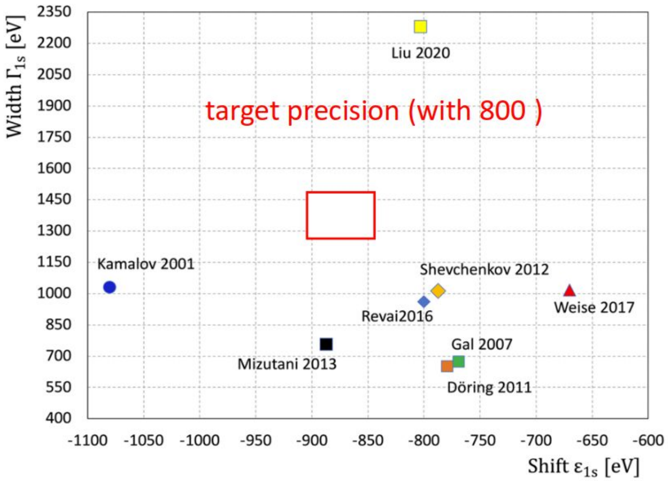
Main Scientific Goal:

- First measurement of **Kaonic Deuterium** X-ray transition to the **1s-level**
- Determine its **Shift** and **Width** induced by the presence of the **Strong Interaction**
- Providing unique data to investigate the **QCD** in the **Non-Perturbative regime with Strangeness**.

AntiKaon-Deuteron Scattering Length:

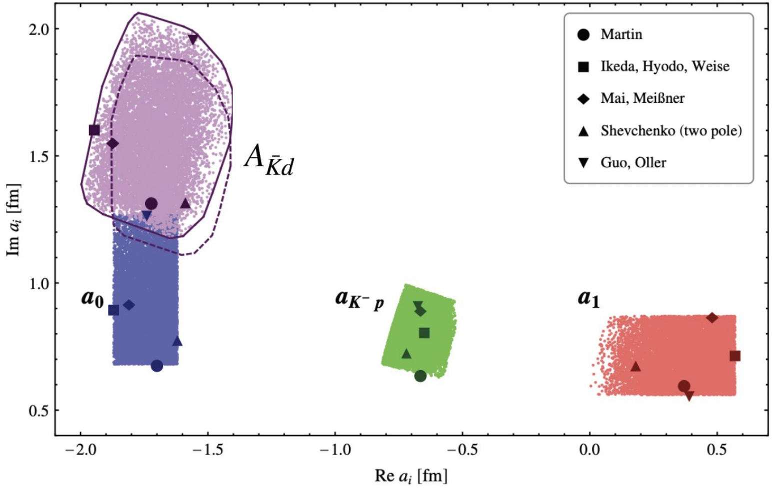
$$\epsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu^2 a_{K^-d} \,/\, (1 + 2\alpha\mu(\ln\alpha - 1)a_{K^-d})$$

Shevchenko, N. V. Few Body Syst. 63, 22



The SIDDHARTA-2 Scientific Goal: Kaonic Deuterium

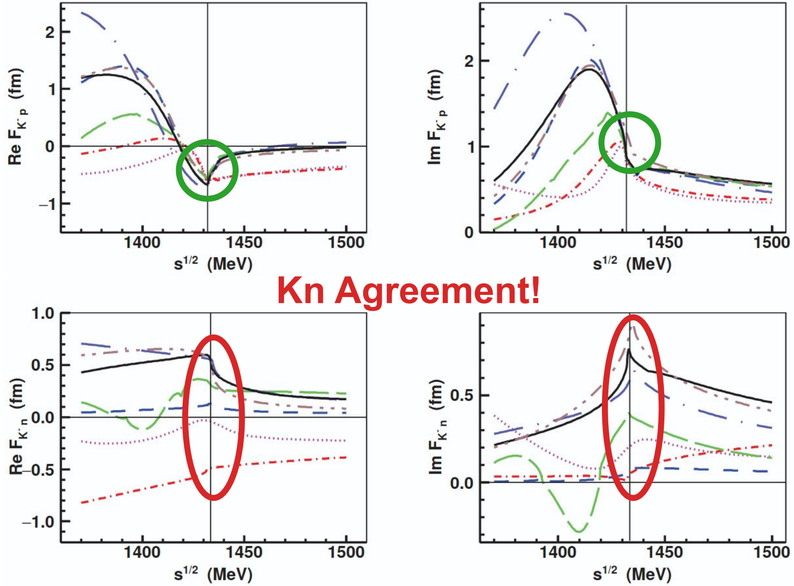
Combined analysis of the **Kaonic Deuterium** and **Kaonic Hydrogen** measurements



Maxim Mai, Vadim Baru, Evgeny Epelbaum, and Akaki Rusetsky Phys. Rev. D 91, 054016

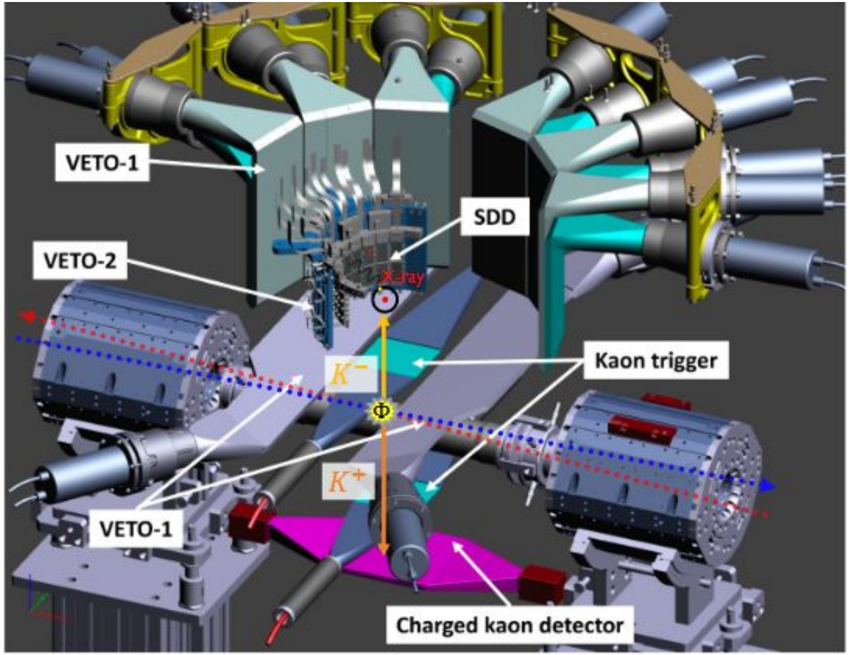
Kp Agreement!

Kn Agreement!



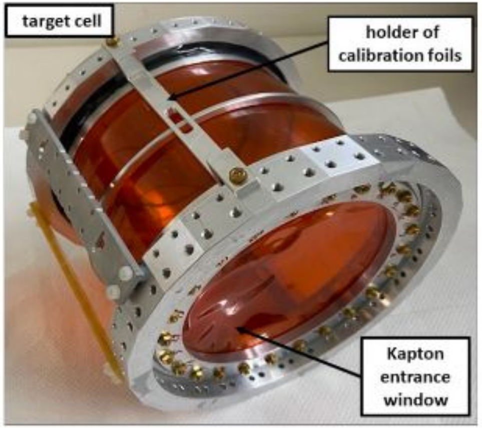
Aleš Cieplý, et al. AIP Conf. Proc. 2020; 2249 (1): 030014

The SIDDHARTA-2 Experimental Setup



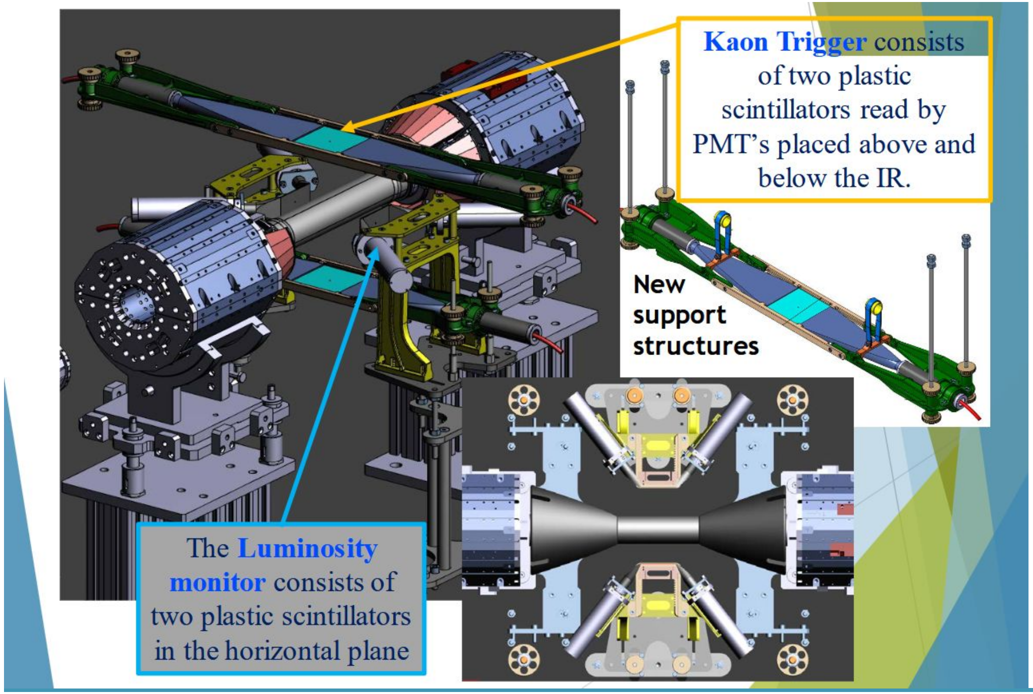
Kaon Trigger: two plastic scintillators read by photomultipliers placed above and below the interaction region.

Cryogenic gaseous target cell surrounded by **384 SDDs**

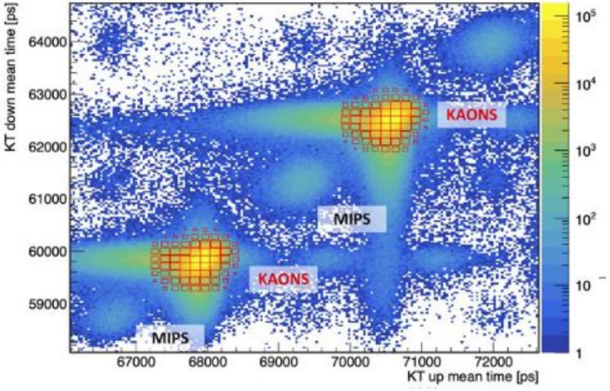


18

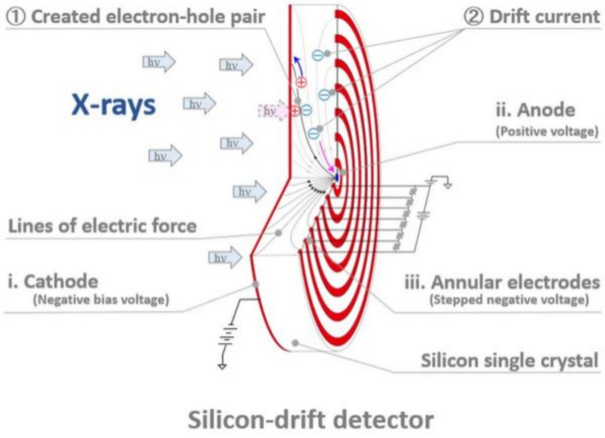
The SIDDHARTA-2 Experimental Setup: Luminometer

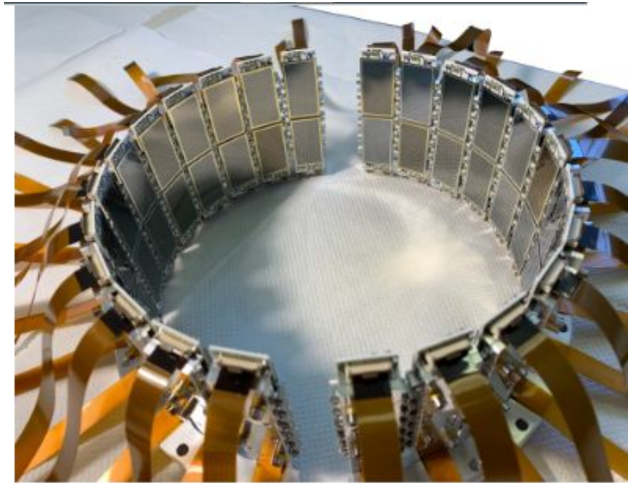


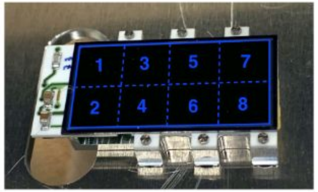
Dr. Magdalena Skurzok



Silicon Drift Detectors (2020-2021)



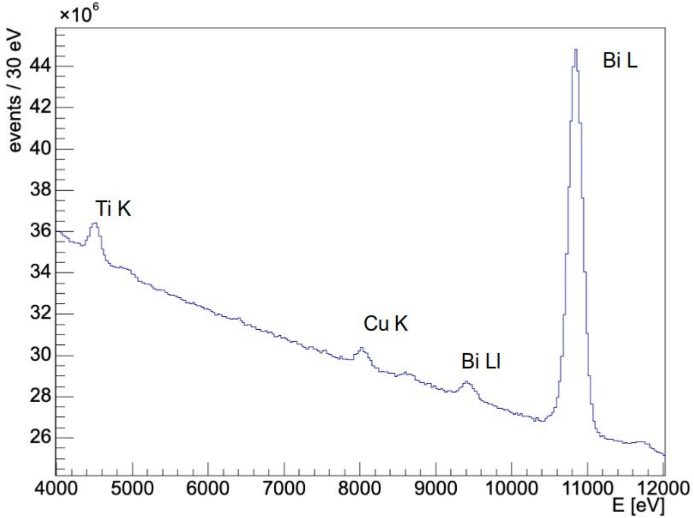




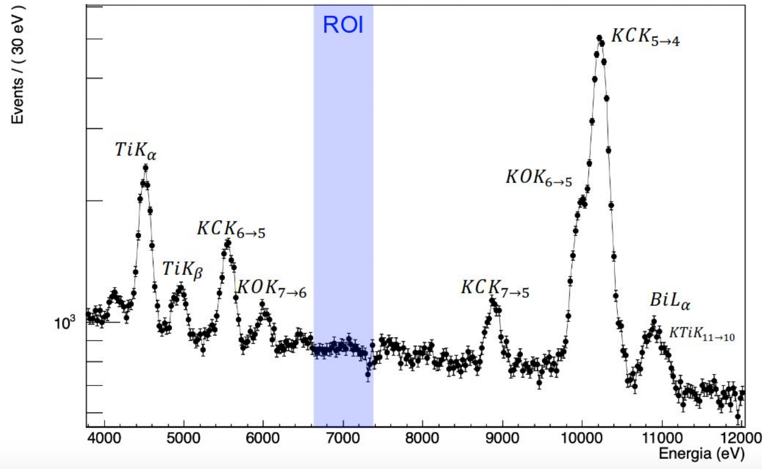
- **8 SDD units** (0.64 cm²)
- **Total Active Area** of 5.12 cm²
- **Thickness** of 450 μm ensures a **High Efficiency** at 5-12 keV

Kaonic Deuterium X-ray Energy Spectrum

Raw Spectrum



Bkg Selected Spectrum



Background reduced by a factor $3x10^4$

Extended Maximum-Likelihood Fit of the X-ray Spectrum

- We perform an **Extended Maximum-Likelihood fit** to the binned spectrum, including **Systematic Uncertainties** as **Nuisance Parameters**

- The full model is implemented in **ROOT / RooFit:**

$$f(E;\theta) = \underbrace{\sum_{n=0}^{18} y_n G_n(E;\mu,\sigma)}_{\substack{\text{Contaminant}\\ \text{X-ray Lines}}} + \underbrace{y_{2p\to1s} V_{2p\to1s}(E;\mu,\sigma,\Gamma) + \sum_{n=3}^{7} y_{n\to1s} V_{n\to1s}(E;\mu,\sigma,\Gamma)}_{\text{Kaonic Deuterium Lines } K\alpha,\ K\beta,\ldots} + \underbrace{y_{em} e^{\lambda_{em}E} + y_{had} e^{\lambda_{had}E} + C}_{\text{Background E.M and hadronic}}$$

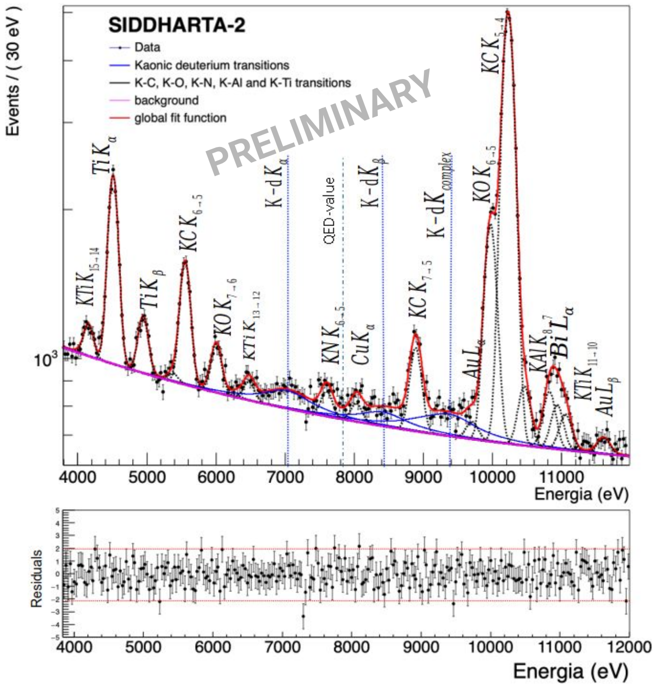
Eur. Phys. J. A (2023) 59 3, 56

- The **Total Negative Log-Likelihood** is: $-2\ln\mathcal{L}_{\text{tot}} = -2\ln\mathcal{L}_{\text{ext}} - 2\ln\mathcal{L}_{\text{nuisance}}$

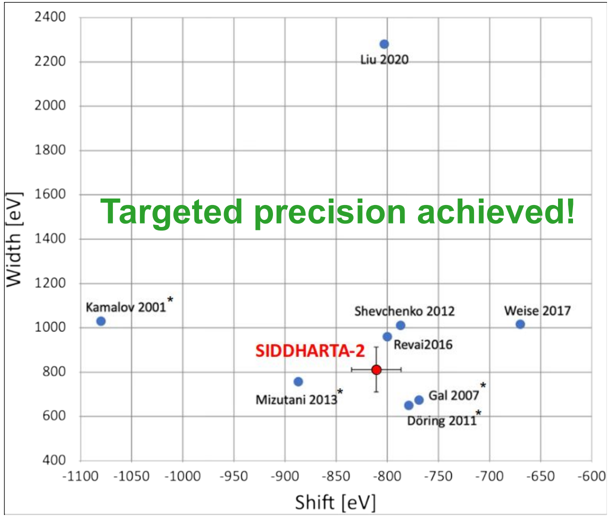
$$-2\ln\mathcal{L}_{\text{nuisance}} = \underbrace{\frac{(\delta\mu_{cal})^2}{\sigma^2_{cal}} + \frac{(\delta\mu_{stab})^2}{\sigma^2_{stab}}}_{\text{Calibration + Stability}} + \underbrace{\frac{(FF-FF_0)^2}{\sigma^2_{FF}} + \frac{(noise-noise_0)^2}{\sigma^2_{noise}}}_{\text{Energy Resolution}} + \underbrace{\frac{(\lambda_{em}-\lambda^0_{em})^2}{\sigma^2_{\lambda_{em}}} + \frac{(\lambda_{had}-\lambda^0_{had})^2}{\sigma^2_{\lambda_{had}}}}_{\text{E.M. and Hadronic Background}}$$

Phys.Scripta 97 (2022) 114002   Measur.Sci.Tech. 32 (2021) 9, 095501   Measur.Sci.Tech. 33 (2022) 9, 095502

Kaonic Deuterium Shift and Width Results



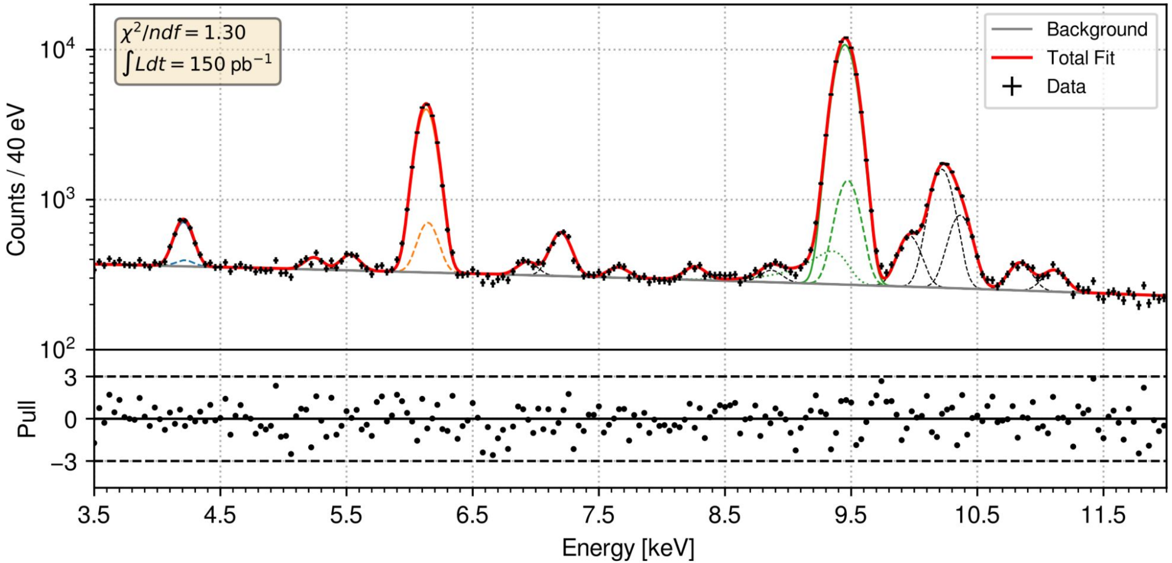
$$\varepsilon_{1s} = -810.9 \pm 24.5\ (\text{stat.}) + 2.1\ (\text{syst.})$$
$$\Gamma_{1s} = 812 \pm 97\ (\text{stat.}) + 33\ (\text{syst.})$$



Targeted precision achieved!

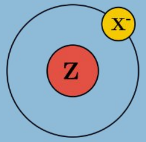
High Precision X-ray Spectroscopy in KNe

The **Kaonic Neon (KNe)** spectrum exhibits several transitions with **Intense Yields** resulting from the **Radiative De-Excitation** in the X-ray range of the kaonic atom during its **Cascade Process**.



MultiConfigurational Dirac-Fock Calculations with MCDFGME code

Ab Initio Input



- **Ab Initio Approach:** based only on **Physical Laws** and **Fundamental Constants.**
- Supports **Normal, Exotic,** or **Mixed Atomic Systems.**
- Supported **Exotic Particles:**

K^- : Kaons
μ^- : Muons
π^- : Pions
Σ^- : Sigmas
$\bar{p}^-$: Antiprotons
X^- : Test Particles

MCDF Framework

Basis Wavefunctions:

- Dirac Equation (spin-½ particles)

$$[c\boldsymbol{\alpha}\cdot\mathbf{p} + \beta mc^2 + V(\mathbf{r})]\,\psi_i(\mathbf{r}) = \varepsilon_i\psi_i(\mathbf{r})$$

- Klein-Gordon Equation (spin-0 particles)

$$[-\hbar^2c^2\nabla^2 + m^2c^4]\,\phi(\mathbf{r}) = [E - V(\mathbf{r})]^2\,\phi(\mathbf{r})$$

Multi-Configuration Dirac-Fock:

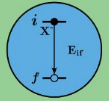
$$\Psi = \sum_{v=1}^{NCF} W_v\phi^v(1,2,...,N;J,J_z)$$

$$\mathrm{E_{tot}} = \sum_{\nu\mu} W_\nu W_\mu \langle\phi^\nu|H|\phi^\mu\rangle / \sum_\nu W_\nu^2$$

Total Energies Contributions:

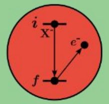
- QED (All-Orders)
- Breit Interaction
- Recoil Effect
- Nuclear Finite Size
- Screening Effect

Output Quantities

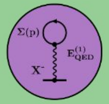


Energy Levels & Transitions

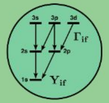
Radiative Transition Probabilities



Auger Decay Rates



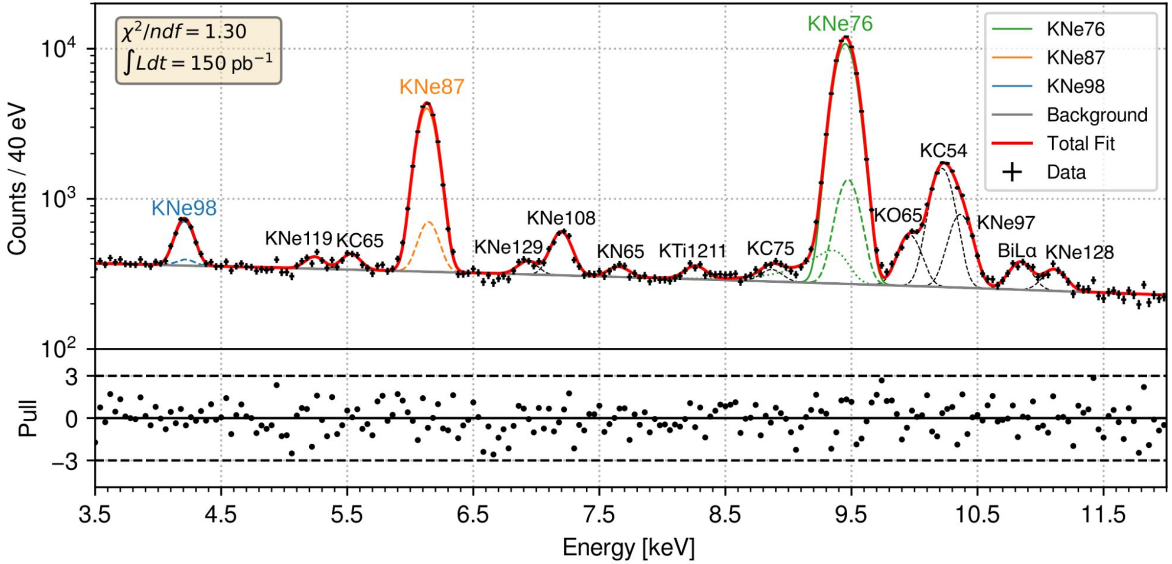
QED Self-Energy & Vacuum Polarization

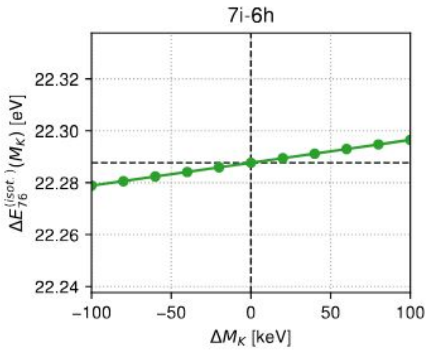


Parameters for Atomic Cascade

High Precision X-ray Spectroscopy in KNe

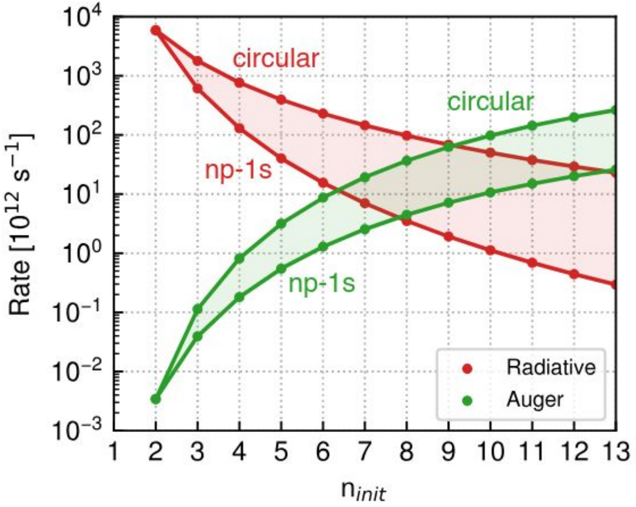
Dirac-Fock Calculations are employed to determine the transition energies of the spectral peaks. **Nuclear Shifts and Widths** for n>4 are negligible (Recoil,FNS,QCD)

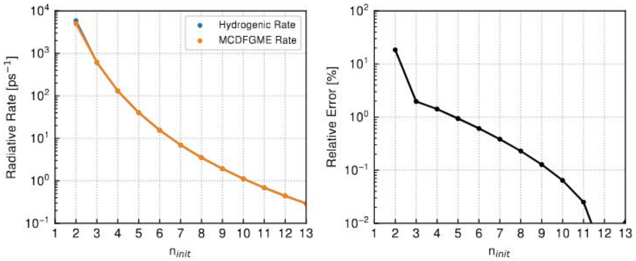




Calculations to Reveal the Cascade Mechanism in KNe

- **Qualitative trends** in **kaonic X-ray Yields** can be explained by the interplay between **Radiative** and **Auger decay** rates
  → X-ray emission dominates for n<10
- **Quantitative predictions** require accurate **Cascade Calculations**



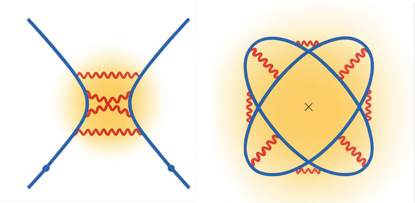


Burbidge, G.R., de Borde, A.H., 1953. Phys. Rev. 89, 189–193.

$$\Gamma^R_{n,\,l\to n',\,l\pm1} = \frac{4\mu Z^4}{3}\alpha^3 \left|R^{n,\,l}_{n',\,l\pm1}\right|^2 (\Delta E_{if})^3$$

$$\Gamma^A_{n,\,l\to n',\,l\pm1} = \frac{32}{3}\left(\frac{Z_e}{Z}\right)^2 \frac{\pi}{\mu^2}\frac{l}{2l+1}\left|R^{n,\,l}_{n',\,l\pm1}\right|^2 \frac{y^2}{1+y^2}\frac{\exp\left[y(4\tan^{-1}y-\pi)\right]}{\sinh(\pi y)}$$

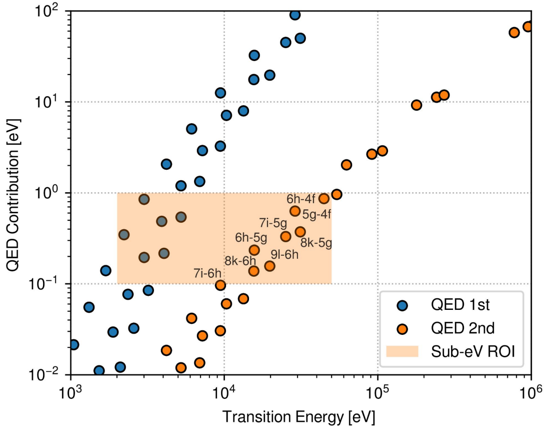
Kaonic Atoms for Bound-State QED Studies



Scattering   Bound-State

Transition	$E_{if}^{(exp.)}$	$\delta E_{if}^{(stat.)}$	$\delta E_{if}^{(sys.)}$	$E_{if}^{(calc.)}$	$E_{if}^{(QED)}$	$E_{if}^{(QED1)}$	$E_{if}^{(QED2)}$
9l-8k	4206.97	3.43	2.00	4201.45	2.09	2.07	0.02
8k-7i	6130.57	0.65	1.50	6130.31	5.09	5.05	0.04
7i-6h	9450.23	0.37	1.50	9450.28	12.66	12.56	0.10
6h-5g[a]	15673.30	0.52	9.00	15685.39	32.75	32.51	0.24

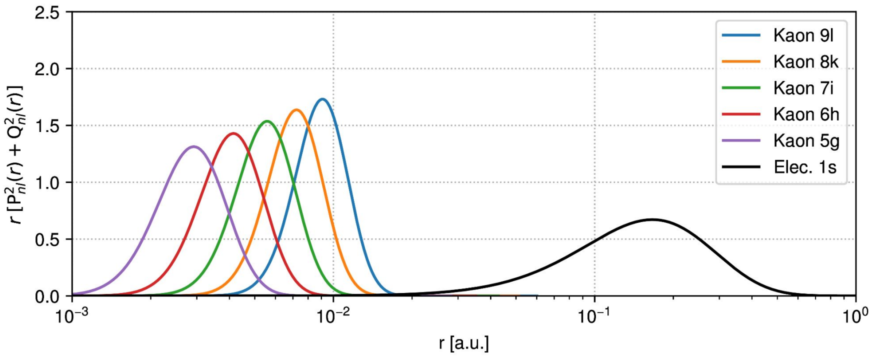
- **QED Contributions** exceed experimental uncertainties **(~8σ for the 7-6)**
- Many transitions lie in the **sub-eV ROI**, enabling **Precision BSQED Tests**.
- **Submitted to PRL!** (arXiv:2508.08161)

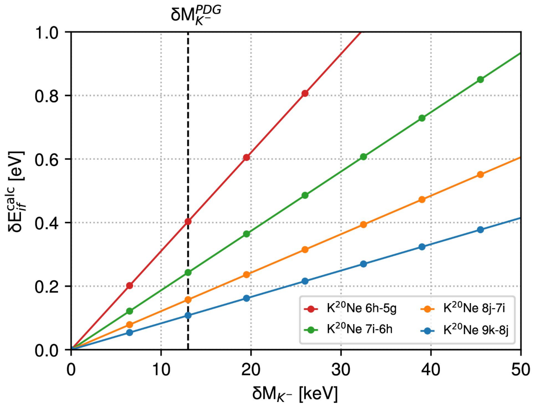


Benchmarks: Electronic Screening & Kaon-Mass Uncertainty

- Evaluation of **Electronic Screening** effects and **Uncertainty on the Kaon Mass (~13 keV)** on the observed lines in comparison to the size of QED contributions

- **Both Effects are Small (< 0.5 eV)** relative to the QED contributions and, moreover, electronic screening is negligible for the considered transitions.



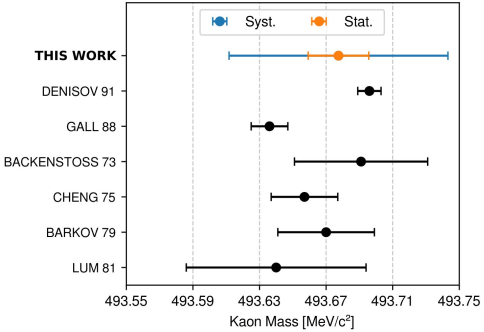


Kaon WFs are well inside the 1s electron orbit -> **Neon Fully Ionized!**

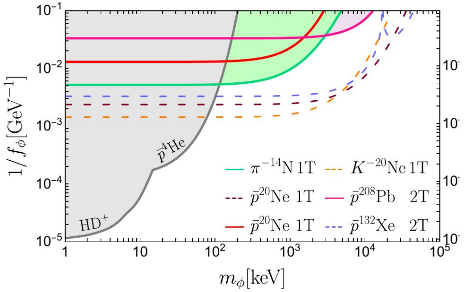
Fundamental Physics: Kaon Mass determination & BSM Physics

- Transitions with **Sub-eV Statistical Precision** already provide a **Statistical Uncertainty of ~18 keV** on the Kaon Mass.

Transition	M_{K^-} [MeV]	$\delta M_{K^-}^{\text{stat.}}$ [keV]	$\delta M_{K^-}^{\text{syst.}}$ [keV]
7i-6h	493.674	19	78
8k-7i	493.699	52	121
7i-6h + 8k-7i	493.677	18	66



- **A KNe Dedicated Optimized Run can reach < 10 keV** via:
  - **×2** improvement by **Doubling Statistics** (150 pb^{-1} → 300 pb^{-1})
  - **×2** improvement by **Optimized Gas Target Design** (lower statistical and systematic→0)
- **Exclusion Limits** can be set on hypothetical particles with **Yukawa-type couplings** using these transitions.



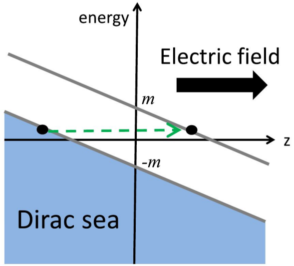
constrain uds-scalar [arXiv:2502.03537]

Kaonic Atoms as Probes of Strong Fields QED: Schwinger Limit for KF

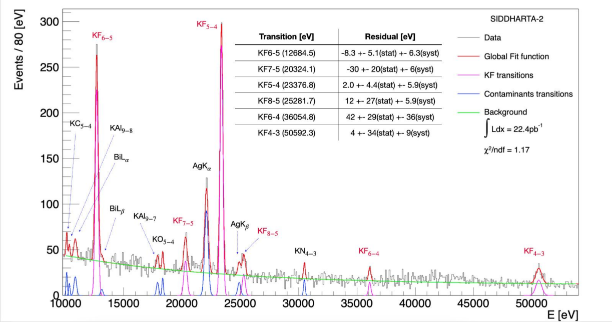
- The **Schwinger Limit** for spontaneous **e^+- e^- Pair Creation** is:

$$E_c = \frac{m_e^2 c^3}{q_e \hbar} \approx 1.32 \times 10^{18} V/m \qquad \langle E \rangle_{nl} = \int d^3r \, |\psi_{nl}(\mathbf{r})|^2 E(\mathbf{r})$$

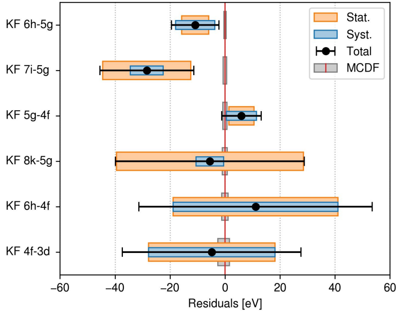
Above E_c ~ Dielectric Breakdown

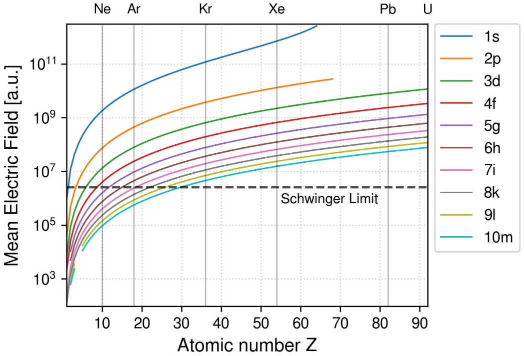


- BSQED contribution enhanced by the **Nonlinear Electric-Field dependence** of **Vacuum Polarization diagrams**
- In **KF 4f→3d (50.6 keV)** the **Average Orbital Electric Field** approaches the **Schwinger limit** (**a First in Exotic Atoms!**).



Transition [eV]	Residual [eV]
KF6-5 (12684.5)	-8.3 +- 5.1(stat) +- 6.3(syst)
KF7-5 (20324.1)	-30 +- 20(stat) +- 6(syst)
KF5-4 (23376.8)	2.0 +- 4.4(stat) +- 5.9(syst)
KF8-5 (25281.7)	12 +- 27(stat) +- 5.9(syst)
KF6-4 (36054.8)	42 +- 29(stat) +- 36(syst)
KF4-3 (50592.3)	4 +- 34(stat) +- 9(syst)





Beyond SIDDHARTA-2: EXKALIBUR

EXtensive **K**aonic **A**toms research: from **LI**thium and **B**eryllium to **UR**anium a unique opportunity for measurements of kaonic atoms along the periodic table

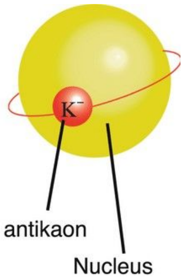
The measurement for the first EXKALIBUR module were selected based on two criteria:

Feasibility with minimal modifications/addings of the already existent SIDDHARTA-2 setup and within a reduced timescale

Impact i.e. the maximal scientific outcome:

- Precision measurements along the periodic table at DAΦNE for:
- Selected light kaonic atoms (LHKA) – Li, Be, B
- Selected intermediate and heavy kaonic atoms (IMKA) – Al, C, O, S, Pb

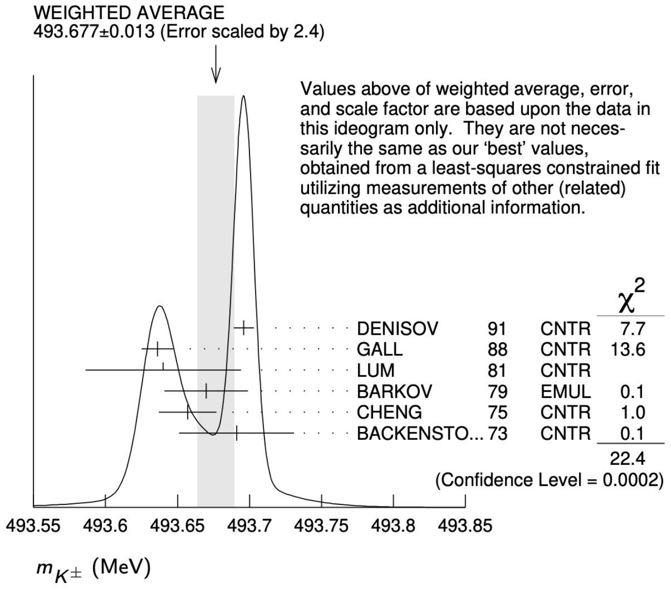
Dedicated runs with different types of detectors: CZT detectors, SDDs



EXtensive **K**aonic **A**toms research: from **LI**thium and **B**eryllium to **UR**anium

EXKALIBUR: Kaonic Neon for the Charged Kaon Mass

EXtensive **K**aonic **A**toms research: from **LI**thium and **B**eryllium to **UR**anium a unique opportunity for measurements of kaonic atoms along the periodic table

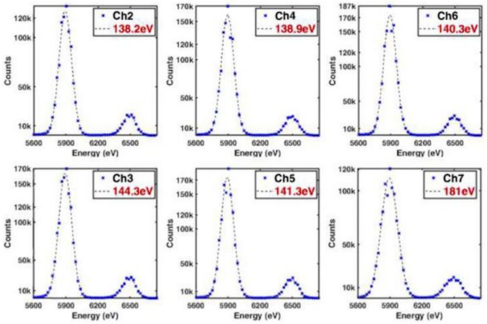


- The first measurement we plan doing is the kaonic neon high-n levels transition with precisions below 1 eV, to extract the charged kaon mass (5-7 keV precision).
- By using a gaseous target, we can resolve the ambiguity in the charged kaon mass determination, providing a new precise value through the measurement of kaonic neon high-n transitions. Moreover, the measurement also provides a precision test of QED in atomic systems with strangeness

EXKALIBUR: Light Mass (low-Z) Kaonic Atoms (LHKA)

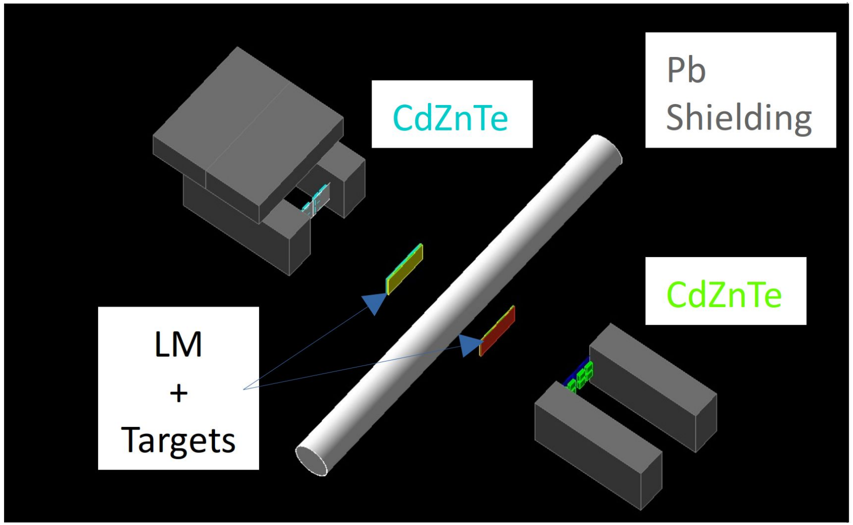
- After the kaonic neon, measurement of light mass (Li, Be, B) kaonic atoms high and low-n transitions, to study in detail the strong interaction between kaon and few nucleons (many body).

- Now precise measurements for these kaonic atoms of the shifts, widths and yields will result in a significative improvement on the knowledge of the interactions of kaons in matter, with a great impact on the low energy QCD and astrophysics (equation of state for neutron stars).



Replacing the gaseous target with a multi-element (Li-Be-B) solid target and new 1 mm thick SDDs for higher detection efficiency up to 50 keV

EXKALIBUR: Intermediate-mass Kaonic Atoms measurements with CdZnTe setups



- **Kaonic Oxygen:** key role in the description of the nuclear-matter density distribution which enters in the formula for the density-dependent optical potentials
- **Kaonic Aluminium:** 3->2 QCD – never measured
- **Kaonic Sulphur:** 4->3 the inconsistent measurements

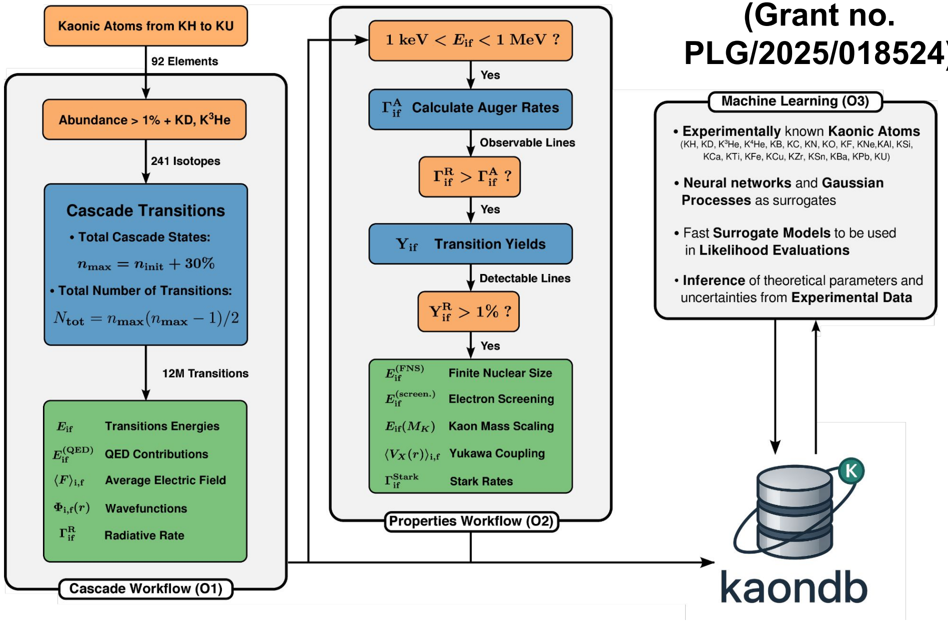
Building a (Strange) Periodic Table of Kaonic Atoms

Dr. Magdalena Skurzok

(Grant no. PLG/2025/018524)

Awarded 500,000 Core-Hours on the **Helios Supercomputer** (PLGrid) to build a **Kaonic Atoms Database (KaonDB)**

- **Cascade Workflow O1:** KH–KU, **~12M transitions**
- **Properties Workflow O2:** **Observable** and **Detectable**
- **Machine Learning O3:** Inference from Experiments
- Deliver an **Online-Accessible Database (FAIR principles)**



Content

- High Precision X-ray Spectroscopy of Kaonic Atoms with SIDDHARTA
- Studying QCD, QED and BSM Physics with Kaonic Atoms
- Beyond Kaonic Atoms: Impact of Crystal Spectrometers

Why Crystal Spectrometers?

State-of-the-art detectors (SDD, HPGe, CZT):

- **Excellent Efficiency**, timing, large solid angle
- **Energy Resolution** ~100 eV (SDD, CZT, HPGe)

But… **to reach sub-eV resolution**, fundamental for precision QED, strong interaction, and BSM physics

TES < eV but:

- Extremely **Costly**
- Complex cryogenic operation **(T~mK)**
- **Limited availability** & scalability
- **Impact** mainly in fundamental research

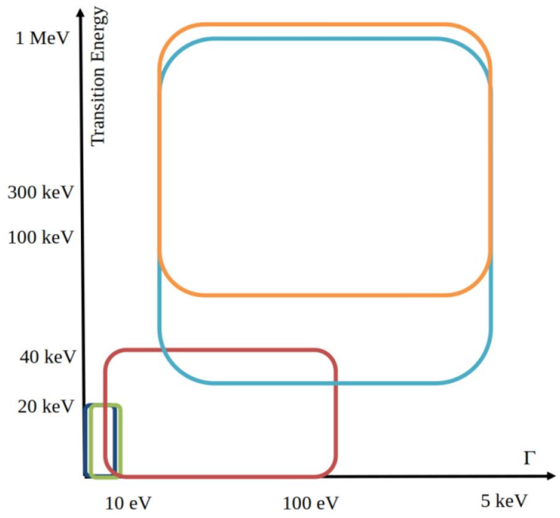
Crystal spectrometers:
- FWHM / E < 0,1 %
- ~ 500 ns time resolution
- Working T ~ 300 K

TES microcalorimeters
- FWHM / E < 0,1 %
- ~ µs time resolution
- Working T ~ 0,05 K

SDDs
- FWHM / E < 2 %
- ~ 100 ns time resolution
- Working T ~ 160 K

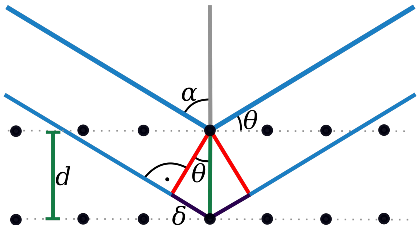
CZT
- FWHM / E ~ %
- ~ 10 ns time resolution
- Working T ~ 300 K

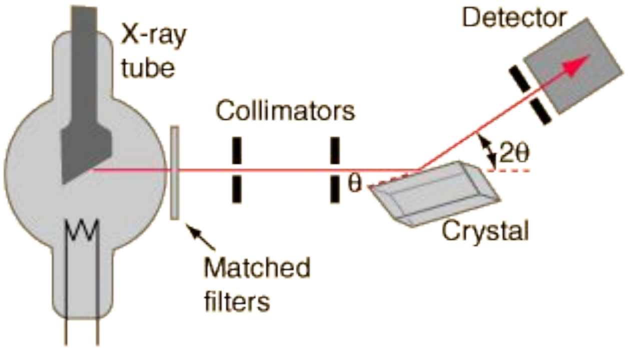
HPGe
- FWHM / E ~ %
- ~ µs time resolution
- Working T ~ 100 K



Crystal Spectrometers for High Precision Spectroscopy

- **Principle:** Bragg diffraction separates X-ray energies → dispersive technique
- **Resolution:** ΔE down to sub-eV (ΔE/E ≈ $10^{-4} – 10^{-5}$), far beyond solid-state detectors
- **Advantages:**
  - Precise energy calibration
  - Natural background suppression (geometry)
  - Suitable for extended sources with mosaic crystals (e.g., HAPG)
- **Limitations:**
  - Small solid angle coverage
  - Efficiency ≈ $10^{-5} – 10^{-8}$
  - Resolution vs. efficiency trade-off (mosaicity, thickness, source size)
  - Configurations: Von Hamos, Johann, Semi-VH … optimized for different needs



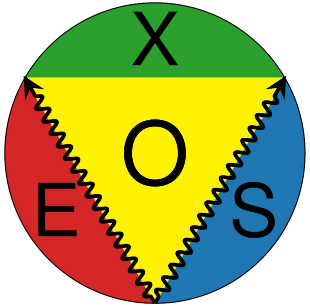


VOXES: High-Resolution Bragg Spectroscopy for Extended Sources

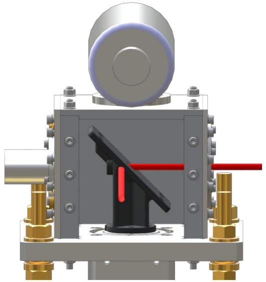
- A **Von Hamos spectromete**r based on Highly Annealed Pyrolytic Graphite (HAPG) **mosaic crystals**
- Designed at INFN-LNF (Frascati) for **extended and diffused X-ray sources**

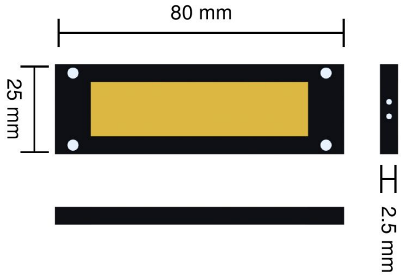
Features:

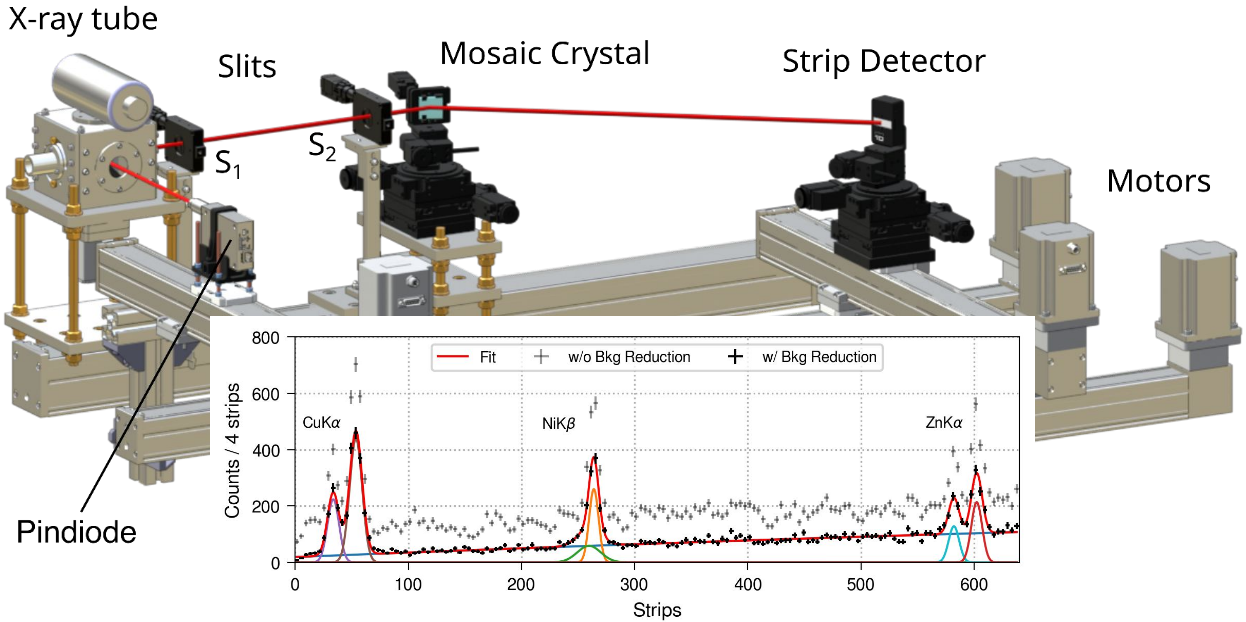
- Uses **Mosaic Crystals** → higher efficiency while maintaining good resolution
- **Flexible geometry** (Von Hamos, Semi-VH) for compact setups
- Works with **sources up to mm/cm** dimensions
- **Resolution** < 10 eV; precision < 1 eV
- **Applications:** fundamental physics, material science, agrifood, cultural heritage



VOXES: High-Resolution Bragg Spectroscopy for Extended Sources

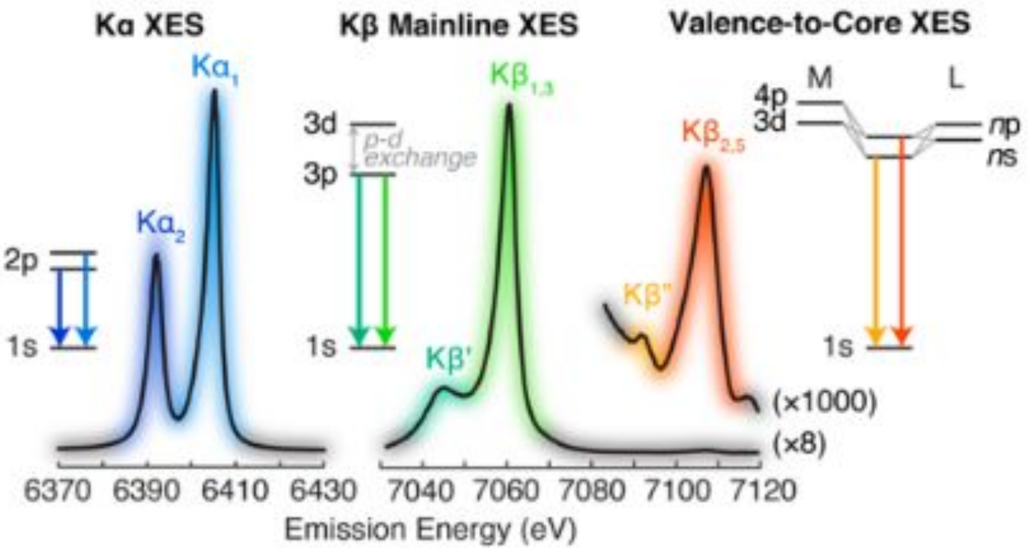


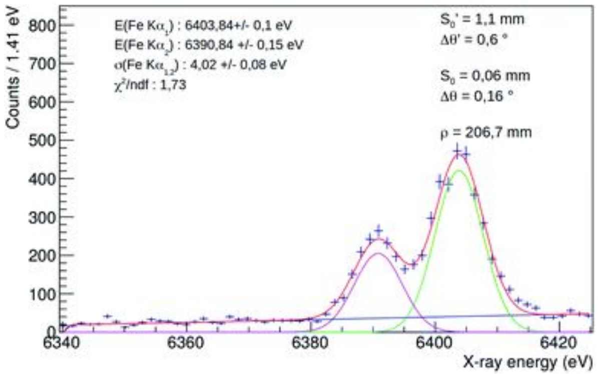




Manti, Simone, et al. *Condensed Matter* 9.1 (2024): 19.

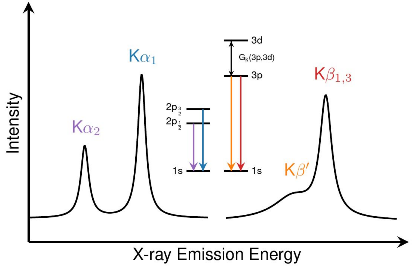
Different Information from Different Emission Lines

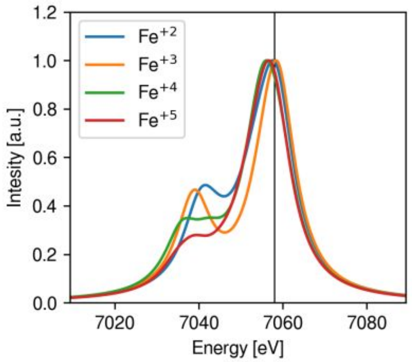


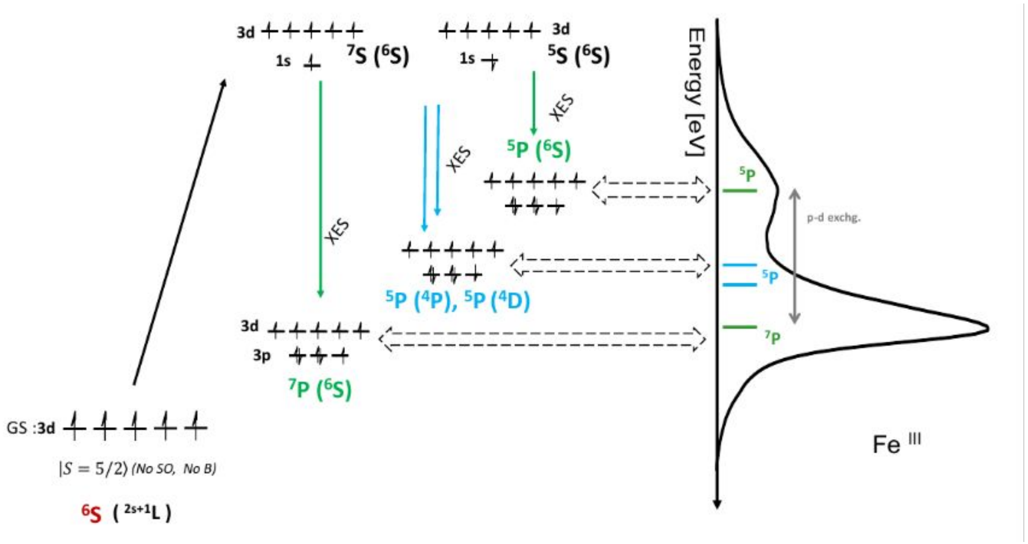


Nicole Lee, Taras Petrenko, Uwe Bergmann, Frank Neese, and Serena DeBeer, Journal of the American Chemical Society 2010 132 (28), 9715-9727 DOI: 10.1021/ja101281e

Kβ Emission Line is sensible to the Metal’s (Spin~Oxidation) State



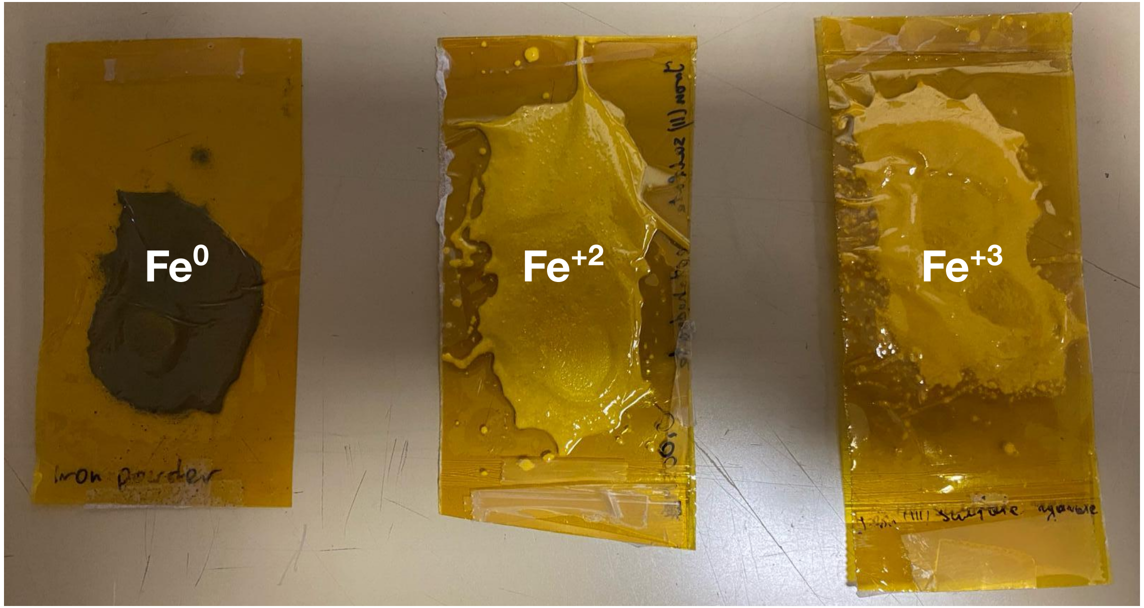




Nicole Lee, Taras Petrenko, Uwe Bergmann, Frank Neese, and Serena DeBeer, Journal of the American Chemical Society 2010 132 (28), 9715-9727 DOI: 10.1021/ja101281e

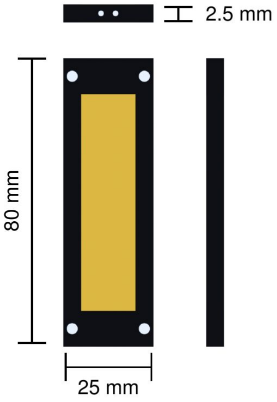
Effects of the Metal’s State on the Kβ Lineshape in Solid/Liquids

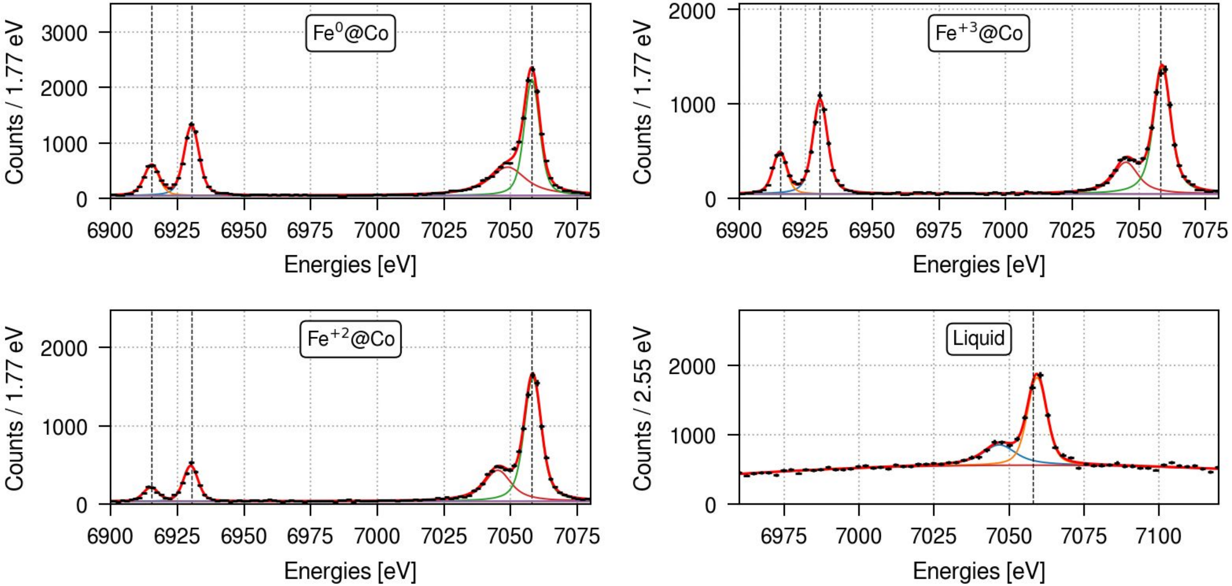
Gabriel Moskal
Jagiellonian University



Effects of the Metal’s State on the Kβ Lineshape in Solid/Liquids

MITIQO





Conclusion

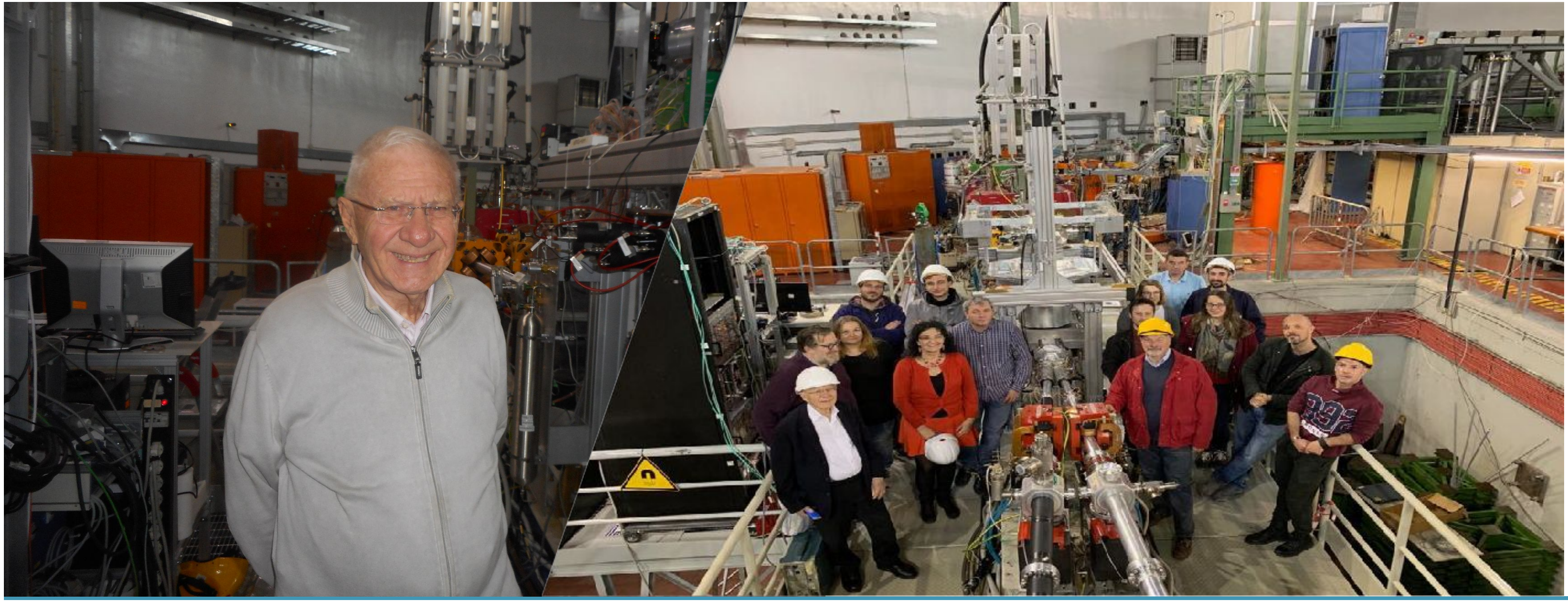
- **High Precision X-ray Spectroscopy of Kaonic Atoms with SIDDHARTA**
- **Studying QCD, QED and BSM Physics with Kaonic Atoms**
- **Beyond Kaonic Atoms: Impact of Crystal Spectrometers**

Part of the SIDDHARTA-2 collaboration

I dedicated this talk to my dear colleagues and friends

Prof Carlo Guaraldo and Dr. Johann Zmeskal who passed away in 2024

You'll be very much missed!



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Thank you for the Attention!