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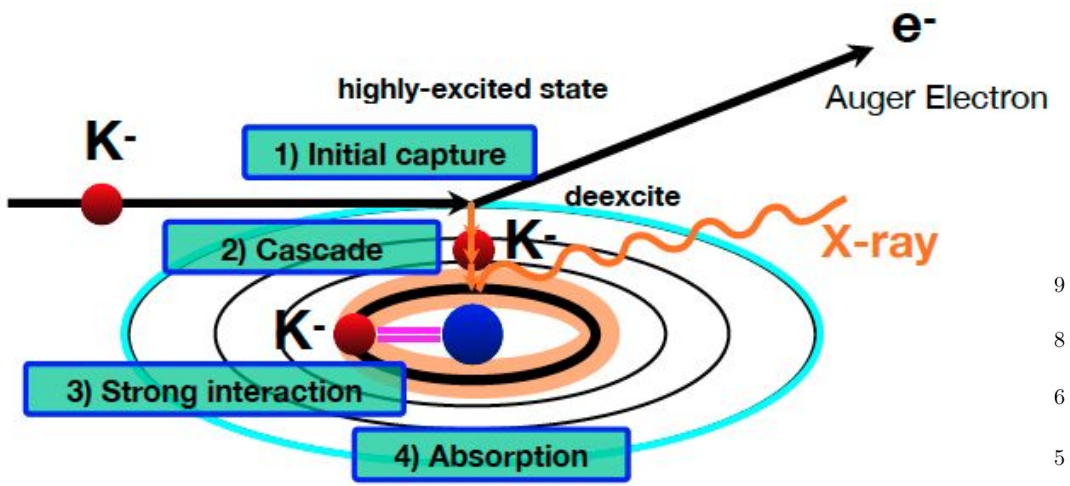
Kaonic atom x-ray spectroscopy at SIDDHARTA-2: from bound-state QED tests to new-physics sensitivity

Trento, ECT*, 13 October 2026

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

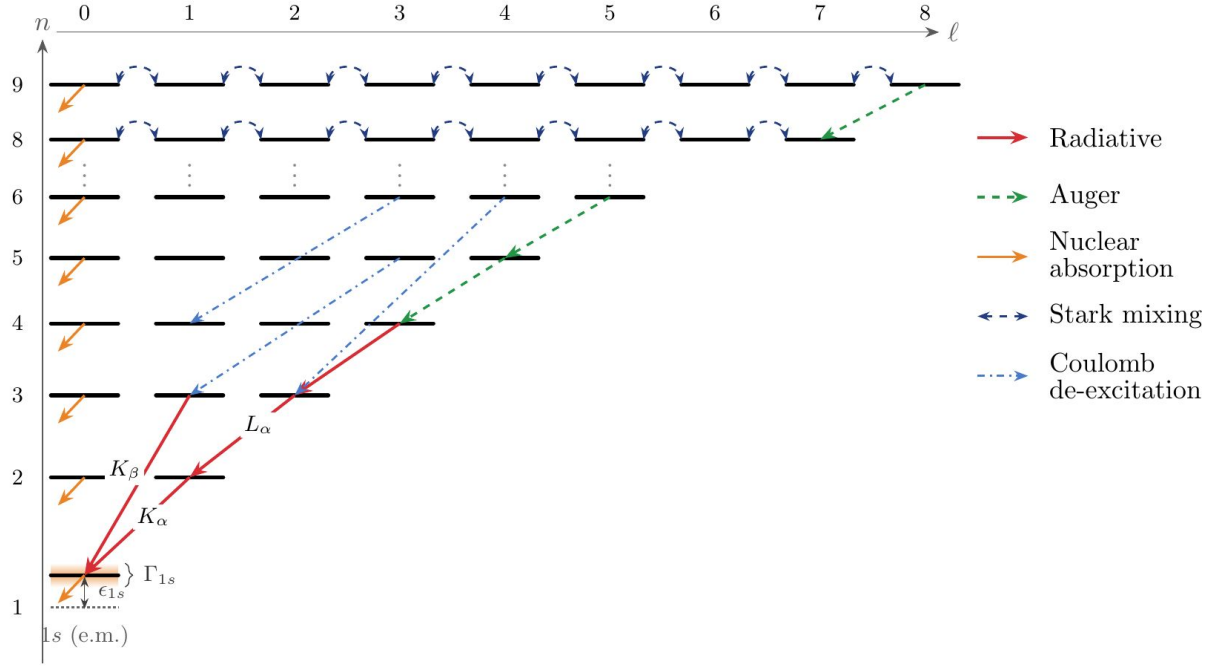
Funded by the European Union

Kaonic atom X-ray spectroscopy



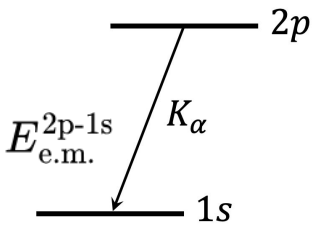
$$n_{\text{init}} \sim n_e \sqrt{\frac{\mu}{m_e}} \qquad n_{\text{init}} \sim 25 \text{ for } K\text{-}p$$

$\mu : K\text{-}p$ Reduced Mass

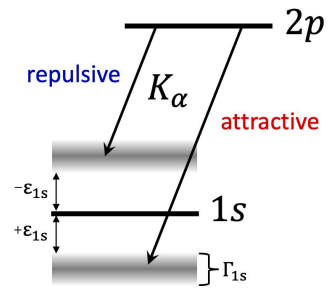


Purely electromagnetic

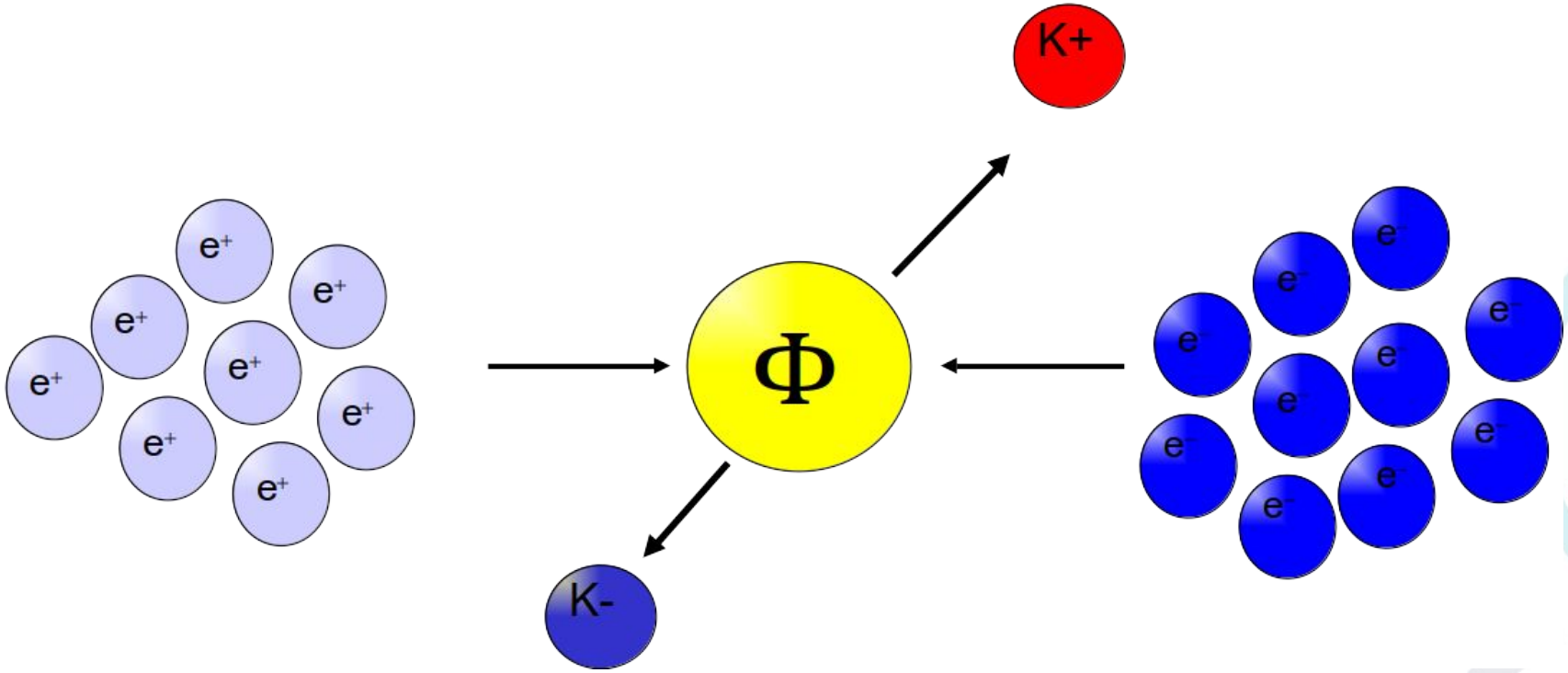
$$\varepsilon_{1s} = E^{\text{2p-1s}}_{\text{meas}} - E^{\text{2p-1s}}_{\text{e.m.}}$$



Electromagnetic + strong interaction

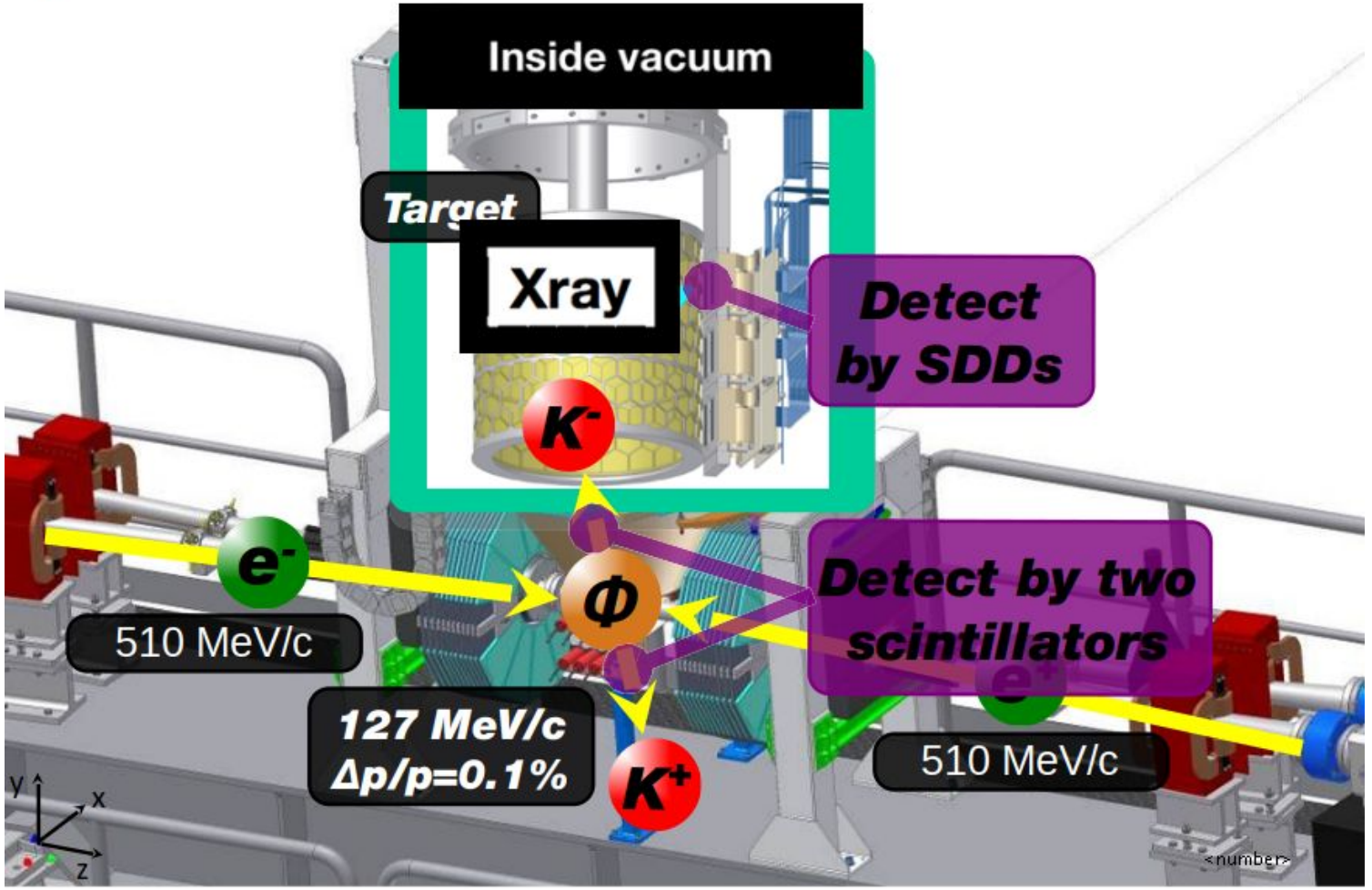


How to produce Kaons? The DAΦNE principle

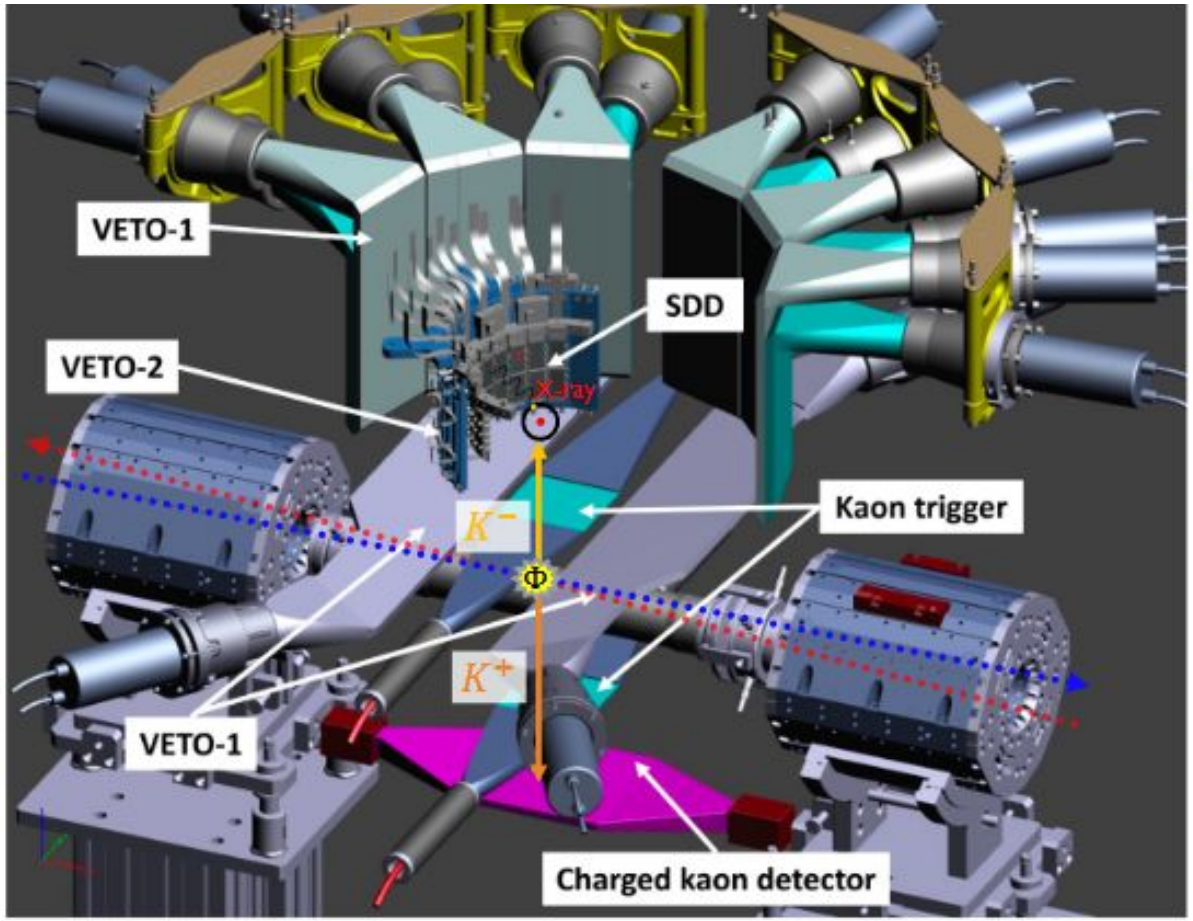


Flux of produced Kaons: about 1000/second

The SIDDHARTA setup overview

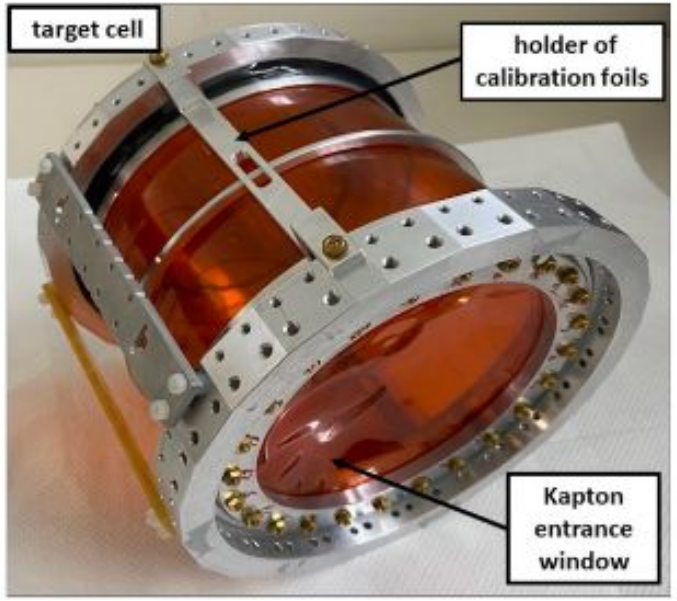


The SIDDHARTA-2 Experimental Setup



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

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



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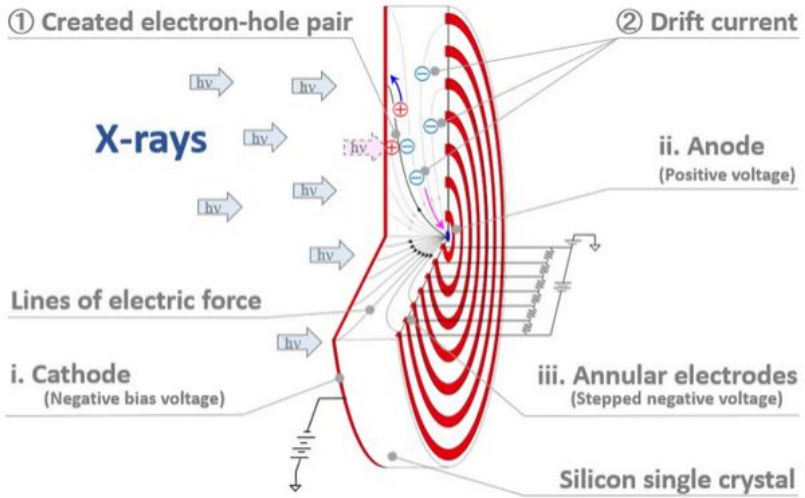
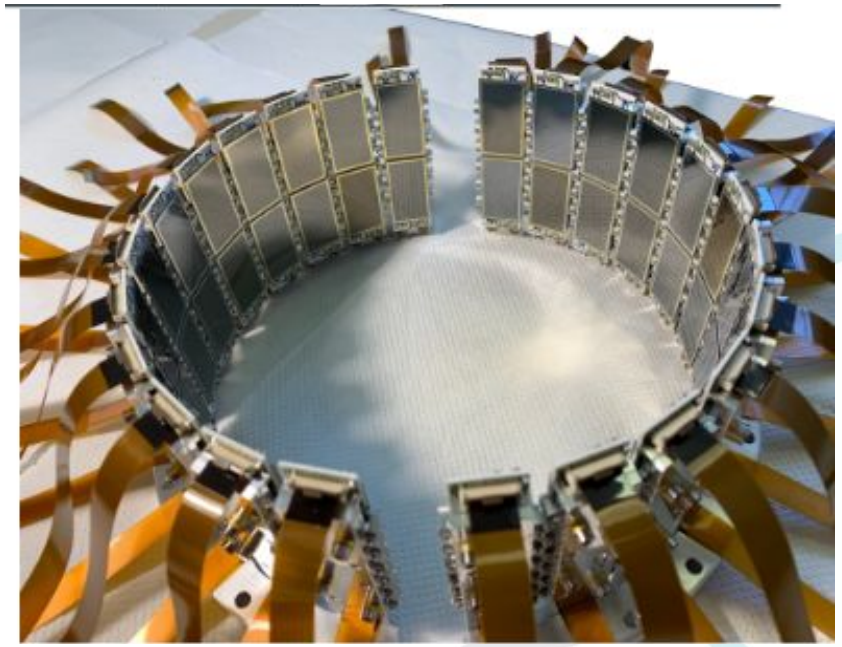
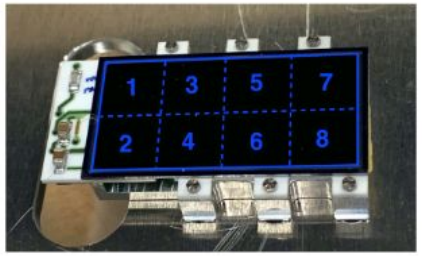
see Diana Sirghi's talk on Thursday morning!

X-ray spectroscopy with Silicon Drift Detectors



Silicon-drift detector

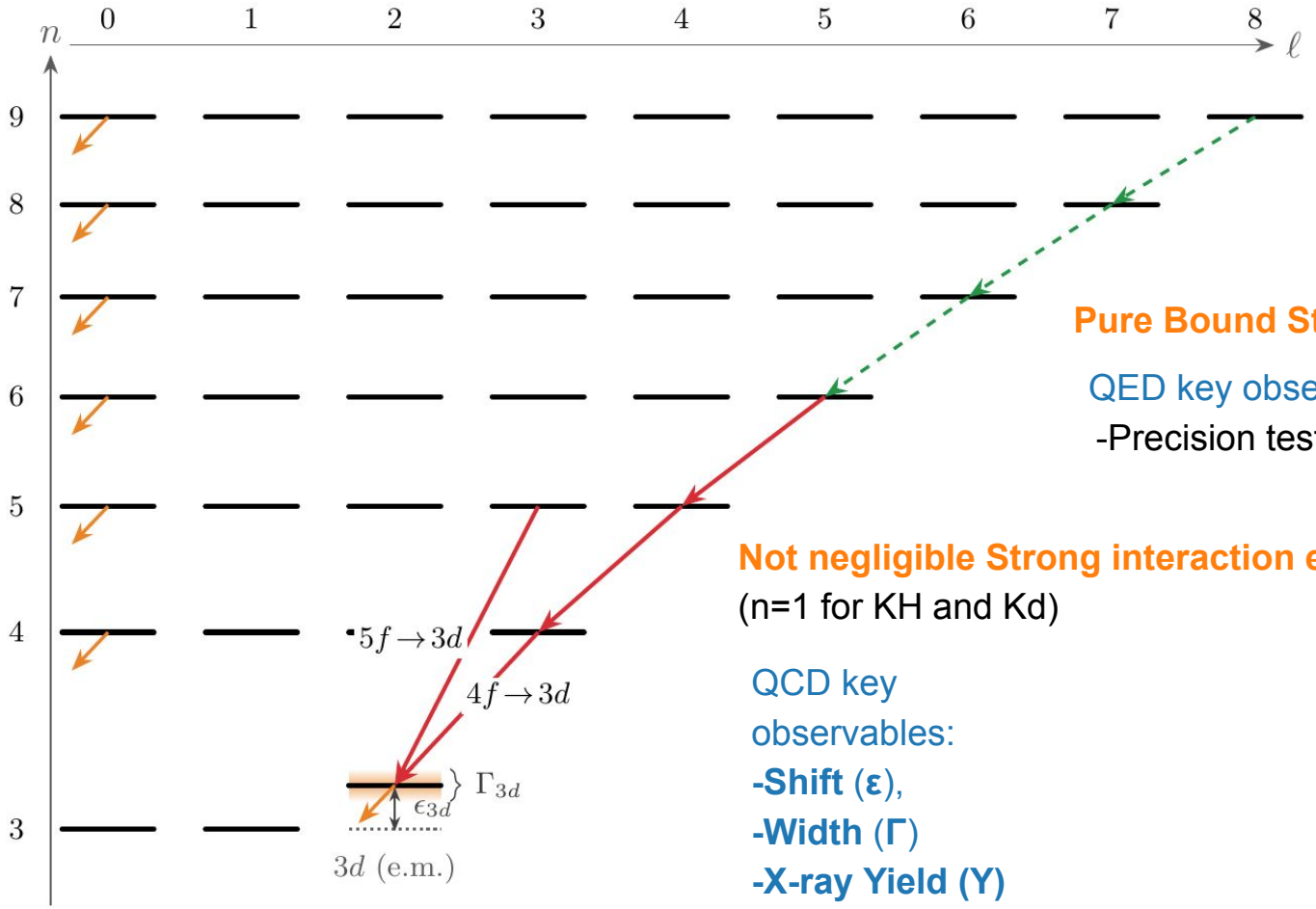


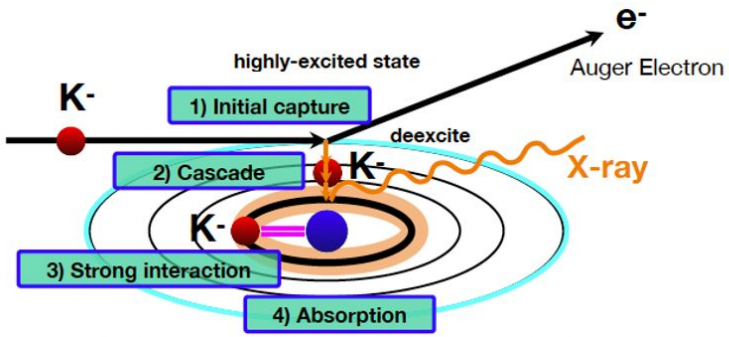


- **8 SDD units** (0.64 cm²)
- **Total Active Area** of 5.12 cm²
- **Thickness** of 450 μm ensures a **High Efficiency** at 5-12 keV

see Diana Sirghi's talk on Thursday morning!

Probing different interactions during the cascade





Pure Bound State QED transition

QED key observables: **Energy** and **X-ray Yield**

-Precision test of QED in Bound-State systems

Not negligible Strong interaction effect

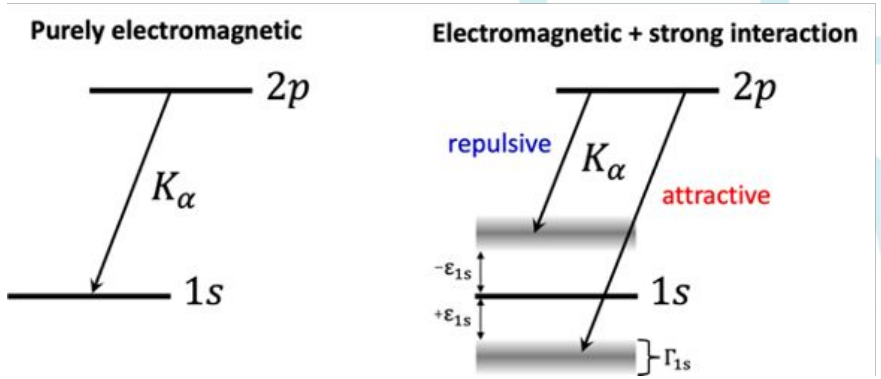
(n=1 for KH and Kd)

QCD key observables:

-Shift (ε),

-Width (Γ)

-X-ray Yield (Y)



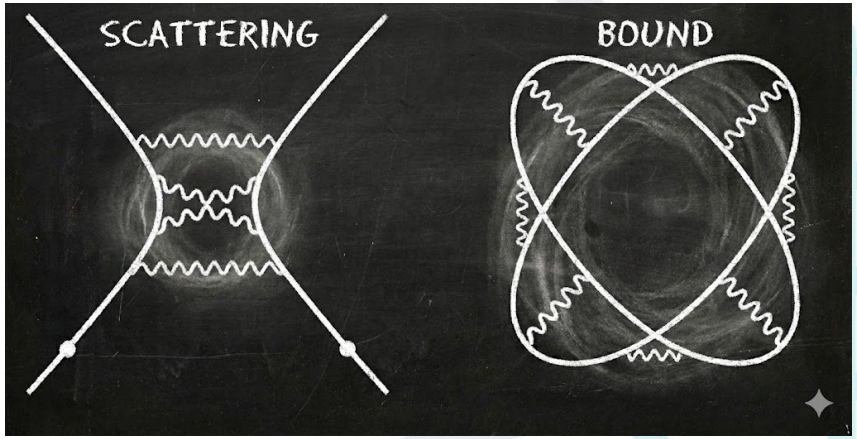
Testing QED in Bound State systems

- **Quantum Electrodynamics (QED)** is the most precise and experimentally verified theory in physics. Its predictions for simple atomic systems, especially **hydrogen**, reach astonishing accuracy.

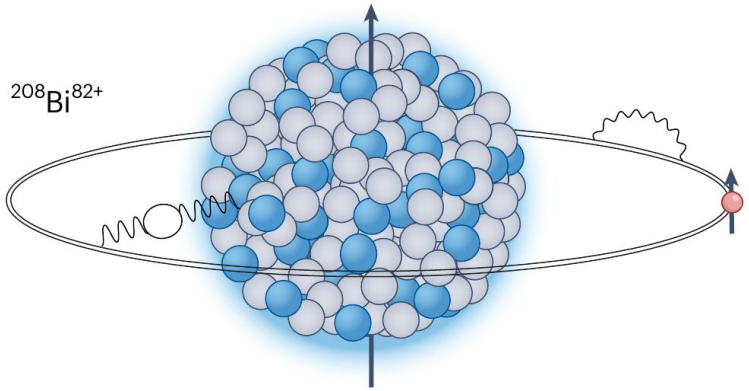
- But for **high-Z atoms**, the perturbation series in (αZ) becomes unreliable.

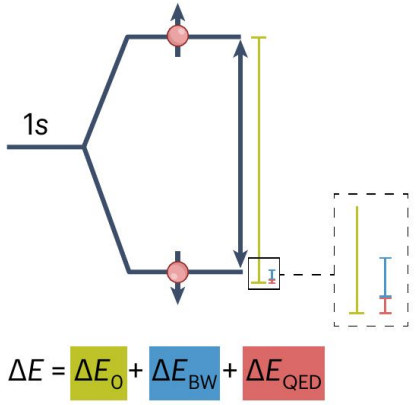
- Tests are required to evaluate **QED contributions** to the transition energies

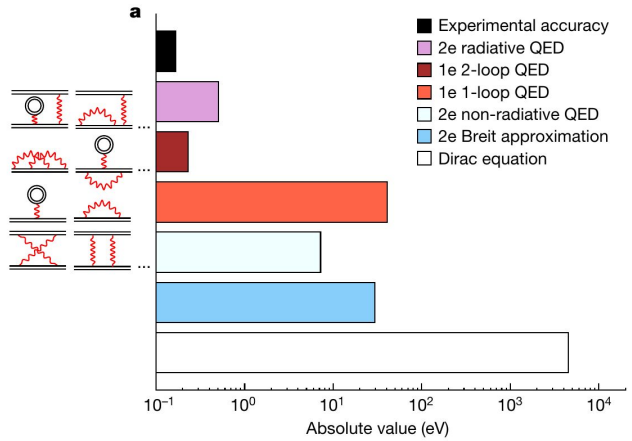
- **Bound State systems** can be used to such scope due to enhanced interaction among particles



Testing QED in Bound State systems



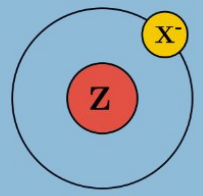




- **Laser:** High power lasers reach very intense fields suitable for **strong field studies.**
- **Highly Charged Ions:** Few electron **high-Z ions generate extreme electric fields** while keeping a simple atomic structure (H-like, He-like, Li-like)
- **Exotic Atoms:** Atoms where an electron is replaced by a heavier particle such as a **muon, pion, kaon, or antiproton** providing clean systems for precision QED tests.

Bound-State QED calculations

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)

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

- Klein-Gordon Equation (spin-0 particles)

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

Multi-Configuration Dirac-Fock:

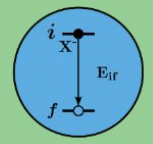
$$\Psi=\sum_{v=1}^{NCF}W_v\phi^v(1,2,...,N;J,J_z)$$

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

Total Energies Contributions:

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

Output Quantities



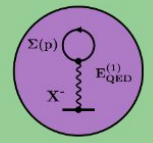
Energy Levels & Transitions



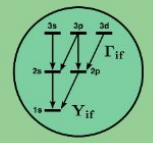
Radiative Transition Probabilities



Auger Decay Rates



QED Self-Energy & Vacuum Polarization

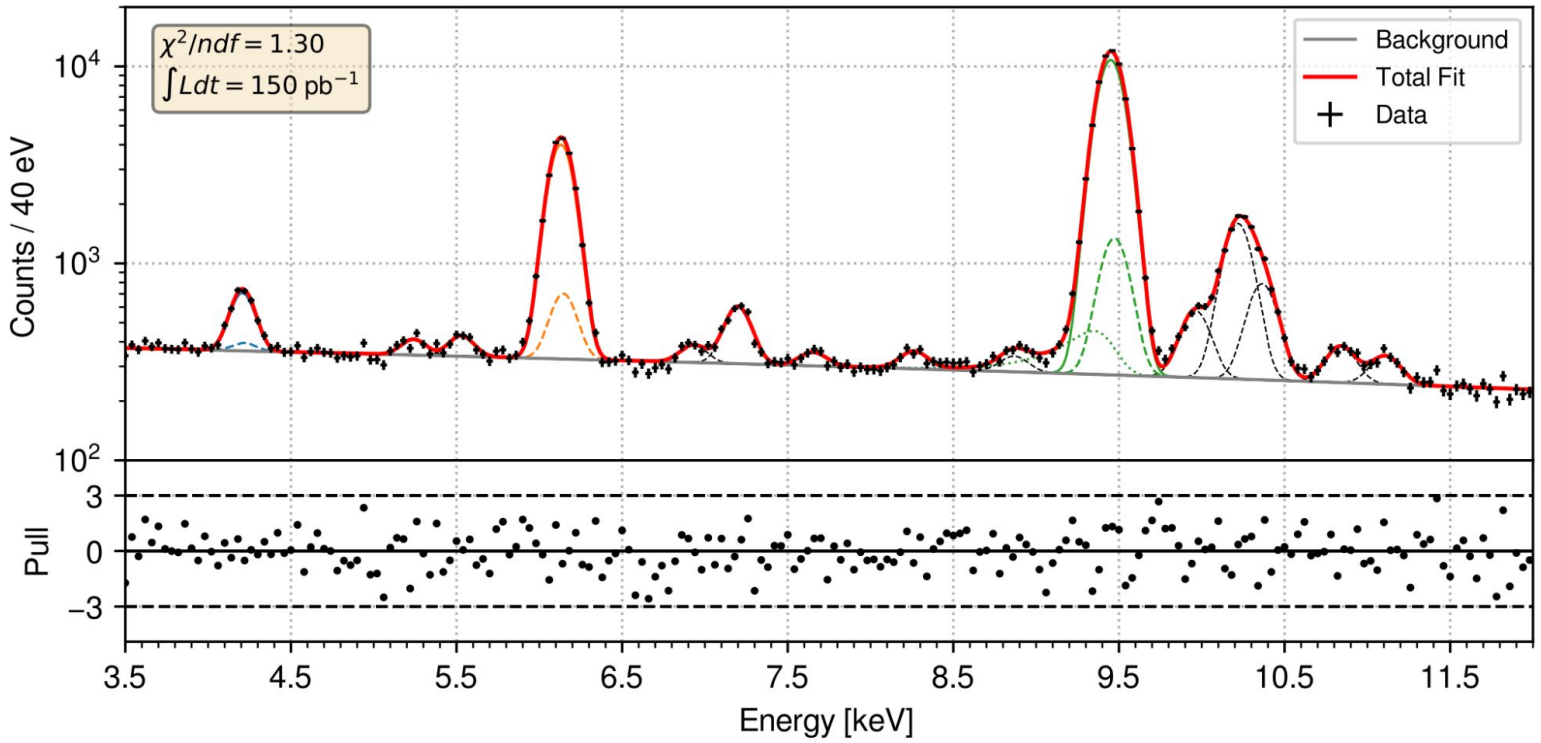


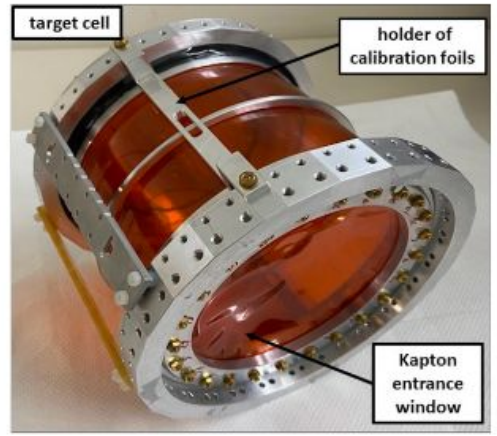
Parameters for Atomic Cascade

see Paul Indelicato's talk on Thursday morning!

Kaonic Neon X-ray spectrum

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**.





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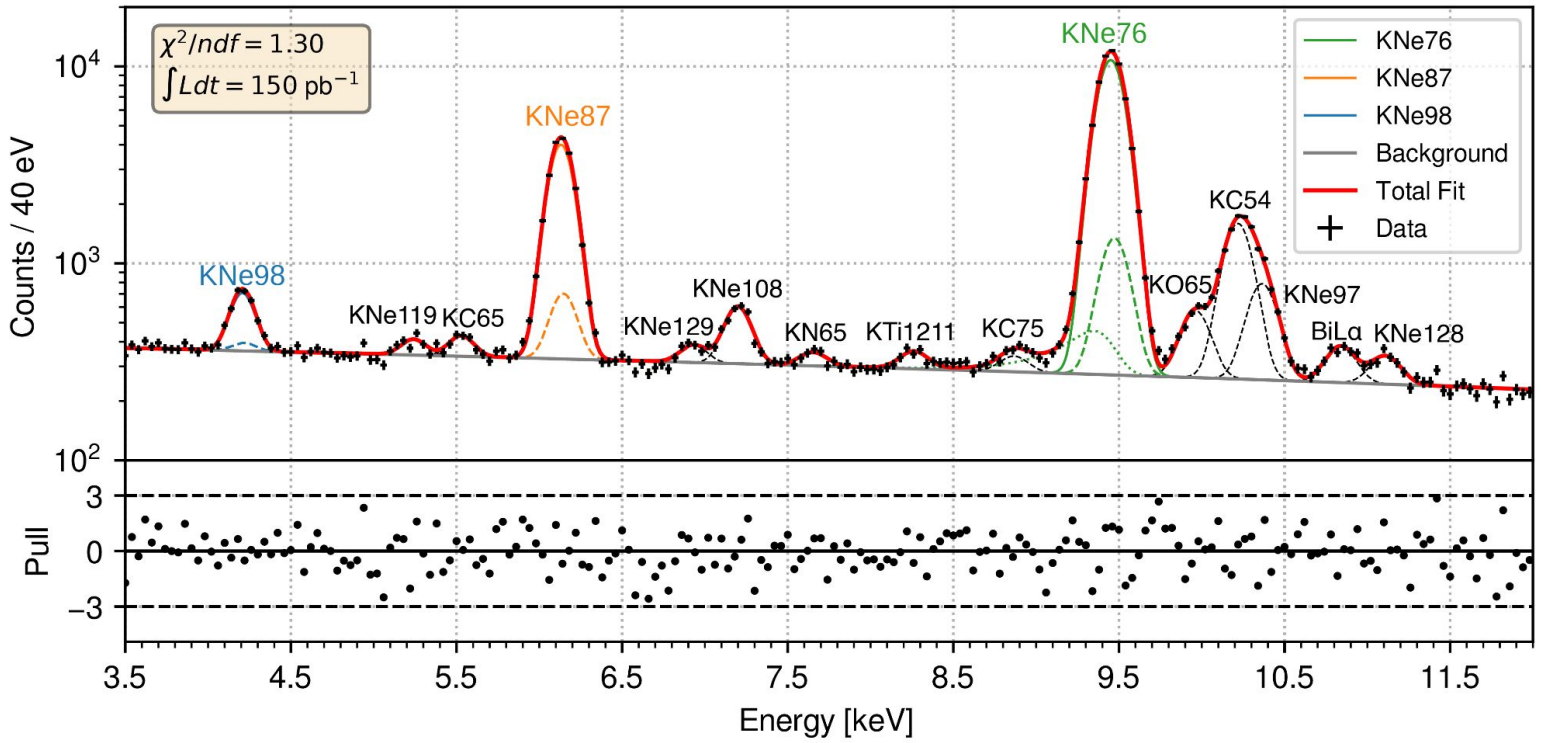
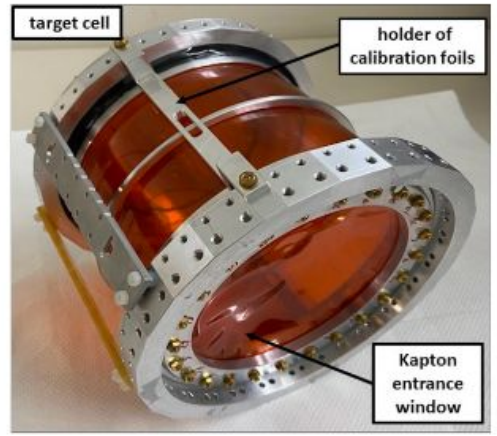


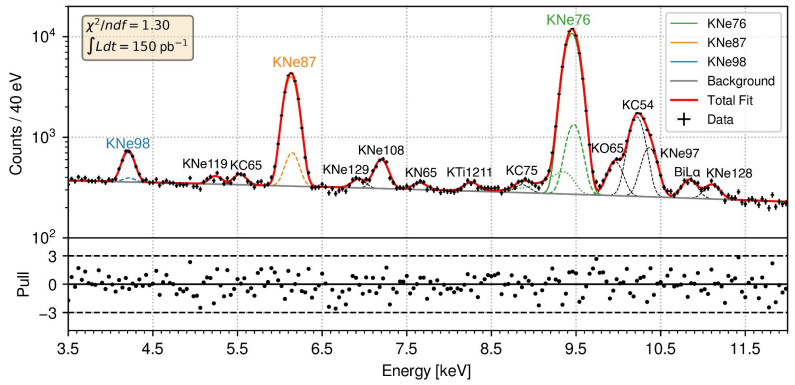


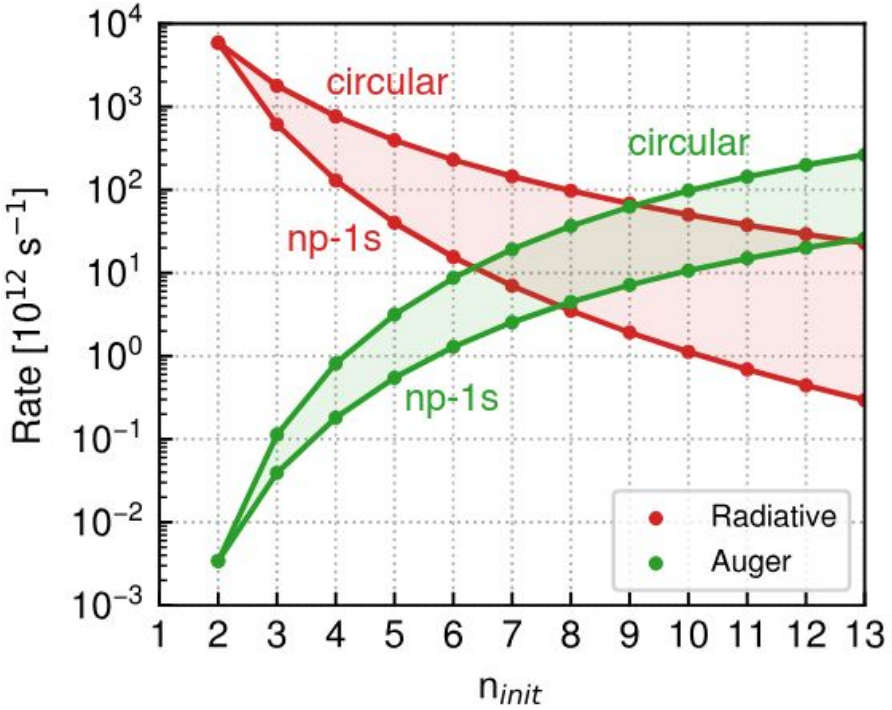
Kaonic Neon X-ray spectrum

- **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**
  → Currently in development

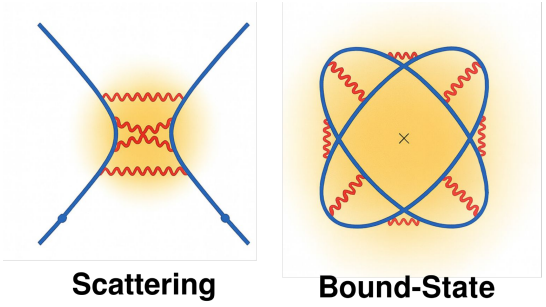
$$\Gamma^R_{n,l\to n',l\pm1} = \frac{4\mu Z^4}{3}\alpha^3 \left|R^{n,l}_{n',l\pm1}\right|^2 (\Delta E_{if})^3$$

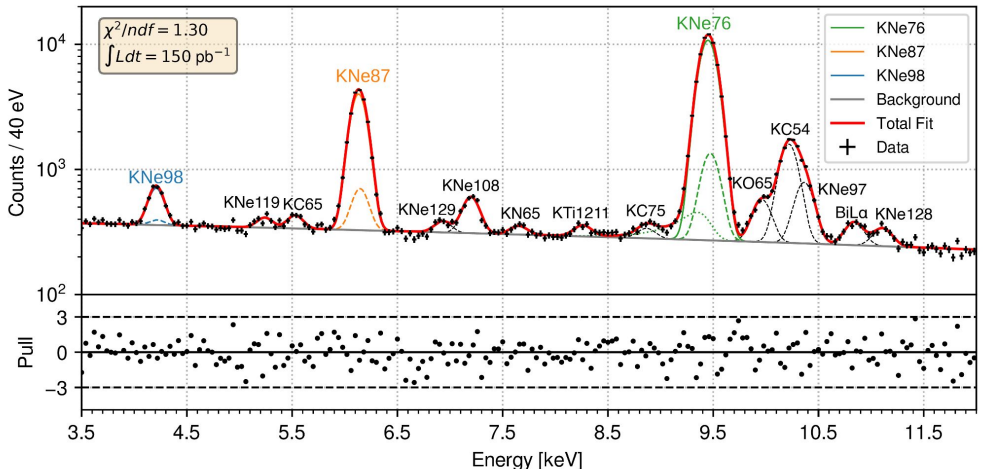
$$\Gamma^A_{n,l\to n',l\pm1} = \frac{32}{3}\left(\frac{Z_e}{Z}\right)^2 \frac{\pi}{\mu^2}\frac{l}{2l+1}\left|R^{n,l}_{n',l\pm1}\right|^2 \frac{y^2}{1+y^2}\frac{\exp\left[y(4\tan^{-1}y-\pi)\right]}{\sinh(\pi y)}$$



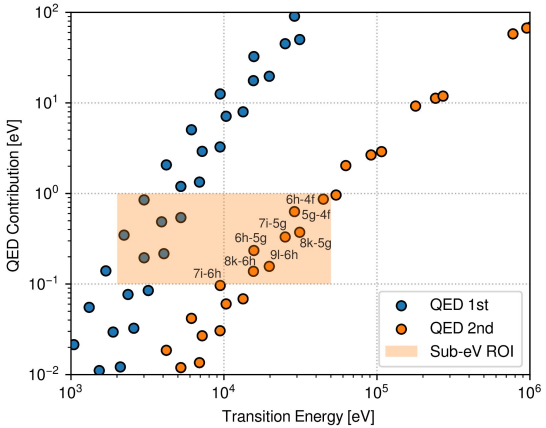


Bound-state QED with kaonic atoms





- **Dirac-Fock vs Data** in KNe show **Negligible Nuclear Effects** (FNS, Recoil, QCD Shifts).
- **BSQED Contributions** exceed experimental uncertainties **(~8σ for the 7i-6h)**
- For KNe many transitions **2nd Order QED contributions** lie in the **sub-eV ROI**, enabling **Precision BSQED Tests**.



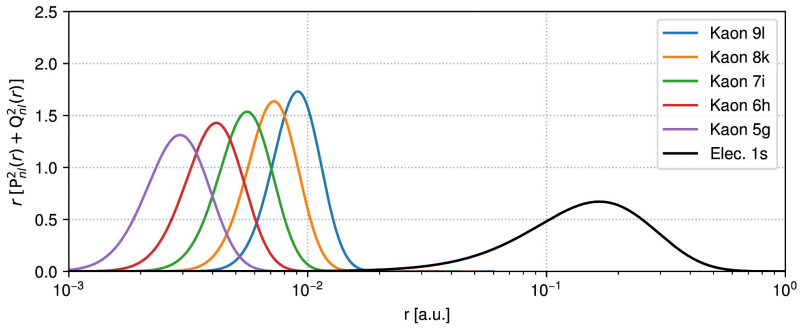
Transition	$E_{if}^{(exp.)}$	$\delta E_{if}^{(stat.)}$	$\delta E_{if}^{(sys.)}$	$E_{if}^{(calc.)}$	$E_{if}^{(QED)}$	$E_{if}^{(QED1)}$	$E_{if}^{(QED2)}$
9l-8k	4206.97	3.43	2.00	4201.45	2.09	2.07	0.02
8k-7i	6130.57	0.65	1.50	6130.31	5.09	5.05	0.04
7i-6h	9450.23	0.37	1.50	9450.28	12.66	12.56	0.10
6h-5g[a]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

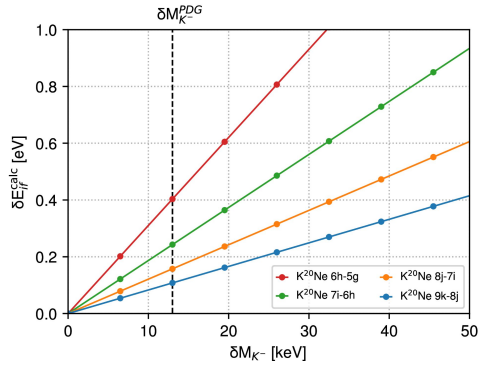
Electronic screening and kaon mass

- 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.

Transition	$E_{if}^{(exp.)}$	$\delta E_{if}^{(stat.)}$	$\delta E_{if}^{(sys.)}$	$E_{if}^{(calc.)}$	$E_{if}^{(QED)}$	$E_{if}^{(QED1)}$	$E_{if}^{(QED2)}$	$\Delta E_{if}^{(isot.)}$	$\Delta E_{if}^{(screen.)}$	$\Delta E_{if}^{(PDG)}$
9l-8k	4206.97	3.43	2.00	4201.45	2.09	2.07	0.02	9.90	-0.38	0.11
8k-7i	6130.57	0.65	1.50	6130.31	5.09	5.05	0.04	14.45	-0.27	0.16
7i-6h	9450.23	0.37	1.50	9450.28	12.66	12.56	0.10	22.28	-0.18	0.24
6h-5g[a]	15673.30	0.52	9.00	15685.39	32.75	32.51	0.24	37.01	-0.11	0.40

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

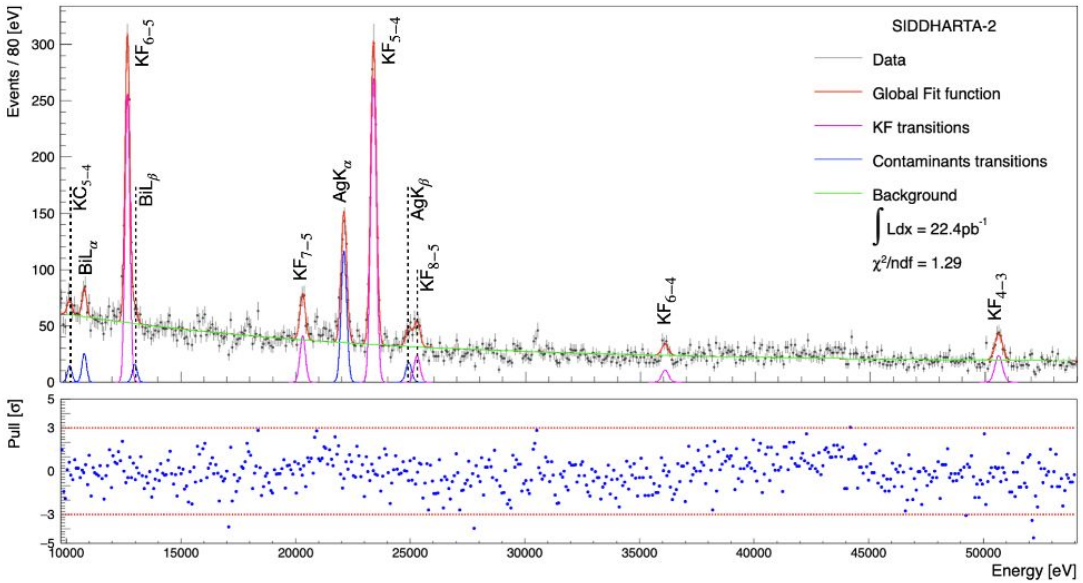




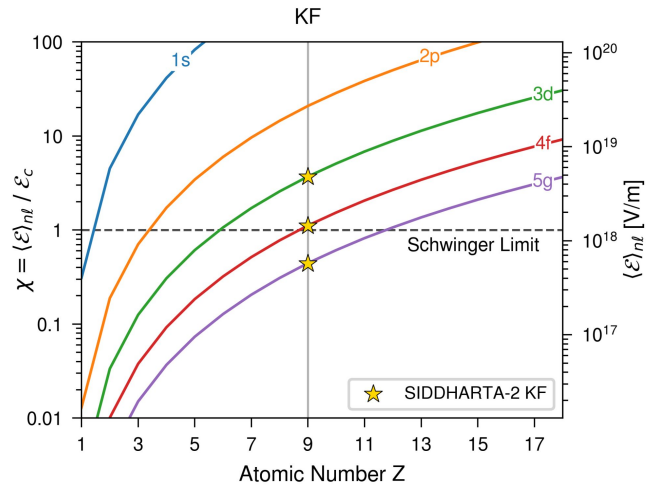
Manti, S., et al. "Precision test of bound-state QED at intermediate Z with kaonic neon." *Physical Review A* 113.2 (2026)

Strong-field QED with Kaonic Atoms

- Interest in Studying **QED in Strong Fields with Exotic Atoms** (e.g., **Antiprotons** with PAX@CERN, **Muons** at J-PARC)
- Search for Transitions where the **Electric Field** experienced by the Exotic Particle Exceeds the **Schwinger Limit E_c**



$$E_c = \frac{m_e^2 c^3}{q_e \hbar} \approx 1.32 \times 10^{18} V/m$$



Clozza, F., (2026). Bound-state QED test above the Schwinger limit with kaonic fluorine. *arXiv preprint arXiv:2604.19387.*

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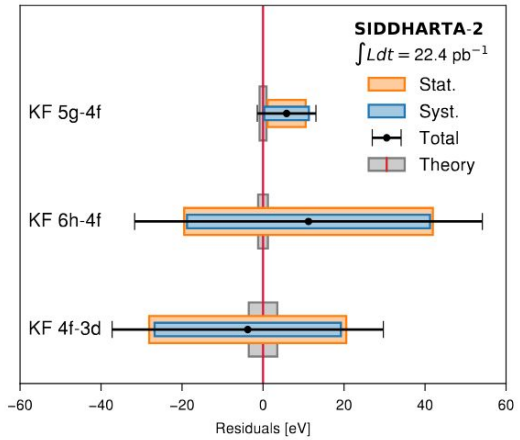
- Search for Transitions where the **Electric Field** experienced by the Exotic Particle Exceeds the **Schwinger Limit E_c**

Line	$E_{if}^{(\mathrm{exp.})} \pm (\mathrm{stat.}) \pm (\mathrm{sys.})$	$E_{if}^{(\mathrm{calc.})}{}^{+\delta_{if}^{+}}_{-\delta_{if}^{-}}$	$E_{if}^{(\mathrm{QED})}$
6h–5g	$12673.9 \pm 5.9 \pm 7.1$	$12684.69^{+0.42}_{-0.43}$	23.49
7i–5g	$20298.8 \pm 16.3 \pm 6.0$	$20327.49^{+0.59}_{-0.64}$	32.26
5g–4f	$23383.2 \pm 4.7 \pm 5.5$	$23377.38^{+1.06}_{-1.06}$	67.54
8k–5g	$25279.6 \pm 36.2 \pm 5.0$	$25285.56^{+0.70}_{-0.85}$	35.65
6h–4f	$36073.3 \pm 30.7 \pm 30.0$	$36062.07^{+1.27}_{-1.28}$	91.02
4f–3d	$50586.7 \pm 24.3 \pm 23.0$	$50590.48^{+4.36}_{-4.36}$	222.99

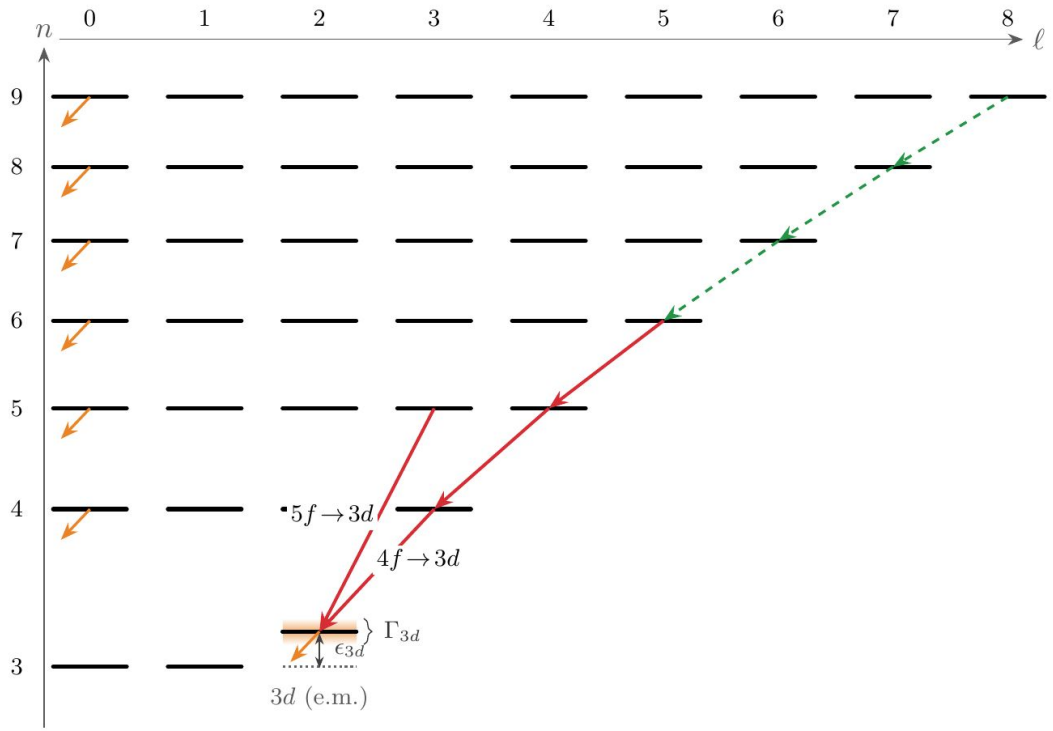


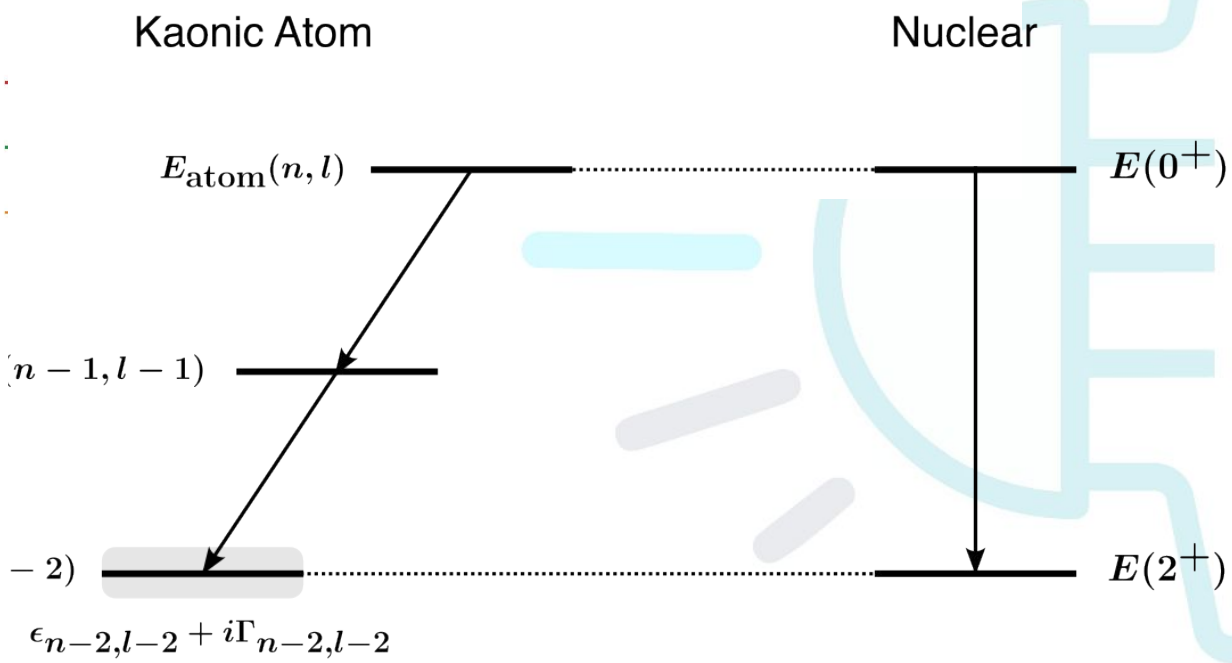
Significant BSQED contribution due to the Nonlinear Dependence of **VP Diagrams** on the Electric Field Strength **(~9σ for 5g-4f with only 22.4 pb^{-1} ~ 2 days)**

Clozza, F., (2026). Bound-state QED test above the Schwinger limit with kaonic fluorine. *arXiv preprint arXiv:2604.19387.*

Probing Nuclear Structure with kaonic atoms

Measurement of Strong Interaction Shift and Width for a given level is only possible by measuring x-rays for a transition where the level is involved! **(e.g. KB ϵ_{2p} and Γ_{2p} only with E(3d-2p))**



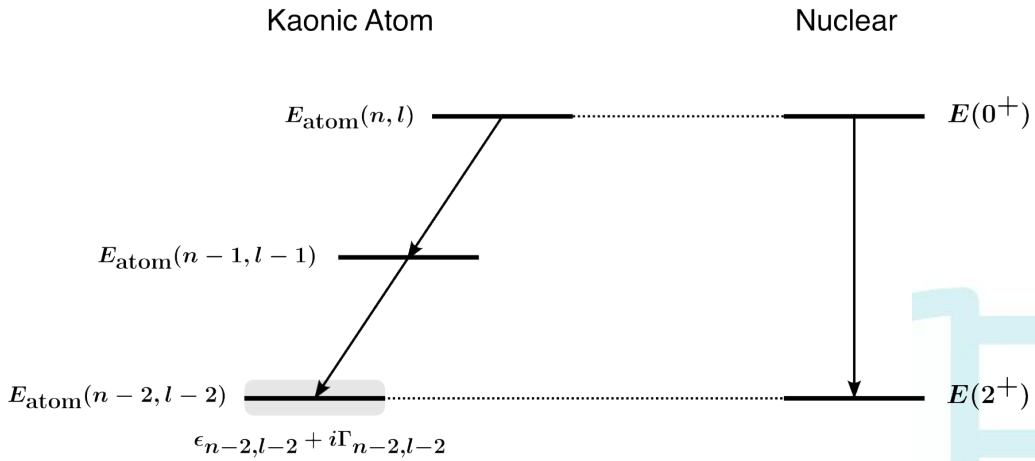


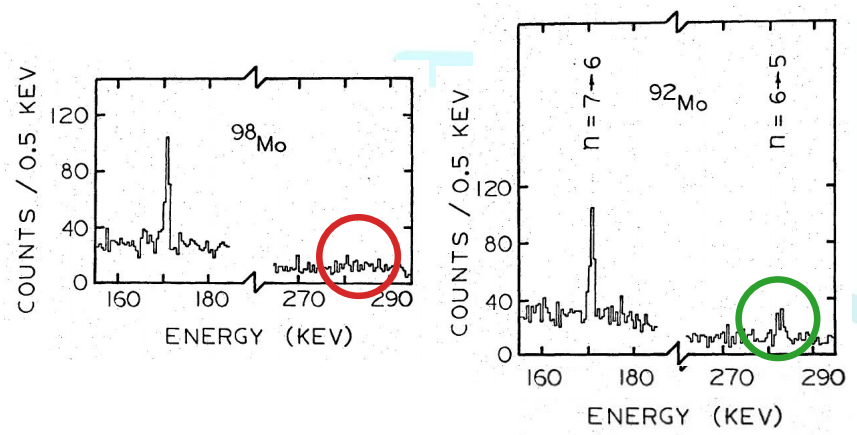
Probing Nuclear Structure with kaonic atoms

- With the **E2 Nuclear Resonance Mixing** is possible to observe strong interaction effect for a level which normally is not observable **(KMo ϵ_{4f} and Γ_{4f} with E(6h-5g))**

- The **E2 Nuclear Resonance Mixing** is inducing **Attenuation** in **Resonant Isotopes** compared to **Non-Resonant ones**

- **Old ~1976 and Inconclusive measurement in KMo** (Attenuation in 6h-5g ~0.16+-0.16)





Godfrey, Gary L., Gary K. Lum, and Clyde E. Wiegand. "Observation of dynamic e2 mixing via kaonic x-ray intensities." *Physics Letters B* 61.1 (1976): 45-46.

E2 Nuclear Resonance Mixing

- KMo as benchmark for E2 resonance, revisiting **inconclusive 1975 measurements** with **modern calculations (MCDFGME)** and **detectors (HPGe)**

$$A = \frac{I^*(n,l;n-1,l-1)}{I(n,l;n-1,l-1)} \simeq \left(1 + \frac{\Gamma^{\text{ind}}_{n,l}}{\Gamma^{\text{rad}}_{n,n-1}}\right)^{-1}, \qquad \Gamma^{\text{ind}}_{n,l} = |\alpha|^2 \Gamma_{n-2,l-2}, \quad \alpha = \frac{\langle H_Q \rangle}{\Delta - i\Gamma/2}$$

- Isotopic comparison enables direct extraction of **Induced Widths** via **Resonant vs Non-Resonant intensity ratios**

Isotope	$E_{\text{atom}}(6h-4f)$ [keV]	ϵ_{4f} [eV]	Γ_{4f} [keV]	$E(0^+ \to 2^+)$ [keV]	$B(E2;0^+ \to 2^+)$ [e^2b^2]
K^{92}Mo	808.59	−12.65	23.88	1509.490 ± 0.030	0.097 ± 0.006
K^{98}Mo	808.84	−14.00	27.90	787.384 ± 0.013	0.267 ± 0.009

Isotope	Δ [keV]	$\lvert\alpha\rvert$	$\Gamma^{ind.}_{6h}$ [eV]	$\Gamma^{rad.}_{6h-5g}$ [eV]
K^{92}Mo	700.9	0.00092 ± 0.00003	0.0201 ± 0.0012	3.30
K^{98}Mo	-21.5	0.0276 ± 0.0005	21.20 ± 0.71	3.31

Manti, S. et al., "Probing Nuclear Structure with Kaonic Atoms through E2 Resonance Mixing," PoS CORFU2025 (2026) 057. DOI: 10.22323/1.509.0057

- **High-throughput search of E2 resonance** across isotopes using kaonic atoms energies and nuclear data to identify unexplored near-degeneracy cases ($\Delta \approx 0$)

- **Impact of KM on ^{98}Mo and ^{100}Mo:** constraints on **RMS neutron radius** and input to **Double-Beta Decay** matrix elements!

Beyond Standard Model physics sensitivity

- The high yields and achieved precision in Kaonic Neon transition attracted theorist to put constrains on BSM physics
- Studying BSM with **Yukawa Coupling** shift on the transition:

$$V_X(r) = -\frac{g_H^X g_N^X}{4\pi}\frac{e^{-m_X r}}{r} \qquad h_n^X(m_X) \equiv \left\langle \frac{e^{-m_X r}}{r} \right\rangle_n = \frac{1}{r_n}\left(1+\frac{m_X r_n}{2n}\right)^{-2n}$$

$$\Delta E_{if}^X = -\frac{g_H^X g_N^X}{4\pi}\Delta h_{if}^X(m_X) \qquad \Delta h_{if}^X(m_X) = h_{n_i}^X(m_X) - h_{n_f}^X(m_X)$$



Tobia Vecchiatto Montorio



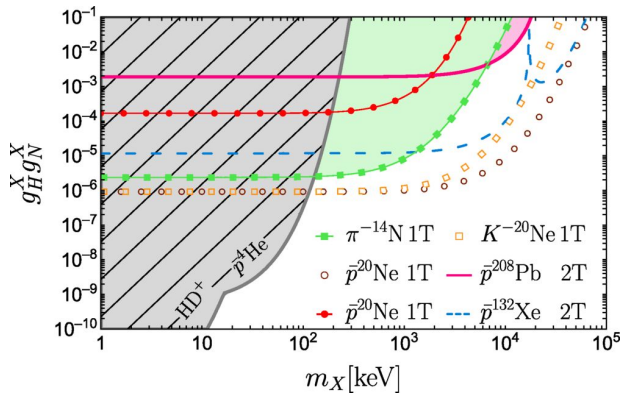
Prof. Francesco D'Eramo

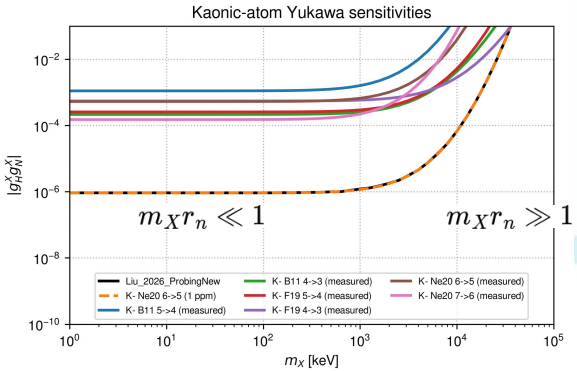
$$\mu = \frac{m_H m_N}{m_H + m_N} \qquad r_n = \frac{n^2}{Z\alpha\mu}$$

- **Sensitivity of the BSM shift** should not exceed **~qσ$_{if}$** (q=2)

$$\left|g_H^X g_N^X\right|_{\text{sens}} = \frac{4\pi q\,\sigma_{if}}{\left|\Delta h_{if}^X(m_X)\right|}$$

$$\sigma_{if} = \sqrt{\sigma_{\text{stat}}^2 + \sigma_{\text{syst}}^2}$$





see Tobia Vecchiatto Montorio's talk on Thursday afternoon!

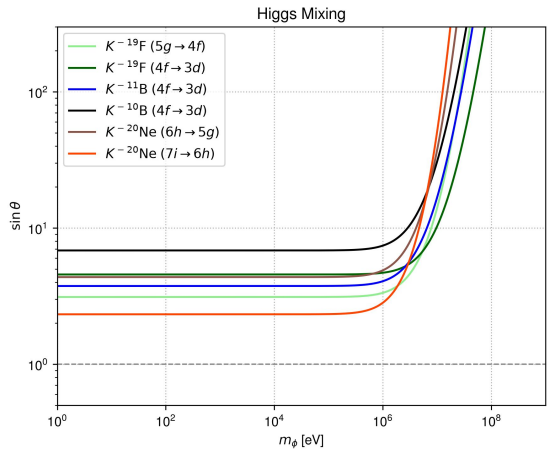
Model-dependent energy shifts

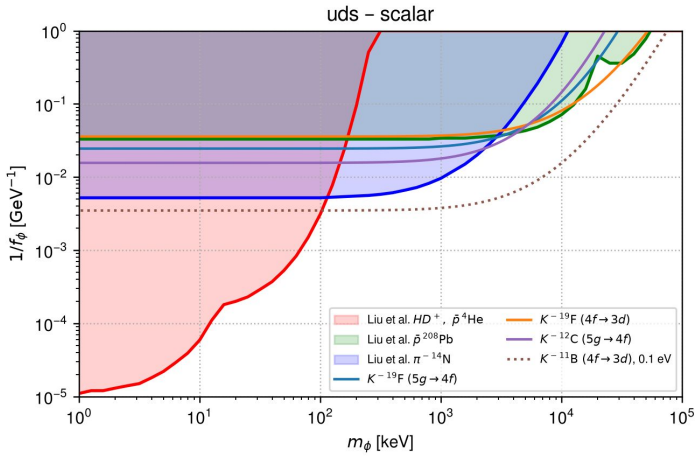
- Each one predicts a **Model-dependent Energy Shift** for **Kaonic-Atom Transitions**
- Model **Shift** and **Sensitivity**:

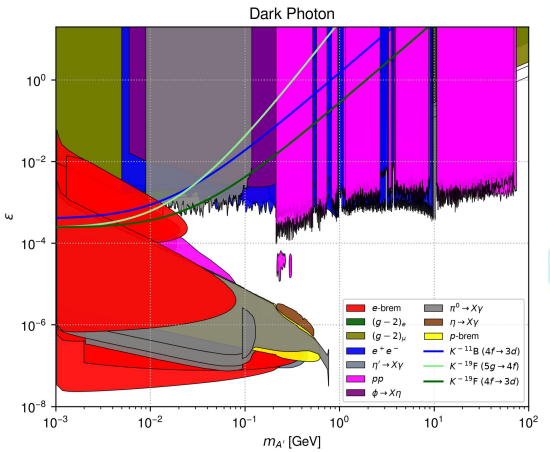
$$\Delta E_{if}^{\mathrm{BSM}}(m_X, \theta) = K_{if}^{M}(m_X)\,\theta^2$$

$$\theta_{\mathrm{sens}}(m_X) = \sqrt{\frac{q\,\sigma_E}{\left|K_{if}^{M}(m_X)\right|}}$$

Model	Mediator / Coupling	Constrained parameter θ
Higgs-Mixed Scalar	Scalar; SM-like mass couplings	$\sin\theta_H$
UDS Scalar	Scalar; Universal u,d,s coupling	$1\ /\ f_\phi$
Gluonic ALP	Spin-0 ALP; CP-violating scalar gluon coupling	$C_g\ /\ \Lambda$
Dark Photon	Vector; Electromagnetic-current coupling	ε
Protophobic Vector	Vector; Suppressed proton coupling	ε_B







see Tobia Vecchiatto Montorio's talk on Thursday afternoon!

Beyond SIDDHARTA-2

Except for the most recent measurements at DAFNE and JPARC on KHe and KH, the database on kaonic atoms dates back to 1970s and 1980s. These measurements are the basis for all the theoretical model used for: $K\bar{N}$, $K\bar{N}N$ interaction at threshold, Kaon mass, Kaonic atoms cascade models

Present status:

- The available data on **"lower levels"** have **large uncertainties**
- Many of them are actually **unmeasured**
- Many of them are **hardly compatible** among each other
- **Absolute yields** are unknown (except for few transitions)

This situation is a proper justification for a new era of **kaonic atoms measurements**

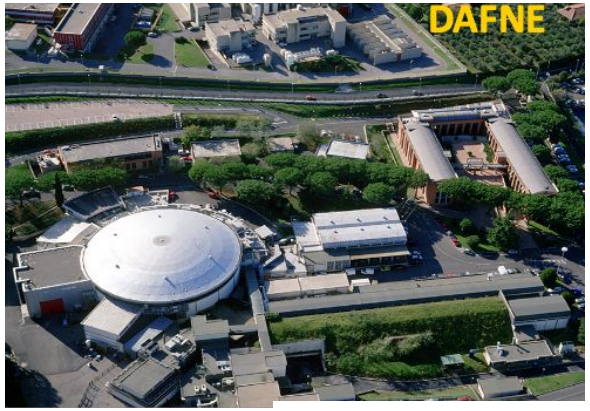
Table 1
Compilation of K^- atomic data

Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)	Ref.
He	3→2	−0.04 ±0.03	–	–	–	[15]
		−0.035±0.012	0.03 ±0.03	–	–	[16]
Li	3→2	0.002±0.026	0.055±0.029	0.95±0.30	–	[17]
Be	3→2	−0.079±0.021	0.172±0.58	0.25±0.09	0.04±0.02	[17]
^{10}B	3→2	−0.208±0.035	0.810±0.100	–	–	[18]
^{11}B	3→2	−0.167±0.035	0.700±0.080	–	–	[18]
C	3→2	−0.590±0.080	1.730±0.150	0.07±0.013	0.99±0.20	[18]
O	4→3	−0.025±0.018	0.017±0.014	–	–	[19]
Mg	4→3	−0.027±0.015	0.214±0.015	0.78±0.06	0.08±0.03	[19]
Al	4→3	−0.130±0.050	0.490±0.160	–	–	[20]
		−0.076±0.014	0.442±0.022	0.55±0.03	0.30±0.04	[19]
Si	4→3	−0.240±0.050	0.810±0.120	–	–	[20]
		−0.130±0.015	0.800±0.033	0.49±0.03	0.53±0.06	[19]
P	4→3	−0.330±0.08	1.440±0.120	0.26±0.03	1.89±0.30	[18]
S	4→3	−0.550±0.06	2.330±0.200	0.22±0.02	3.10±0.36	[18]
		−0.43 ±0.12	2.310±0.170	–	–	[21]
		−0.462±0.054	1.96 ±0.17	0.23±0.03	2.9 ±0.5	[19]
Cl	4→3	−0.770±0.40	3.80 ±1.0	0.16±0.04	5.8 ±1.7	[18]
		−0.94 ±0.40	3.92 ±0.99	–	–	[22]
		−1.08 ±0.22	2.79 ±0.25	–	–	[21]
Co	5→4	−0.099±0.106	0.64 ±0.25	–	–	[19]
Ni	5→4	−0.180±0.070	0.59 ±0.21	0.30±0.08	5.9 ±2.3	[20]
		−0.246±0.052	1.23 ±0.14	–	–	[19]
Cu	5→4	−0.240±0.220	1.650±0.72	0.29±0.11	7.0 ±3.8	[20]
		−0.377±0.048	1.35 ±0.17	0.36±0.05	5.1 ±1.1	[19]
Ag	6→5	−0.18 ±0.12	1.54 ±0.58	0.51±0.16	7.3 ±4.7	[19]
Cd	6→5	−0.40 ±0.10	2.01 ±0.44	0.57±0.11	6.2 ±2.8	[19]
In	6→5	−0.53 ±0.15	2.38 ±0.57	0.44±0.08	11.4 ±3.7	[19]
Sn	6→5	−0.41 ±0.18	3.18 ±0.64	0.39±0.07	15.1 ±4.4	[19]
Ho	7→6	−0.30 ±0.13	2.14 ±0.31	–	–	[23]
Yb	7→6	−0.12 ±0.10	2.39 ±0.30	–	–	[23]
Ta	7→6	−0.27 ±0.50	3.76 ±1.15	–	–	[23]
Pb	8→7	–	0.37 ±0.15	0.79±0.08	4.1 ±2.0	[24]
		−0.020±0.012	–	–	–	[25]
U	8→7	−0.26 ±0.4	1.50 ±0.75	0.35±0.12	45 ±24	[24]

EXKALIBUR

1.1 - High precision kaonic neon measurement
To extract the charged kaon mass with a precision of about 5 keV
BSQED and Physics beyond Standard Model

1.2 - Light kaonic atoms (LHKA)
– solid target Li, Be, B
Low energy strong interaction – kaon multi-nucleon interaction



EXKALIBUR

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



Intermediate kaonic atoms (IMKA)
In parallel we plan dedicated runs kaonic atoms such as *O, Al, S* with CdZnTe detectors
- 200 -300 pb^{-1} of integrated luminosity/target

Manti et al., "EXKALIBUR: Towards a Kaonic Atoms Periodic Table", Acta Phys. Pol. A 148, S89 (2025)

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Thanks for the Attention!

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