ÖAW AUSTRIAN ACADEMY OF SCIENCES

X-ray spectroscopy of hadronic exotic atoms and application in foundations of quantum physics

J. Marton, SMI, Vienna, Austria

8^{th} Meeting GHP- APS
April 10-12, 2019
Denver, CO, USA

https://www.lngs.infn.it/en/pagine/vip-eng

FWF
Project P25529-N20
Project P30635-N36
Project P24756-N20

WWW:OEAW.AC.AT/SMI

Introduction

- In experiments at DAFNE (SIDDHARTA2) and J-PARC (E57) we are studying kaonic atoms by X-ray spectroscopy to probe the strong interaction with strangeness at lowest energies – i.e. in kaonic atoms.

- The most simple cases of these hadronic atoms (and of high interest by theory) are kaonic hydrogen and deuterium.

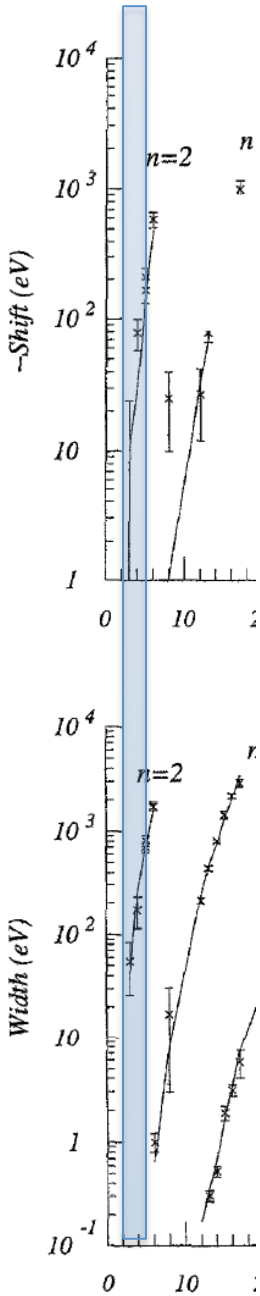
- The observables are the energy shift and width of the atomic transitions to the 1s ground state – measurable by x-ray spectroscopy (energy range 6-8 keV).

- Special semiconductor detector arrays are employed in the experiments providing large solid angle, high efficiency, high energy resolution and background reduction by timing application.

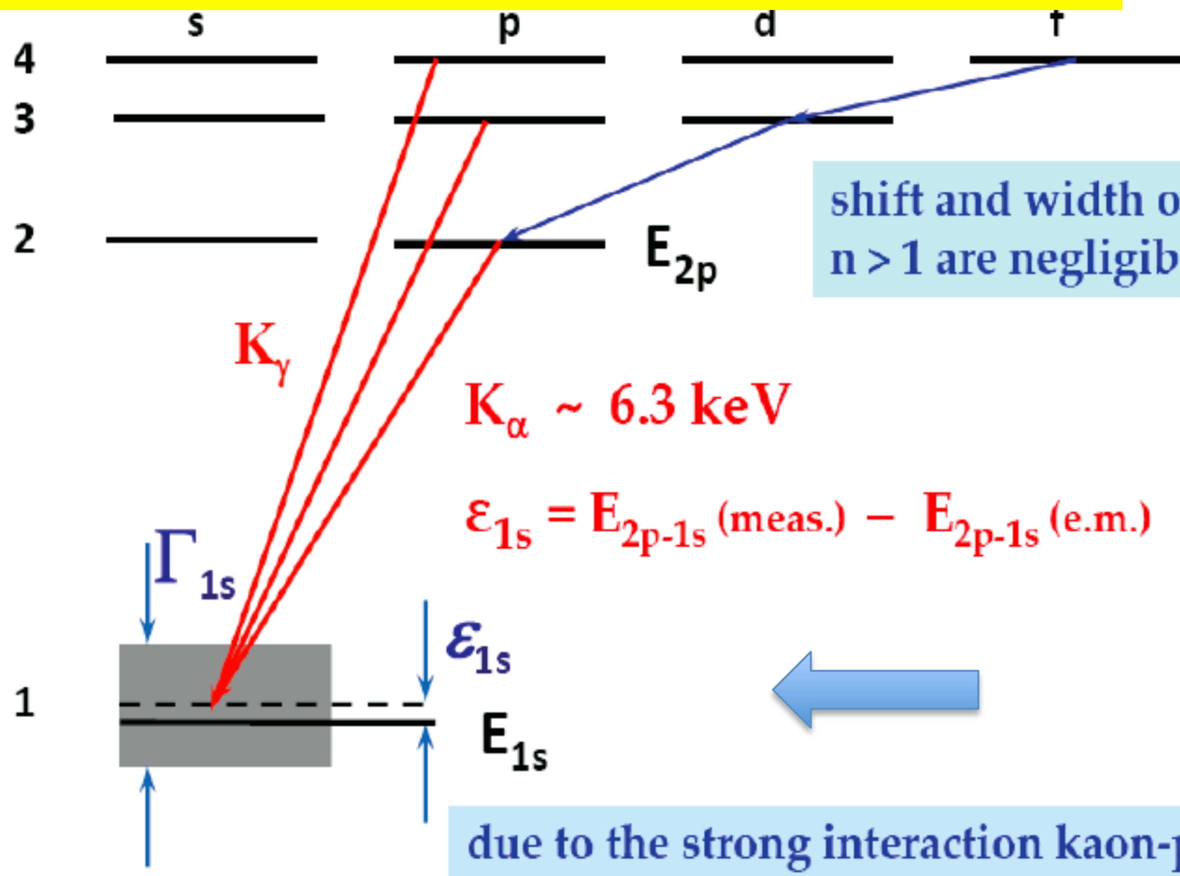
Connection to experiments on foundation of (quantum) physics

- In experiments (VIP2, VIP2-lead) in the underground laboratory Gran Sasso (INFN-LNGS) we are searching for forbidden transitions − testing spin-statistics - which has as direct consequence the Pauli-Exclusion Principle
- The energy region of this forbidden transitions in chosen elements are in the range of transitions in exotic atoms. Therefore, we can apply the same detector technology.

Simplest kaonic atoms (Z=1)



Atomic capture in high n state → subsequent e.m. cascade

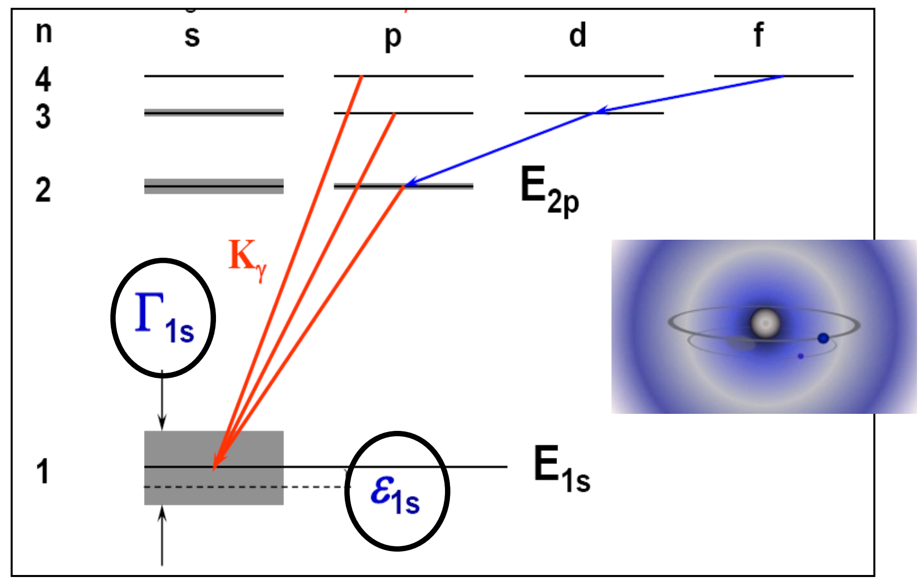


shift and width of states n > 1 are negligible

due to the strong interaction kaon-proton the 1s level is shifted and broadened

Kaonic hydrogen and deuterium

- Principal interaction = electromagnetic
- Strong interaction manifests in hadronic shift and width of the 1s state → **energy displacement** from the electromagnetic value of the 1s state and **broadening** due to K^- absorption

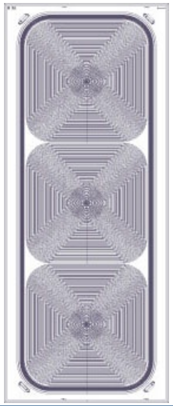


$$\varepsilon_{1s} = E_{1s}^{meas.} - E_{1s}^{e.m.(calc.)}$$

$$E_{1s}^{e.m(calc.)} = E_{KG} + E_{VP} + E_{FS}$$

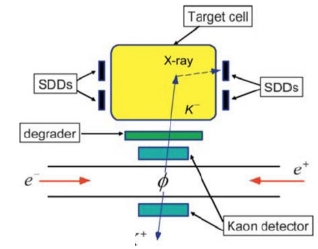
- calculated solving the Klein-Gordon (KG) equation and taking into account vacuum polarization (VP) and final size (FS) effect (accuracy ~1eV).
- Strong interaction effect on 2p state is weak (meV) and experimentally undetermined, nevertheless has severe consequences for the x-ray yield.

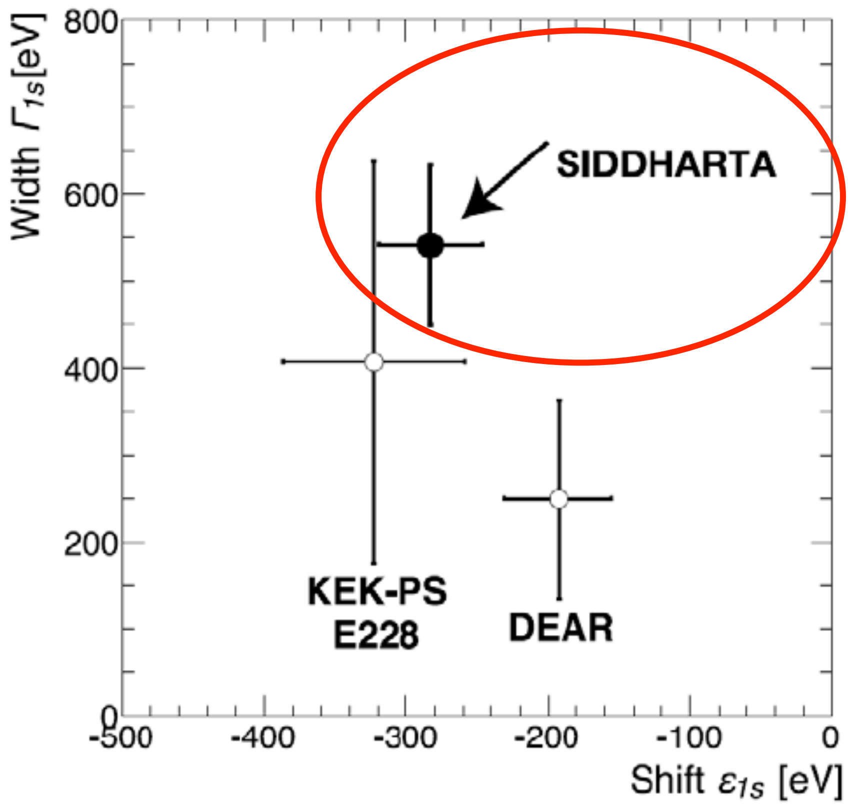
X-ray detectors for exotic atom spectroscopy

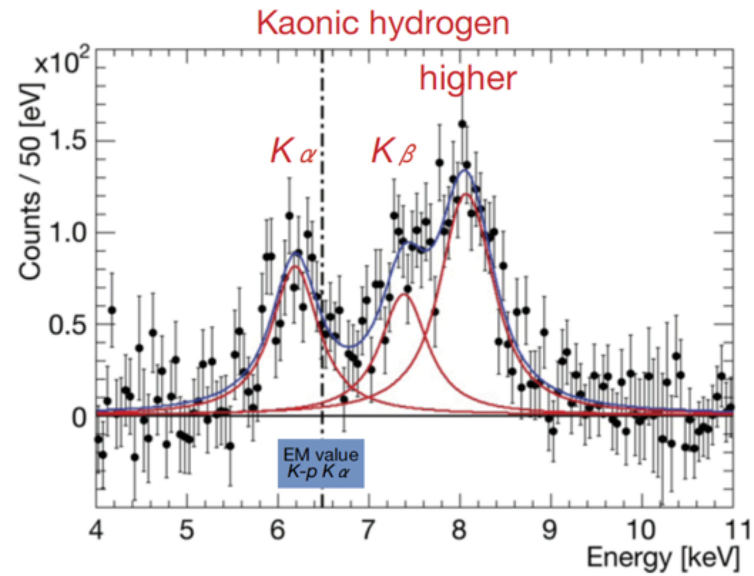


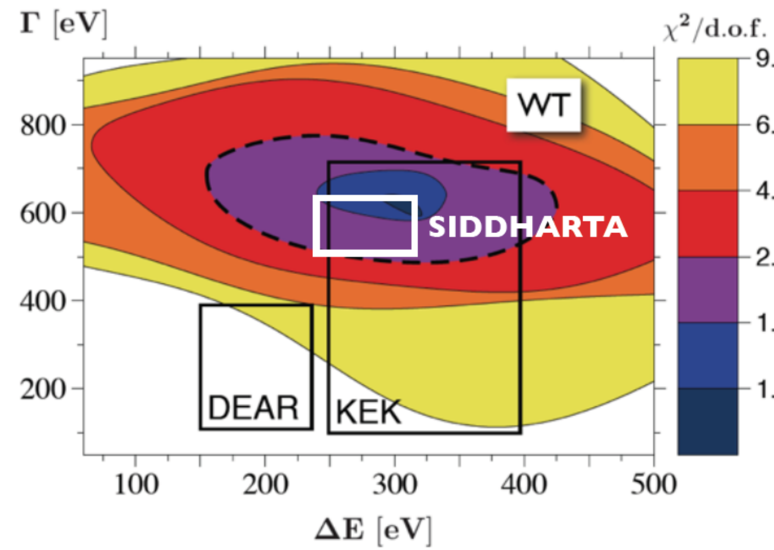
X-ray detector	Si(Li)	CCD	SDD
Effective area [mm^2]	<300	724	100
Thickness of depletion [mm]	4	0.03	0.26
Energy resolution [eV] at 6 keV	~300	~150	~150
Time resolution [ns]	~280	–	~700
Experiment	KpX	DEAR	SIDDHARTA
Number of detectors	60	16	200
Application	K^-p, $K^{-4}He$	K^-p	K^-p, $K^{-3,4}He$

$K^{-}p$ result SIDDHARTA









ε_{1S}= −283 ± 36(stat.) ± 6(syst.) eV

Γ_{1S}= 541 ± 89(stat.) ± 22(syst.) eV

Physics Letters B704 (2011) 113

Chiral SU(3) theory of antikaon-nucleon interactions with improved threshold constraints
Y. Ikeda, T. Hyodo and W. Weise, Nucl. Phys. A881 (2012) 98-114.

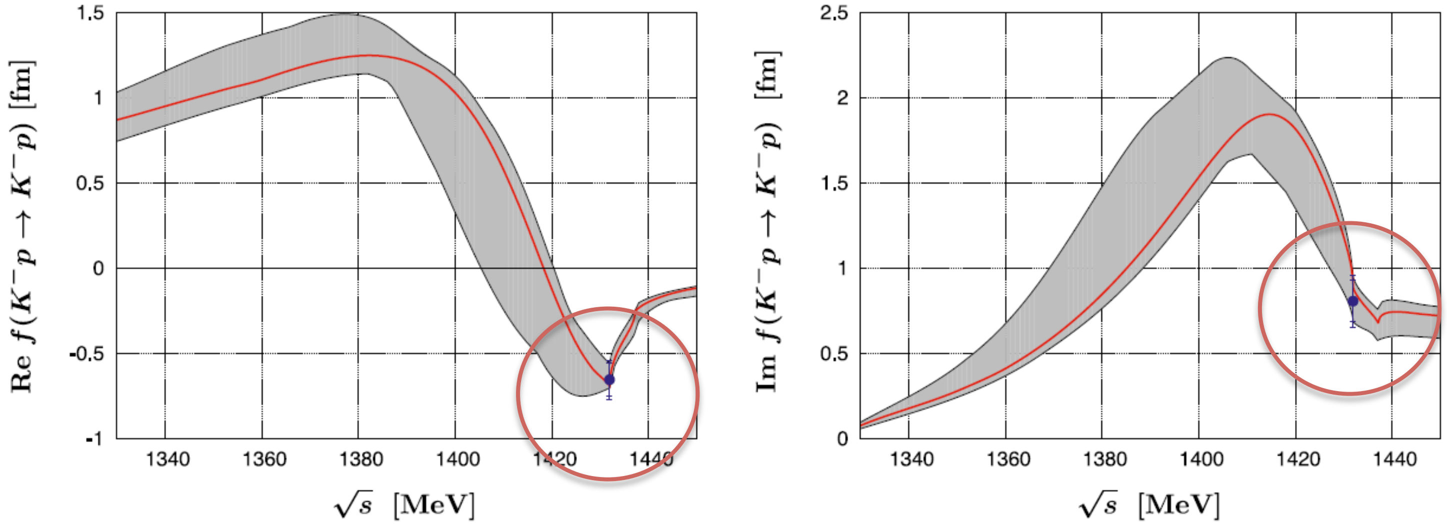


Fig. 4. Real part (left) and imaginary part (right) of the $K^-p \to K^-p$ forward scattering amplitude obtained from the NLO calculation and extrapolated to the subthreshold region. The empirical real and imaginary parts of the K^-p scattering length deduced from the recent kaonic hydrogen measurement (SIDDHARTA [15]) are indicated by the dots including statistical and systematic errors. The shaded uncertainty bands are explained in the text.

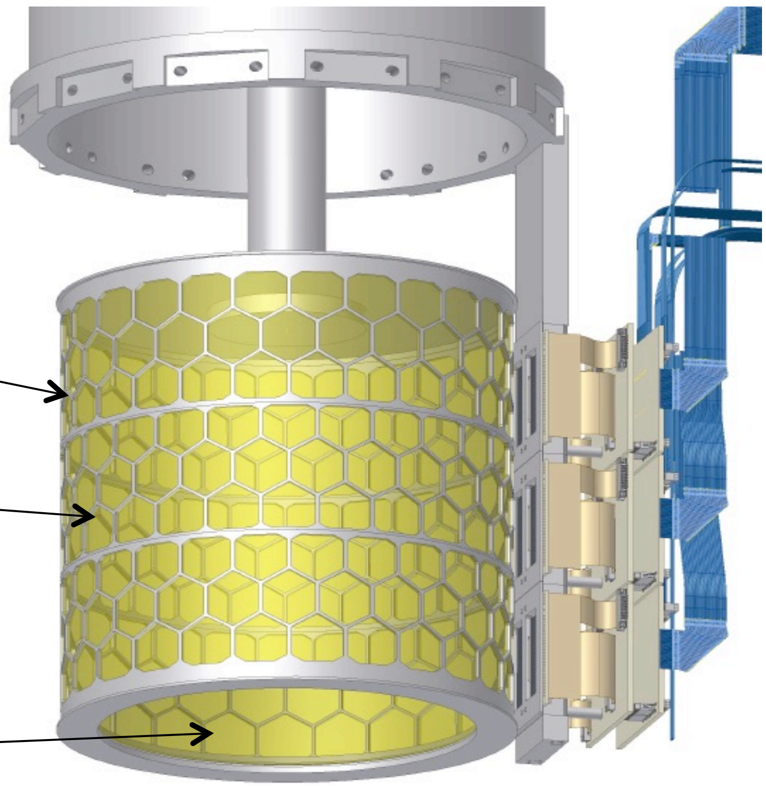
Lightweight cryogenic target (used for KH)

working T 22 K
working P 1.5 bar

Alu-grid

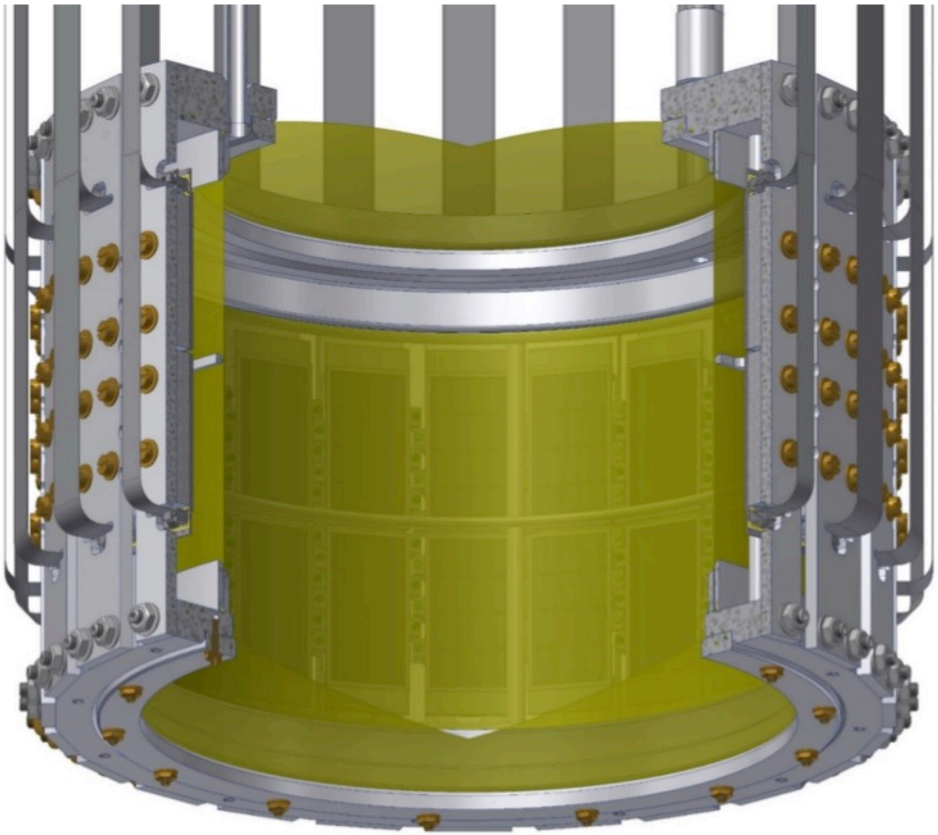
Side wall:
Kapton 50 µm

Kaon entrance
window:
Kapton 75 µm



Cryo-Target – SDD geometry

Working temperature: 30 K
Working pressure : 0.3 MPa



Final test during summer 2017:
Pressurised for 16 days
with P = 0.3 MPa (overP)

Cooling/pressure test

- 2.5 weeks 30 K / 0.19 MPa
- 3.5 days 30 K / 0.31 MPa

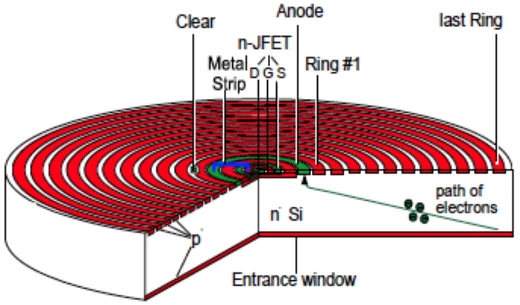
➢ Target cell wall is made of a 2-Kapton layer structure (25 μm + 25 μm + Araldit < 100 μm)

➢ **HP Deuterium generator**

SDD X-ray detectors

• JFET integrated on the SDD

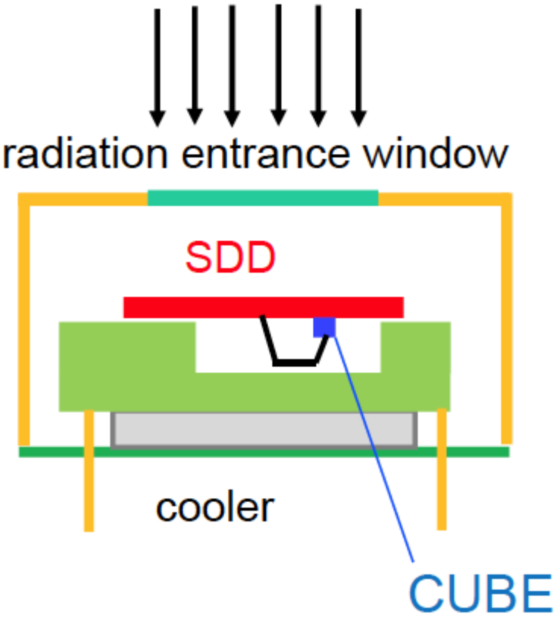
- lowest total anode capacitance
- limited JFET performances
- sophisticated SDD+JFET technology



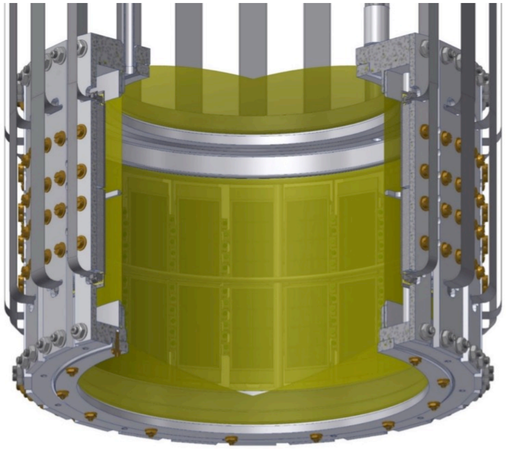
Used in Siddharta

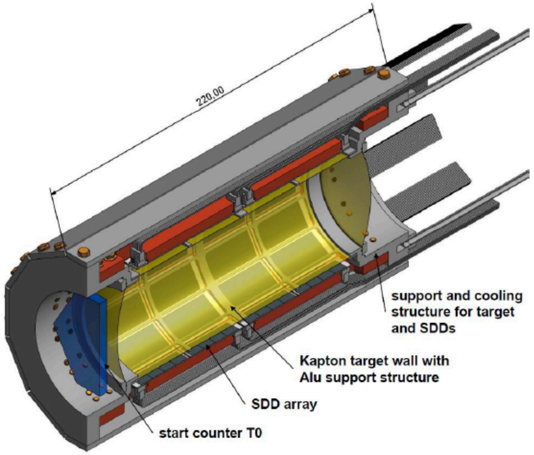
• external CUBE preamplifier (MOSFET input transistor)

- larger total anode capacitance
- better FET performances
- standard SDD technology



Proposed for kaonic deuterium measurement





SIDDHARTA2 @DAFNE

DAFNE – ideal for kaonic atoms

Kaon source (Φ decay in K^-K^+)

Low-energy kaons (127 MeV/c) ideal for stopping

No tracking

With 10 pb^{-1} per day

1.5 10^7 K- per day isotropically

2% per kaon pair stopping in gas

144 SDDs from SIDDHARTA

Kaonic deuterium (E57) @J-PARC

Kaon beam

Kaons at higher momentum (660-1000 MeV/c)

needs degrader

Tracking

With 30 kW beam power

430 10^7 K^- per day

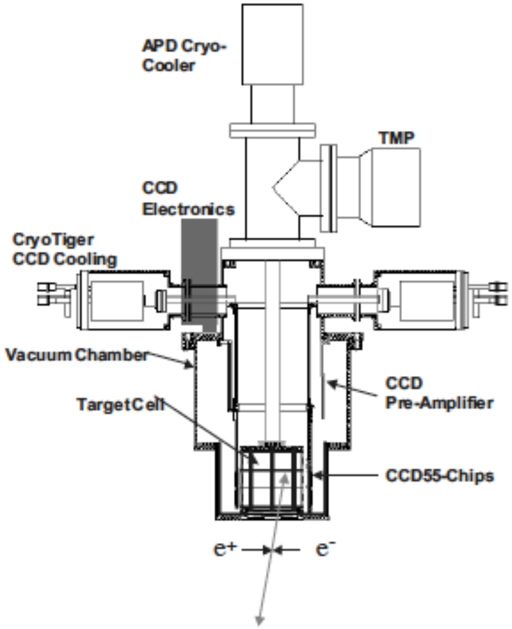
0.03% per kaon pair stopping in gas (660 MeV/c)

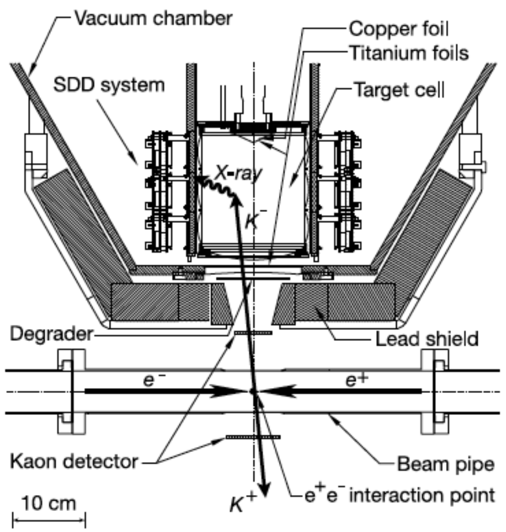
340 SDDs

X-ray Detection Systems

DEAR at DAFNE CCDs

SIDDHARTA2 at DAFNE SDDs





VIP at LNGS CCDs

VIP2 at LNGS SDDs

A

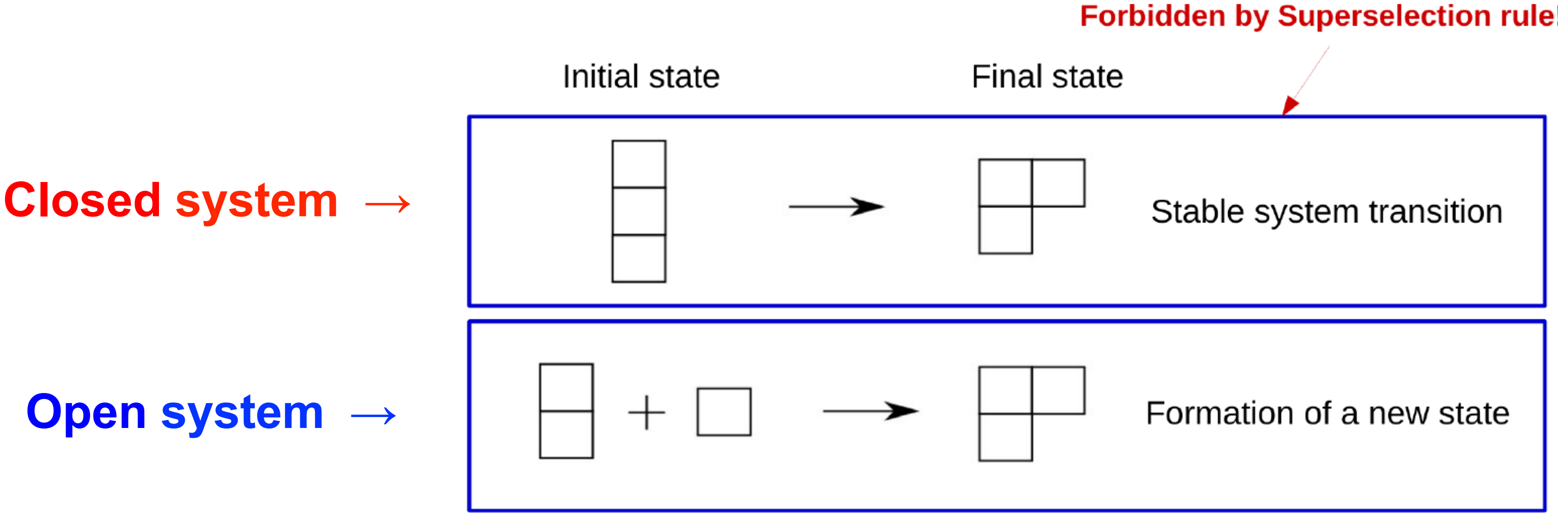
VIP-2

at LNGS Underground Laboratory

*VIP-2 **tests the Pauli Exclusion Principle** (PEP) (spin-statistics) **for electrons** in a clean environment (LNGS) using a method which respects the Messiah-Greenberg superselection rule.*

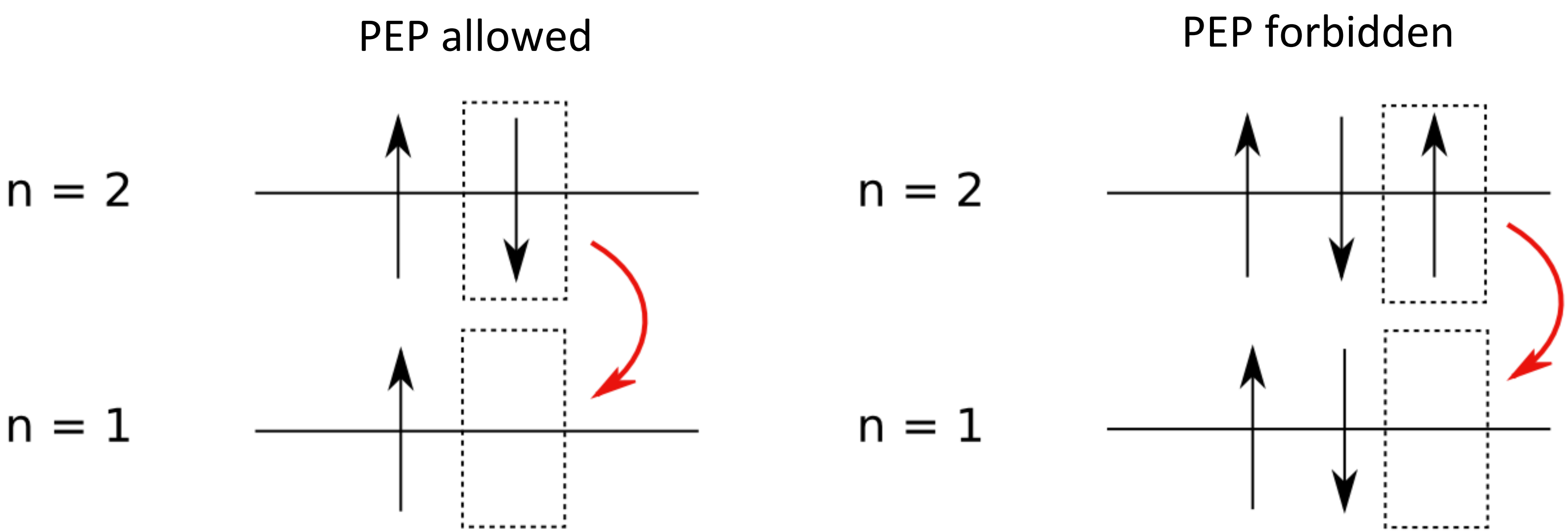
Messiah – Greenberg superselection rule

Superpositions of states with different symmetry are not allowed →
transition probability between two symmetry states is ZERO



A. M. L. Messiah and O. W. Greenberg, Phys. Rev. 136 (1964) B248.
O. W. Greenberg and A. M. L. Messiah, Phys. Rev. 138 (1965) B1155.
G. Gentile, NuovoCimento 17, 493(1940)
H. S. Green, Phys. Rev. 90 (1953) 270.
A. Y. Ignatiev and V. A. Kuzmin, JETP Lett. 47 (1988) 4.
V. N. Gavrin, A. Y. Ignatiev and V. A. Kuzmin, Phys. Lett. B 206 (1988) 343.
O.W. Greenberg, Phys. Rev. Lett. 64, 705 (1990)
R.N. Mohapatra, Phys. Lett. B 242, 407 (1990)
O.W.Greenberg, R.C.Hilborn, Fund.Phys.29, 397(1999)

Principle of VIP2



normal	PEP-forbidden
8048 eV	7747 eV

Cu $K\alpha_1$ transition energies.

$\Delta E \approx 300$ eV resolvable by X-ray spectroscopy

Requirements for VIP2

Due to the anticipated very small PEP violation effects (if any) strong requirements for experiments are obvious:

- Large number of fermions probing the PEP
- Characteristic signal (i.e. unique indicator)
- High efficient detection
- Low background

Putting the Pauli exclusion principle on trial

The exclusion principle is part of the bedrock of physics, but that hasn't stopped experimentalists from devising cunning ways to test it.

If we tightly grasp a stone in our hands, we neither expect it to vanish nor leak through our flesh and bones. Our experience is that stone and, more generally, solid matter is stable and impenetrable. Last year marked the 50th anniversary of the demonstration by Freeman Dyson and Andrew Lenard that the stability of matter derives from the Pauli exclusion principle. This principle, for which Wolfgang Pauli received the 1945 Nobel Prize in Physics, is based on ideas so prevalent in fundamental physics that their underpinnings are rarely questioned. Here, we celebrate and reflect on the Pauli principle, and survey the latest experimental efforts to test it.

The exclusion principle (EP), which states that no two fermions can occupy the same quantum state, has been with us for almost a century. In his Nobel lecture, Pauli provided a deep and broad-ranging account of its discovery and its connections to unsolved problems of the newly born quantum theory. In the early 1920s, before Schrödinger's equation and Heisenberg's matrix algebra had come along, a young Pauli performed an extraordinary feat when he postulated both the EP and what he called "classically non-describable two-valuedness" – an early hint of the existence of electron spin – to explain the structure of atomic spectra.

At that time the EP met with some resistance and Pauli himself was dubious about the concepts that he had somewhat recklessly introduced. The situation changed significantly after the introduction in 1925 of the electron-spin concept and its identification with Pauli's two-valuedness, which derived from the empirical ideas of Lande, an initial suggestion by Kronig, and an independent paper by Goudsmit and Uhlenbeck. By introducing the picture of the electron as a small classical sphere with a spin that could point in just two directions, both Kronig, and Goudsmit and Uhlenbeck, were able to compute the fine-structure splitting of atomic hydrogen, although they still missed a critical factor of two. These first steps were followed by the relativistic calculations of Thomas, by the spin calculus of Pauli, and finally, in 1928, by the elegant wave equation of Dirac, which put an end to all resistance against the concept of spin.

Pauli himself was puzzled by the principle.

Portrait of a young Pauli at Svein Rosseland's institute in Oslo in the early 1920s, when he was thinking deeply on the applications of quantum mechanics to atomic physics.

However, a ... time. Just bef ... made signific ... lication in 19 ... between spin ... a relativistica ... determines th ... or anticommu ... EP for spin-½ ... connection, a ... based on thei

Beguilingly simple

The EP is beguilingly simple to state, and many physicists have tried to skip relativity and find direct proofs that use ordinary quantum mechanics alone – albeit assuming spin, which is a genuinely relativistic concept. Pauli himself was puzzled by the principle, and in his Nobel lecture he noted: "Already in my original paper I stressed the circumstance that I was unable to give a logical rea-

Catalina Curceanu, LNF-INFN, **Dmitry Budker**, Helmholtz Institute, JGU Mainz and UC Berkeley, **Edward J Hall**, Harvard University, **Johann Marton**, Stefan Meyer Institute, Vienna, and **Edoardo Milotti**, University of Trieste and INFN–Sezione di Trieste.

CERN Courier
March 2018

Testing models of non-commutative Quantum Gravity?

Commonly retained there is no bound on quantum gravity models because the typical energy scale (Planck scale 10^{16} TeV) is out of reach of present and future accelerators

Due to the extreme (upper) bounds in experiments testing spin-statistics it is feasible to test the validity of some specific Quantum Gravity approaches like θ Poincare based on the Goenewold-Moyal plane algebra,.

See e.g. A. Addazi et al., arXiv:1712.08082v1 [hep-th] 21 Dec 2017

PEP violation in quantum gravity

A. Addazi, A. Marcianò, Fudan University

VIP-2 underground experiment as a *Crash-Test* of Non-Commutative Quantum Gravity

Pauli Exclusion Principle (PEP) violations induced from non-commutative space-time can be searched VIP-2 experiment set-up. We show that the limit from VIP-2 experiments on non-commutative space-time scale Λ, related to energy dependent PEP violations, are severe: κ-Poincaré non-commutativity is ruled-out up to the Planck scale. In the next future θ-Poincaré will be probed until the Grand-Unification scale! This highly motivates Pauli Exclusion Principle tests from underground experiments as a test of quantum gravity and space-time microscopic structure.

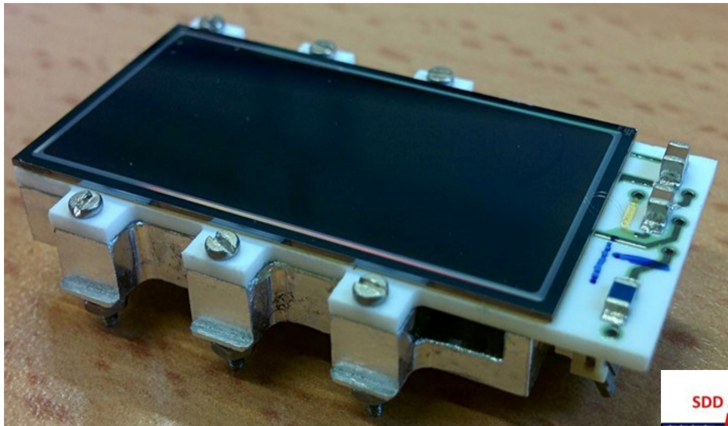
Several proofs exist in the context of QFT which differ in clarity and in their quality of physical insight.

Lüders and Zumino lay out a very clean set of assumptions in their 1958 proof:

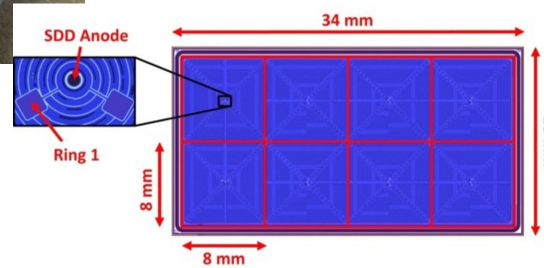
I. The theory is invariant with respect to the proper inhomogeneous Lorentz group (includes translations, does not include reflections)
II. Two operators of the same field at points separated by a spacelike interval either commute or anticommute (Locality)
III. The vacuum is the state of lowest energy
IV. The metric of the Hilbert space is positive definite
V. The vacuum is not identically annihilated by a field

(G. Lüders and B. Zumino, Phys. Rev. **110** (1958) 1450)

SDD detectors



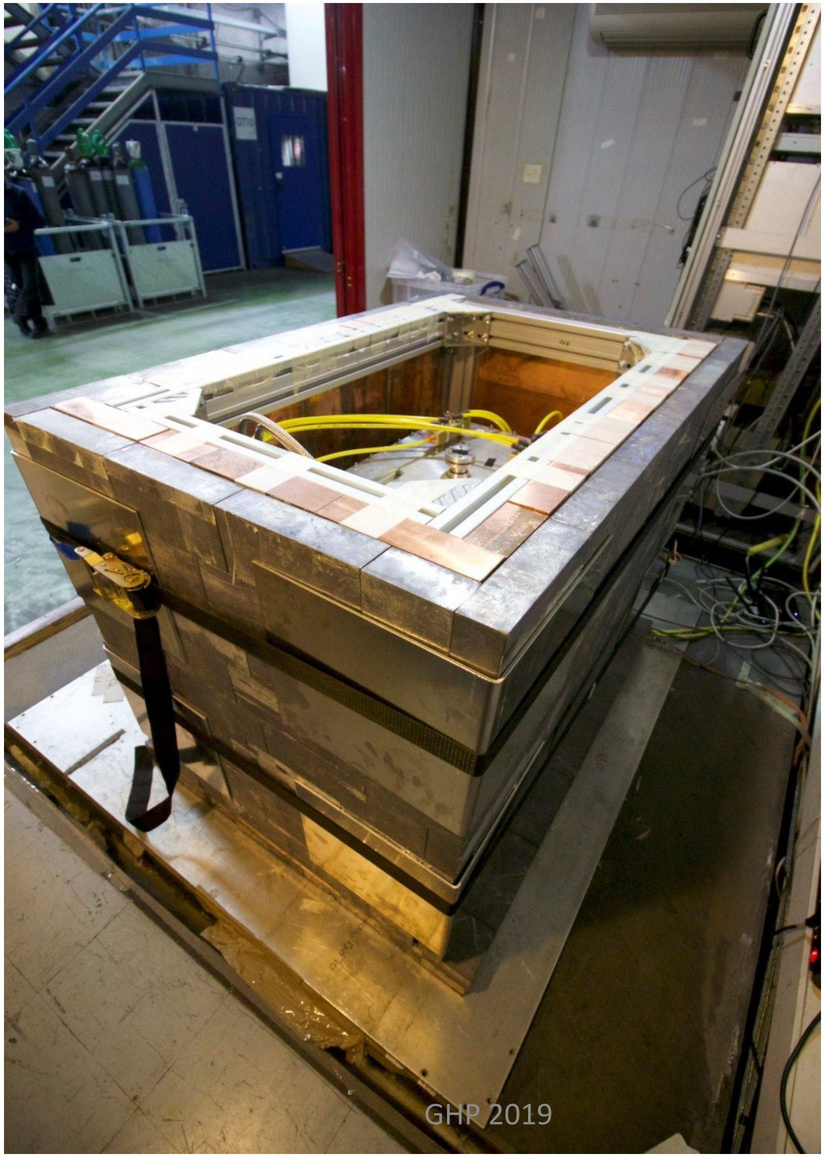
4 ar ays of 2 x 4 SDDs
8mm x 8mm each



Liquid argon closed circuit cooling
-170°C

VIP-2 with final 4 SDD arrays

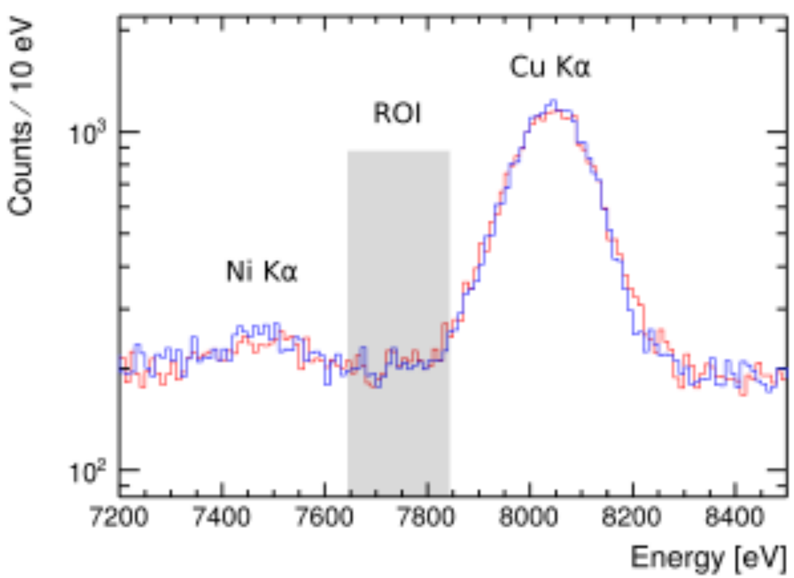
Shielding installation in November 2018:

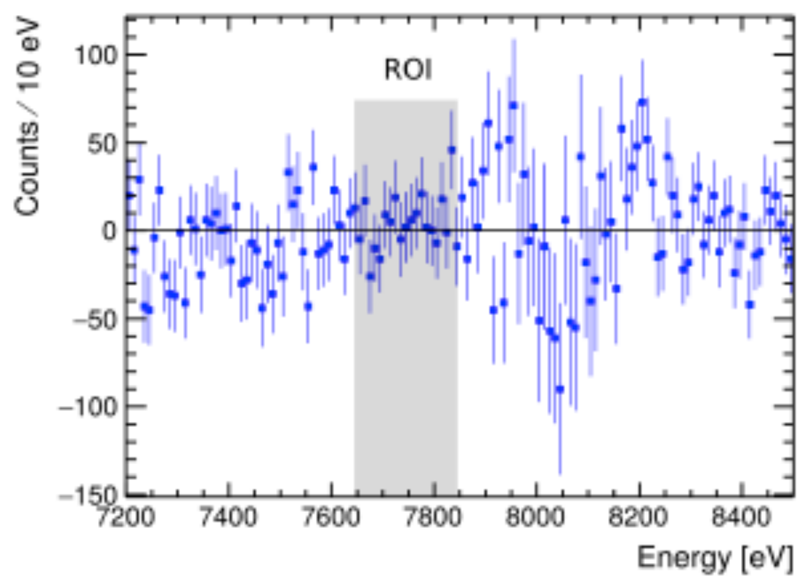


Spectrum subtraction in the ROI yields a new upper limit on the probability for a violation of the PEP of:

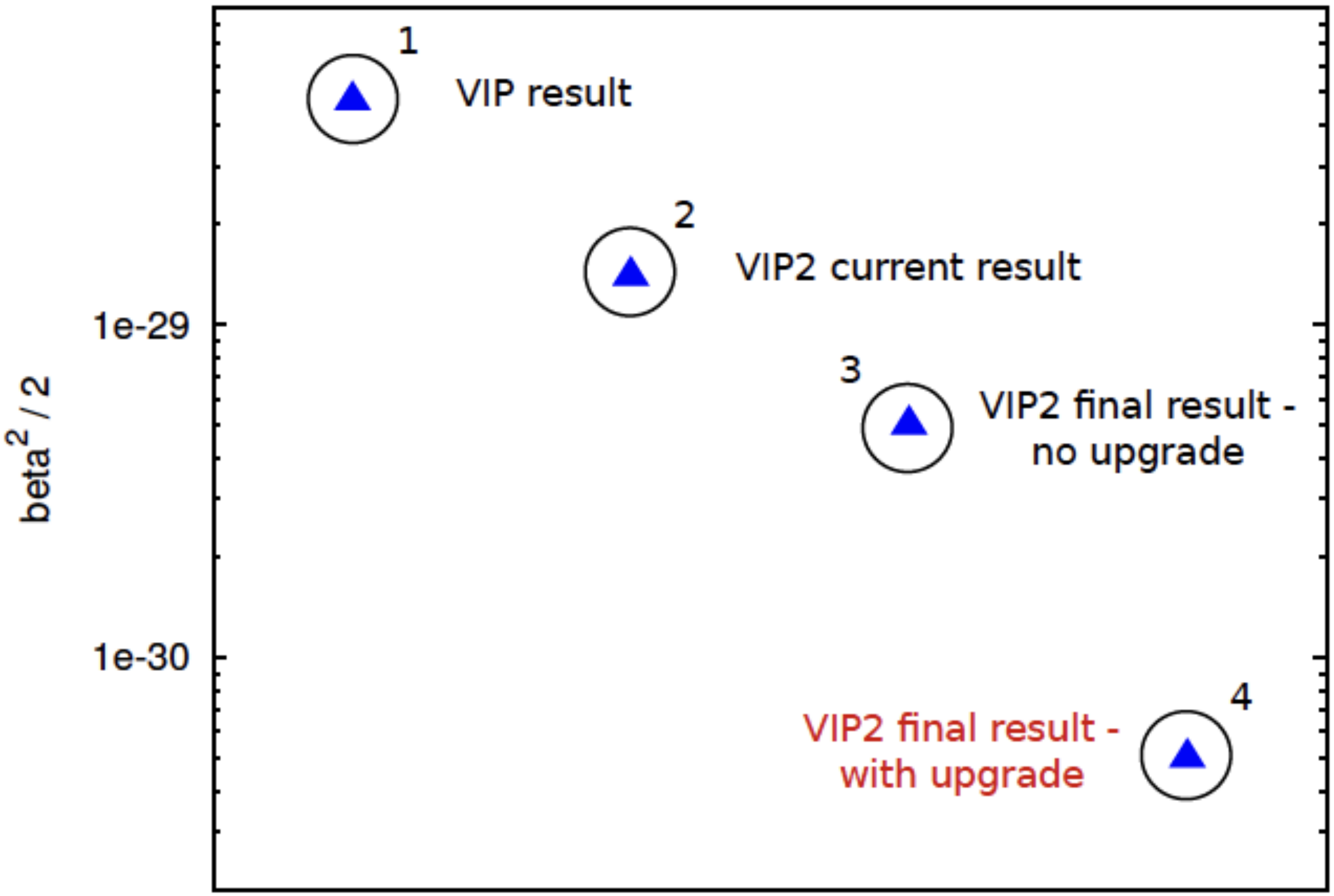
$$1.87 \times 10^{-29}$$

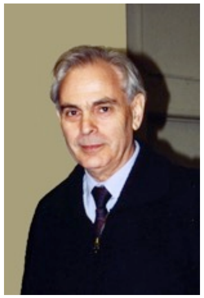
Improvement compared to the VIP experiment by factor 2.5





Toward the final result





Lev Okun
1929-2015

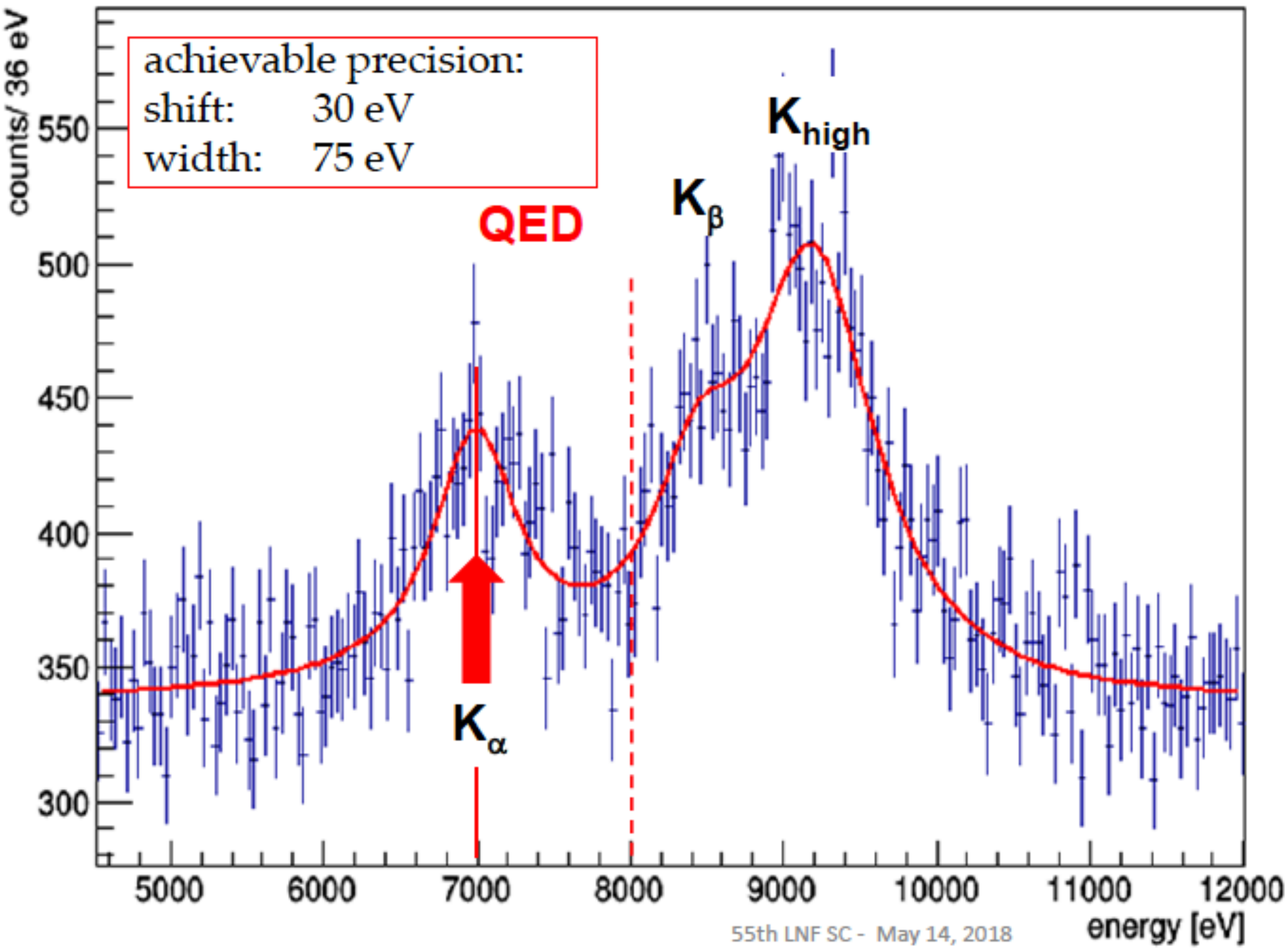
"*The special place enjoyed by the Pauli principle in modern theoretical physics does not mean that this principle does not require further and exhaustive experimental tests. On the contrary, it is specifically the fundamental nature of the Pauli principle which would make such tests, over the entire periodic table, of special interest.*"

Thank you

SPARE

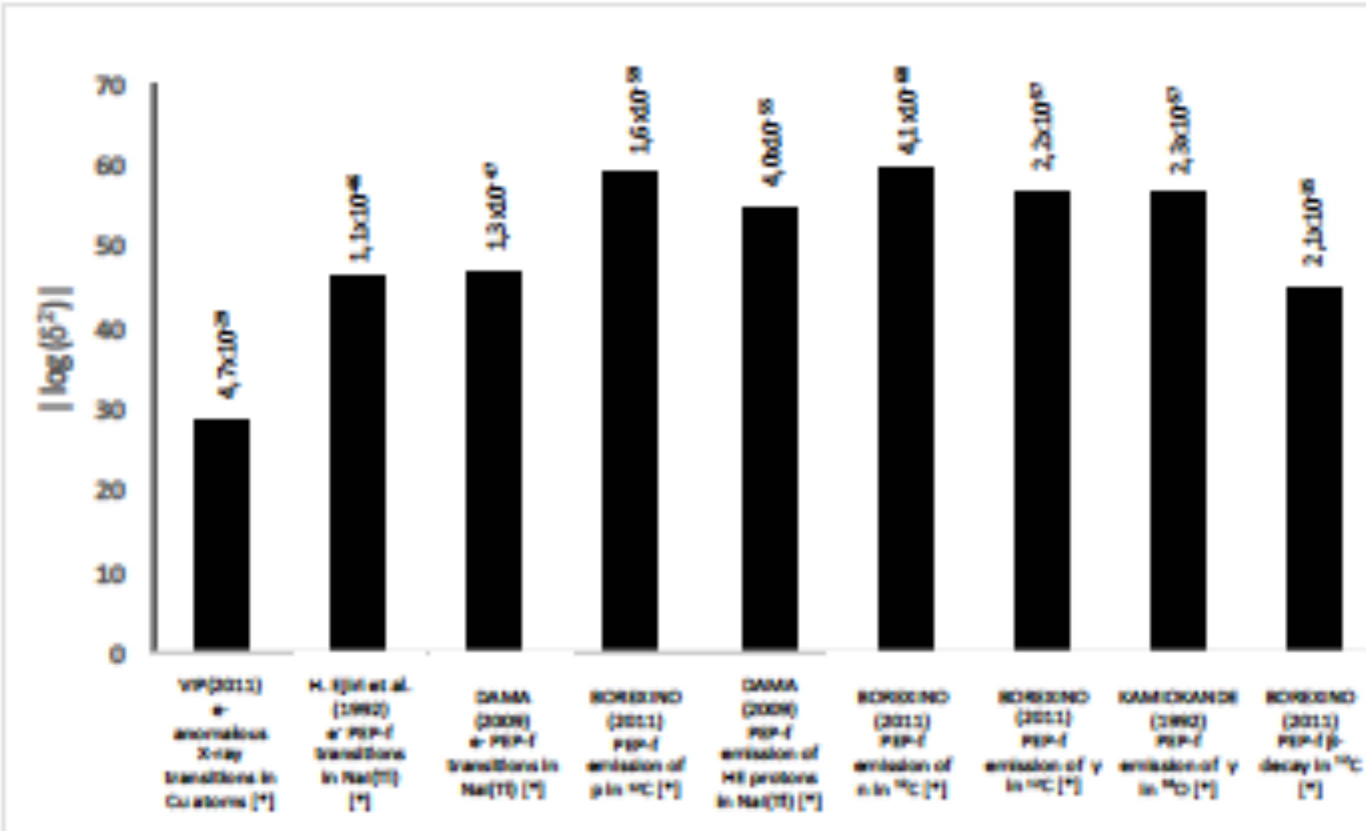
Kaonic deuterium with SIDDHARTA2 at DAFNE

Geant4 simulated K⁻d X-ray spectrum



signal: shift - 800 eV
width 800 eV
density: 5% (LHD)
detector area: 246 cm^2

Kα yield: 0.1 %
yield ratio as in K⁻p
S/B ~ 1 : 4



Stable Transitions

VIP2