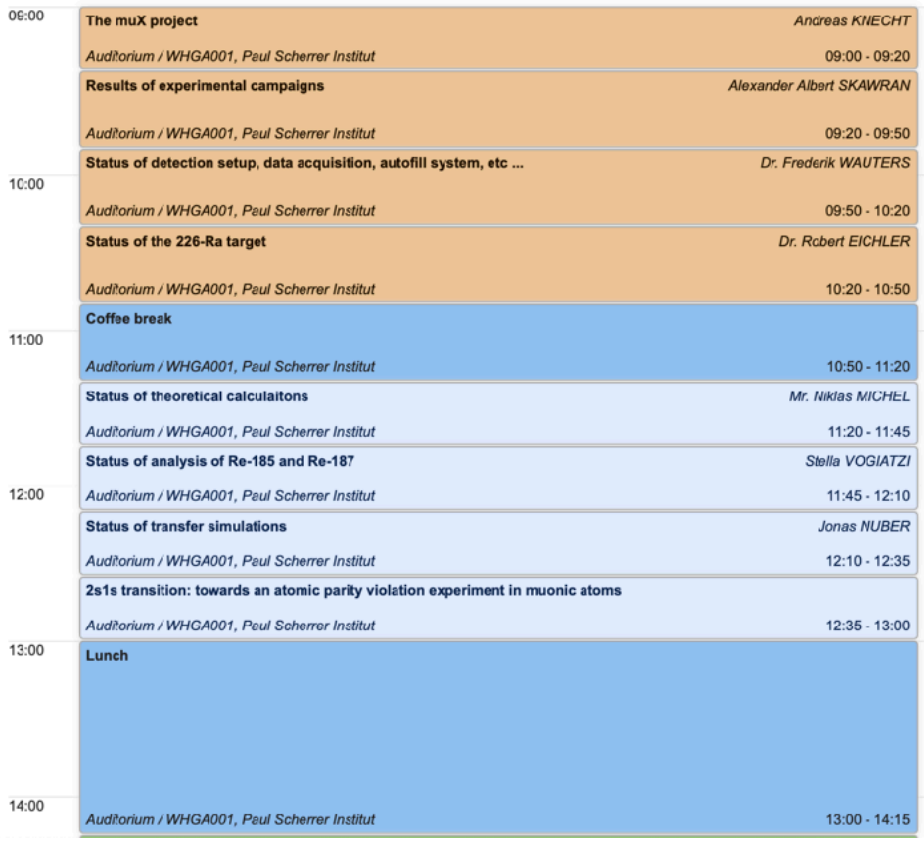
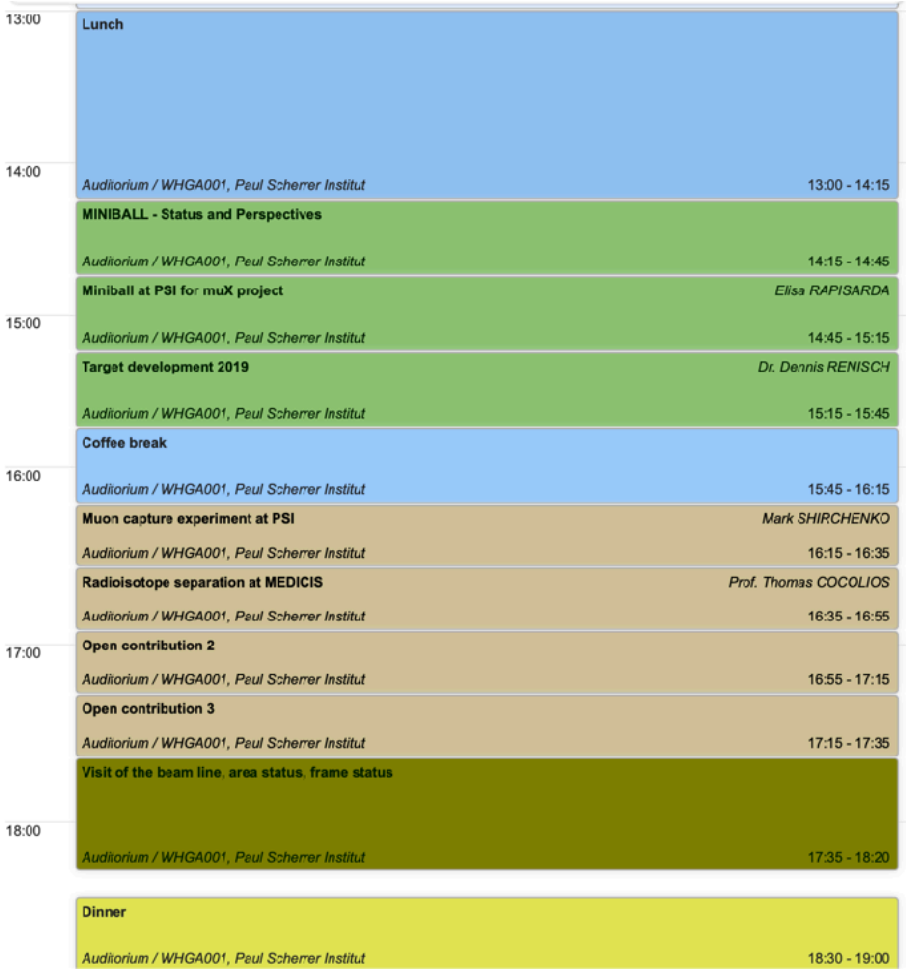
The muX Project

Andreas Knecht
Paul Scherrer Institute

muX collaboration meeting
Paul Scherrer Institut
5. 11. 2018

Schedule

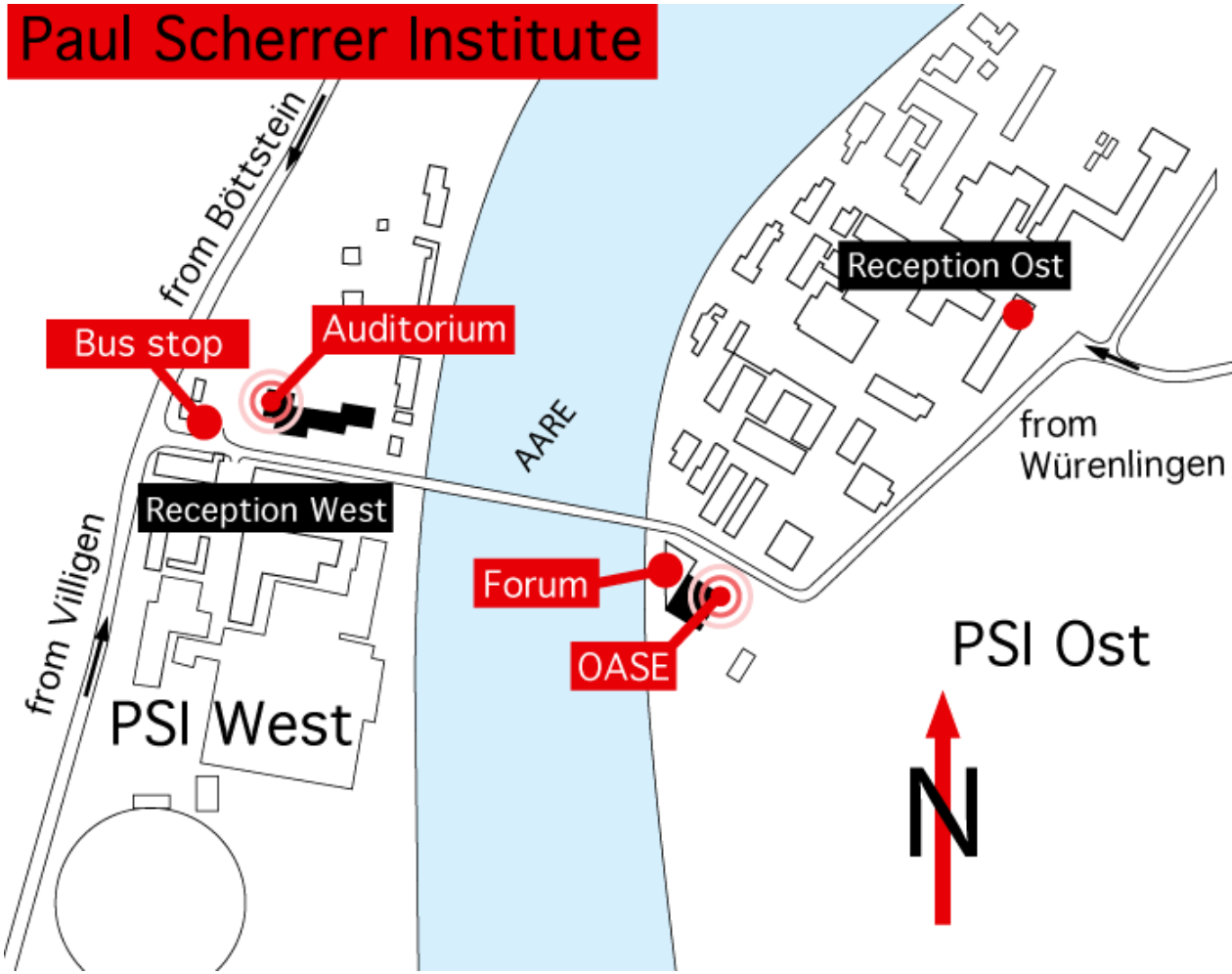




- Some open slots at the end, should have enough time for discussions
- Probably stop for an extended coffee break at 4 pm for LTP seminar

Lunch

- Lunch at OASE at 1 pm
- We do not have a reserved table but crowd should be ok to find enough space



Dinner

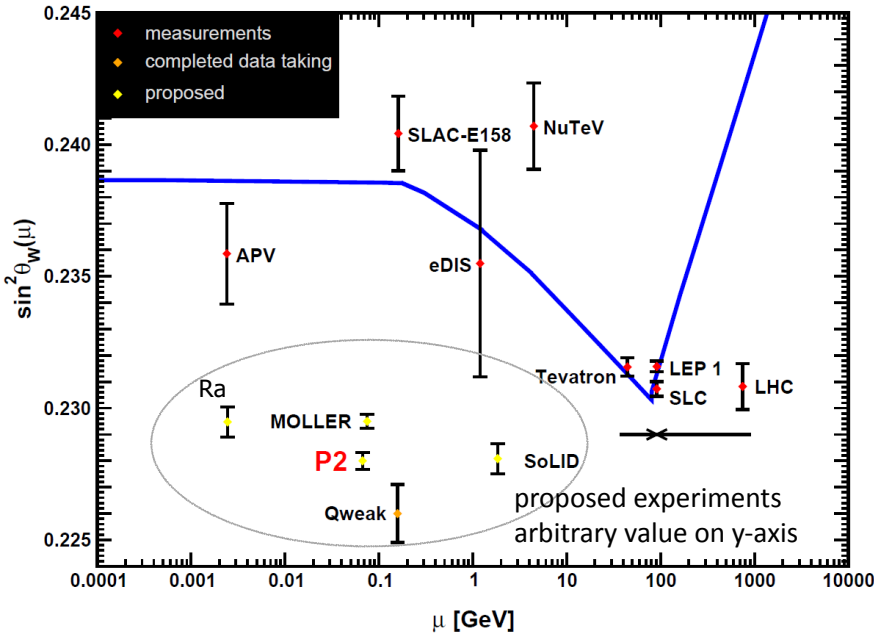
- Dinner at Frohsinn in Würenlingen at 6:30 pm
- We should have enough cars and will meet at 6:15 pm in front of this building

Atomic parity violation in radium

- Weak interaction leads to parity violating effects in atomic transitions
  → enhanced in heavy atoms ($\propto Z^3$) due to large overlap with nucleus

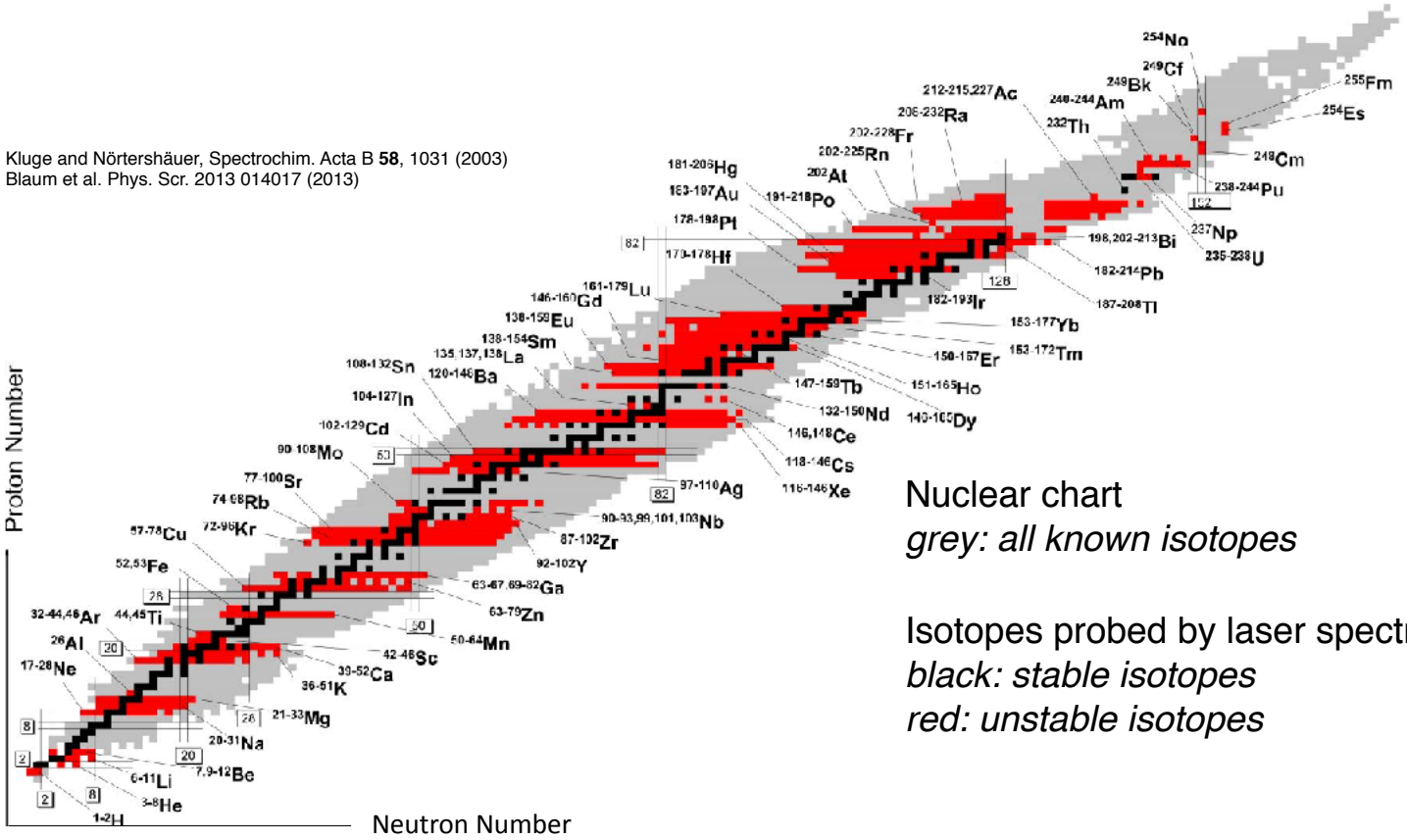
- Extract Weinberg angle using precision atomic calculations
  → Needs knowledge of the radium charge radius with 0.2% accuracy

- Weinberg angle comparable to α and m_e in electromagnetism



Atomic parity violation fixes weak interaction properties at low momentum

Charge radii in nuclear physics



Nuclear chart
grey: all known isotopes

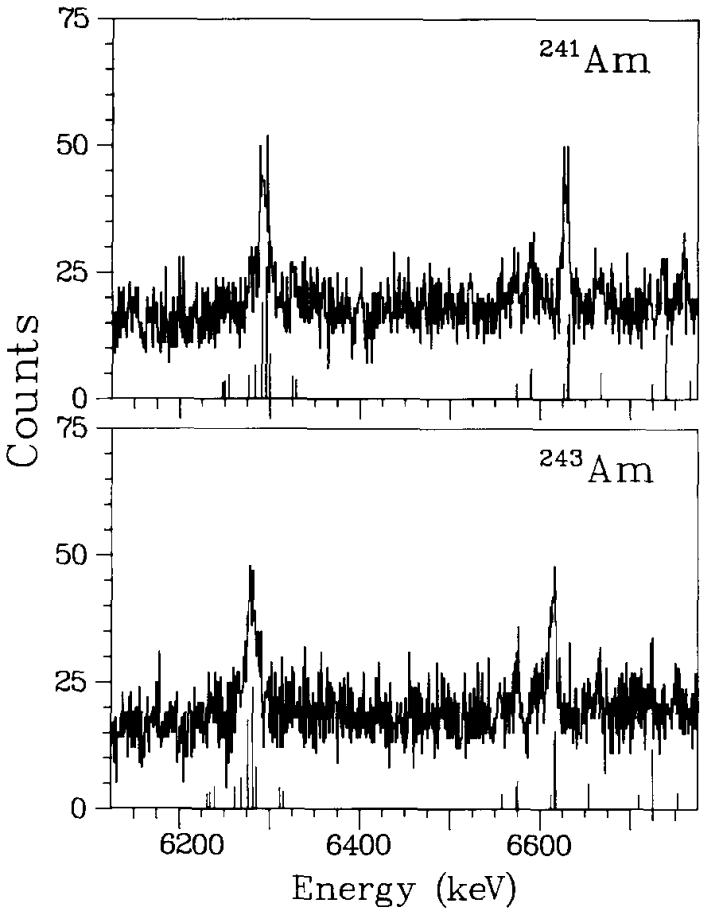
Isotopes probed by laser spectroscopy
black: stable isotopes
red: unstable isotopes

- Large efforts at ion beam facilities to determine charge radii
- Wealth of information on nuclear properties from laser spectroscopy
- Need electron scattering or muonic atom spectroscopy for absolute radii

What about radioactive atoms?

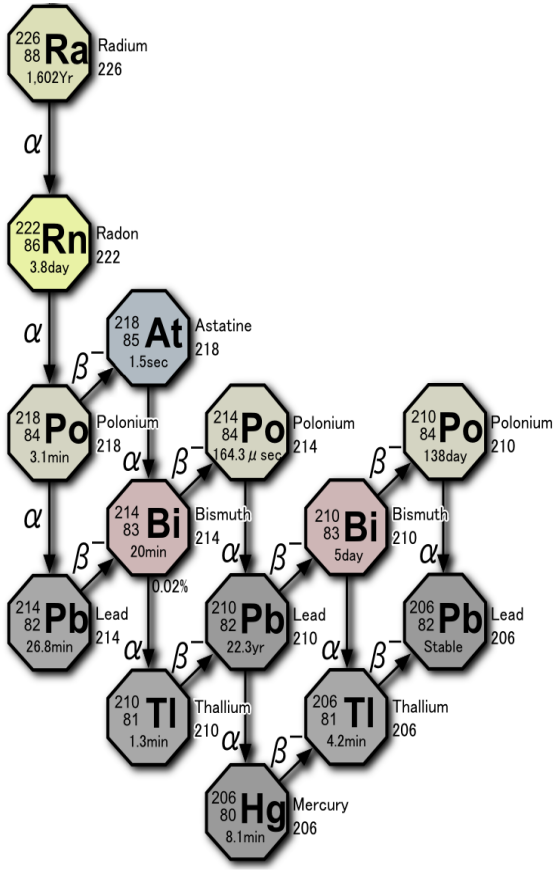
- Most of the stable isotopes have been measured with muonic atom spectroscopy
- In a few special cases also radioactive isotopes, e.g. americium
  - The paper describes the americium target as “modest weight of 1 gram”
- Nowadays: 0.2 µg of open ^{241}Am allowed in experimental hall…

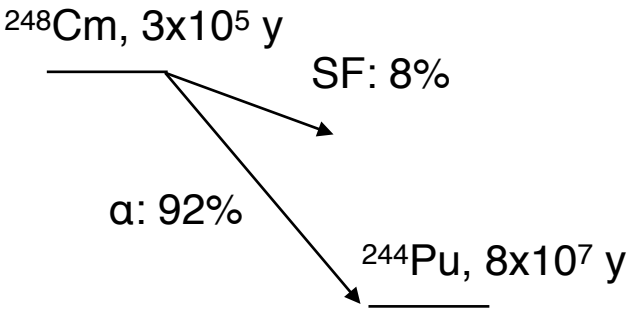
Johnson et al., Phys. Lett. **161B**, 75 (1985)



Cannot stop muons directly in microgram targets
Need new method!

Our radioactive targets



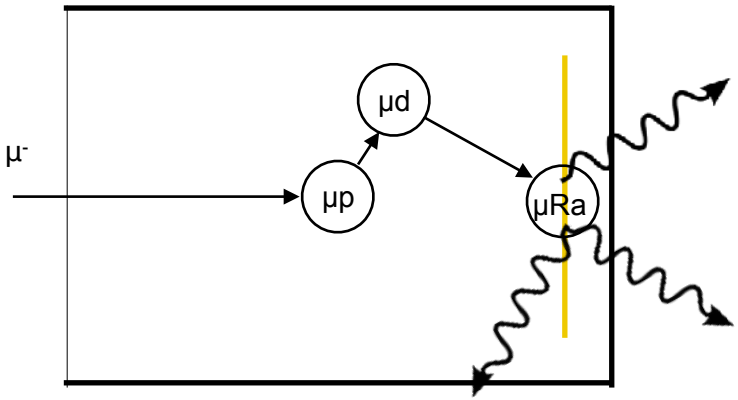


- 5.5 µg target material allowed
- Gamma rate of ~400 kHz from all daughters
- Interest from atomic parity violation

- 32.6 µg target material allowed
- Heaviest nucleus accessible

Transfer reactions

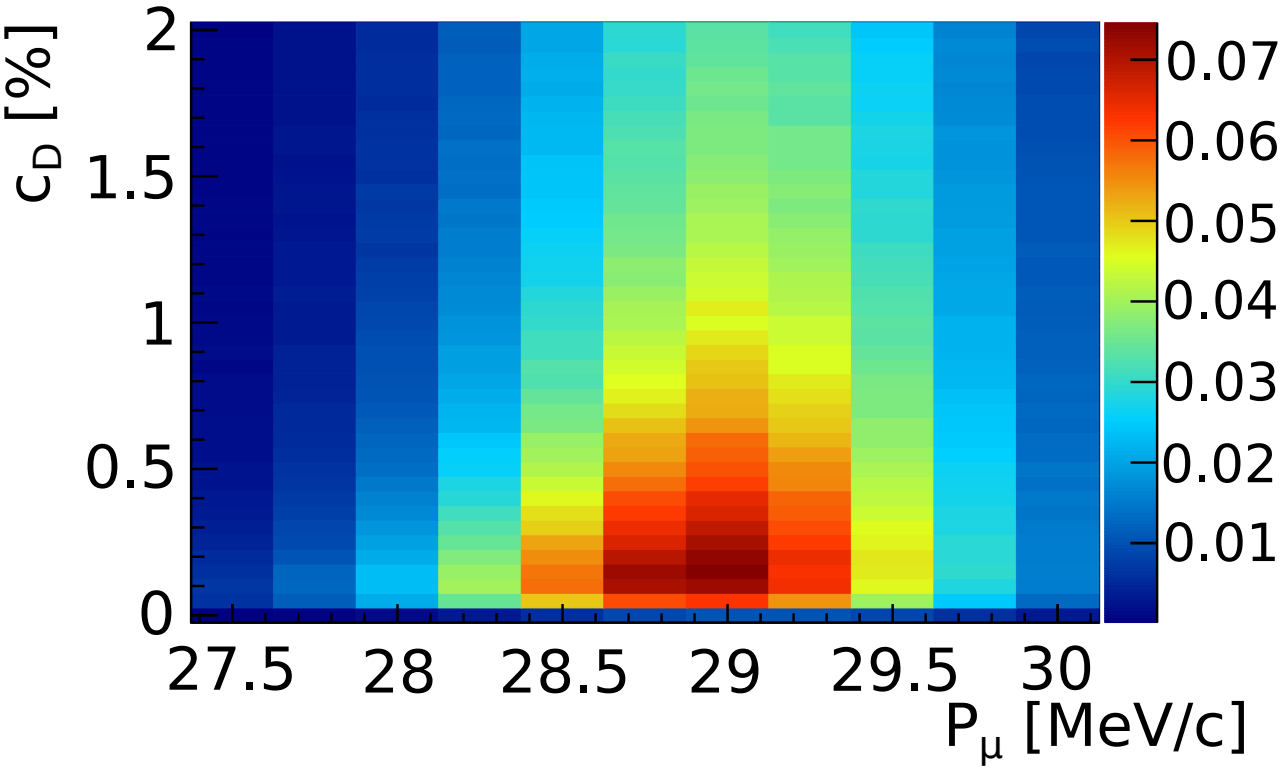
- Stop in 100 bar hydrogen target with 0.25% deuterium admixture
- Form muonic hydrogen μp
- Transfer to deuterium forming μd, gain binding energy of 45 eV
- Hydrogen gas quasi transparent for μd at ~5 eV (Ramsauer-Townsend effect)
- μd reaches target and transfers to μRa
- Measure emitted X-rays from cascade



Inspired by work of Strasser et al. and Kraiman et al.

Simulation of transfer

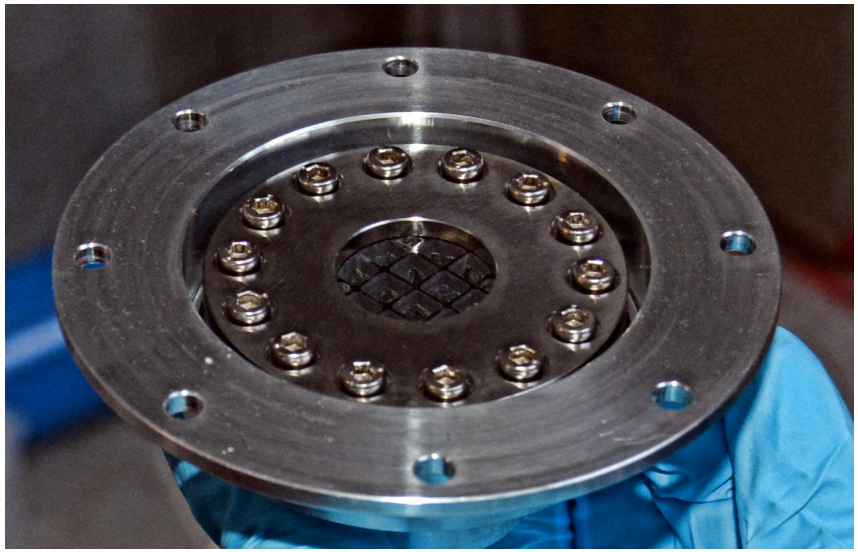
Talk by Jonas

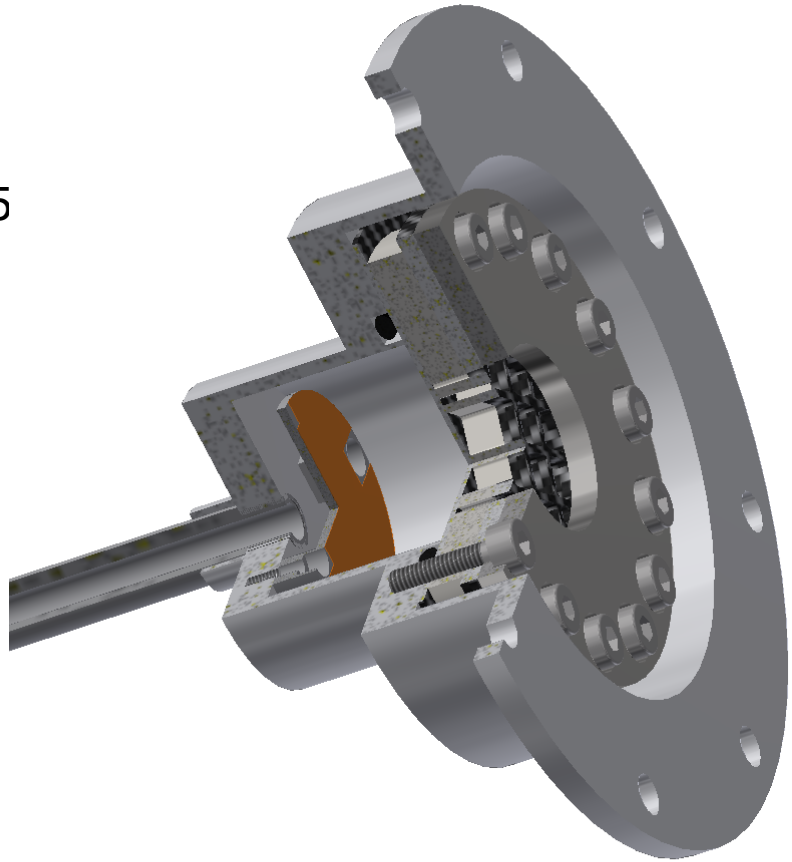


- Developed simulation to predict efficiency of transfer
- Momentum of beam determines stopping distribution with respect to the target
- Deuterium concentration determines speed of transfer but limits range due to μd+D_2 scattering

100 bar hydrogen target

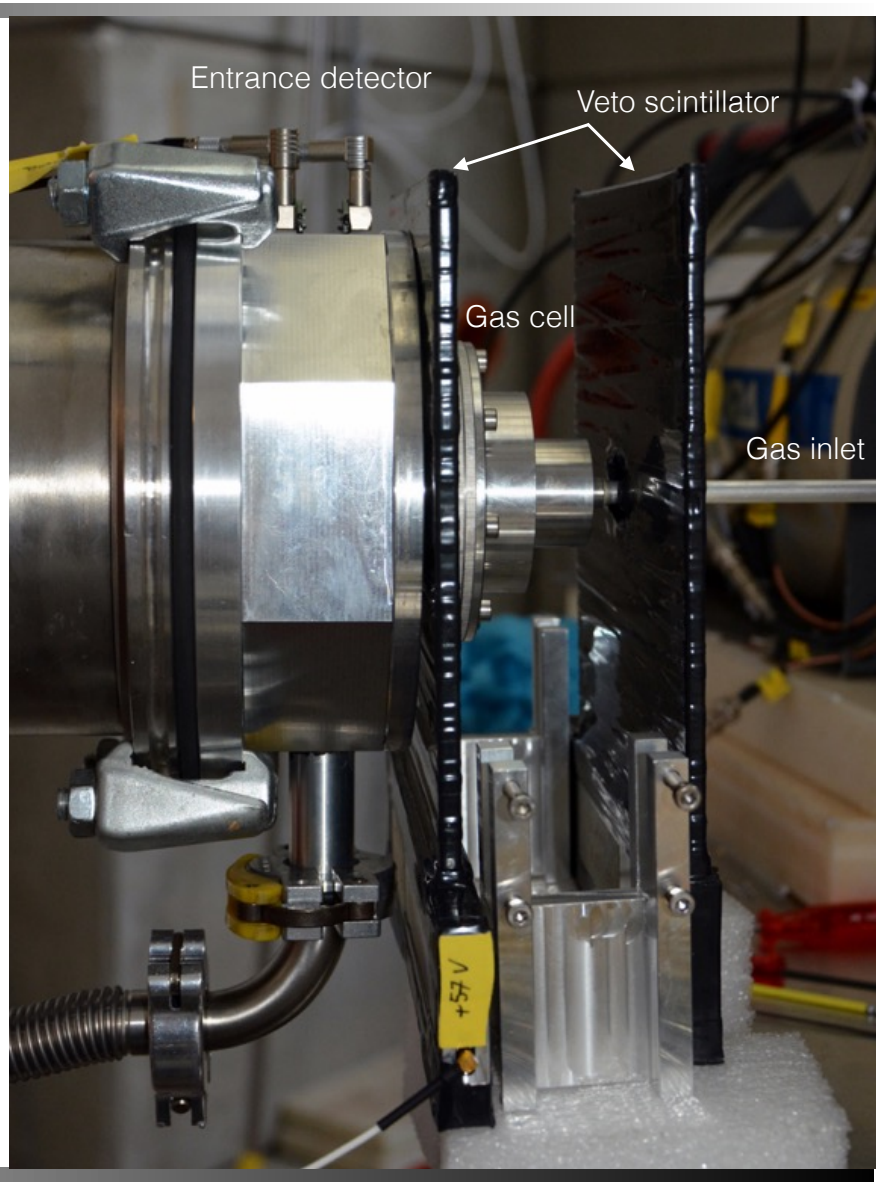
- Target sealed with 0.6 mm carbon fibre window plus carbon fibre/titanium support grid
- Target holds up to 350 bar
- 10 mm stopping distribution (FWHM) inside 15 mm gas volume
- Target disks mounted onto the back of the cell





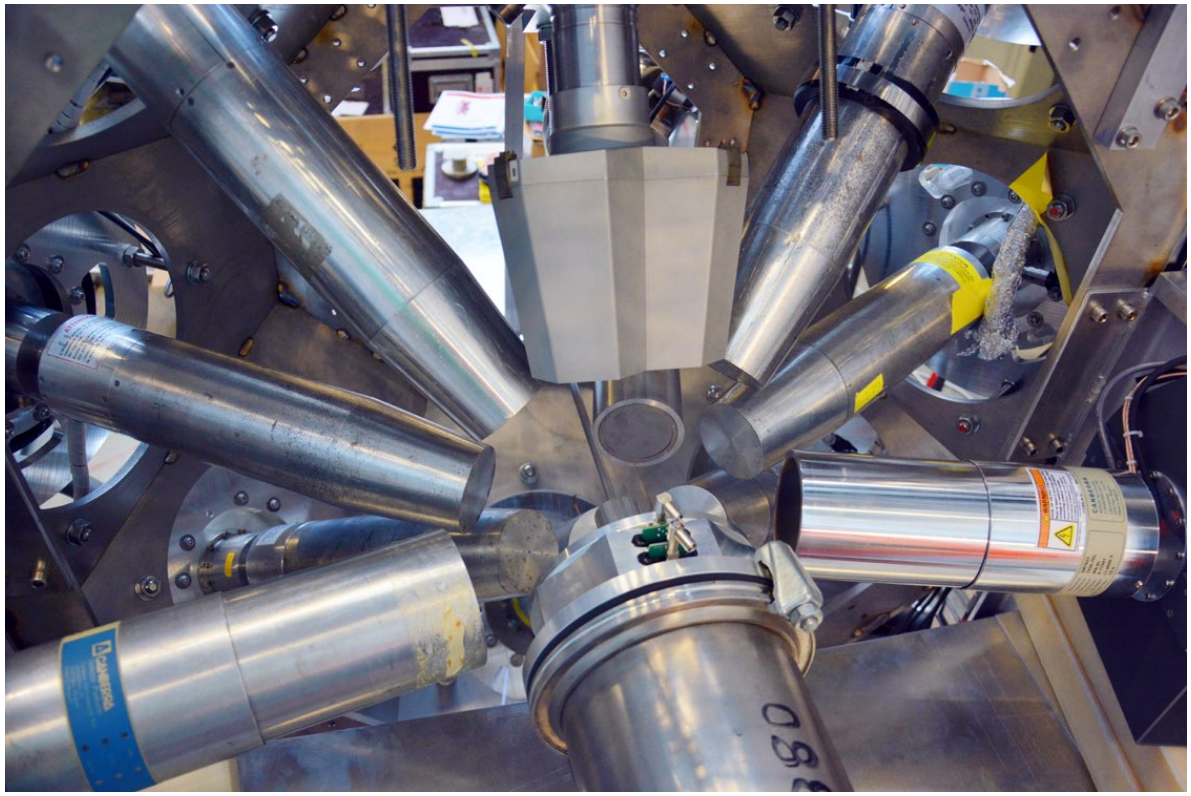
Entrance & veto detectors

- Entrance detector to see incoming muon
- Veto scintillators to form anti-coincidence with decay electron

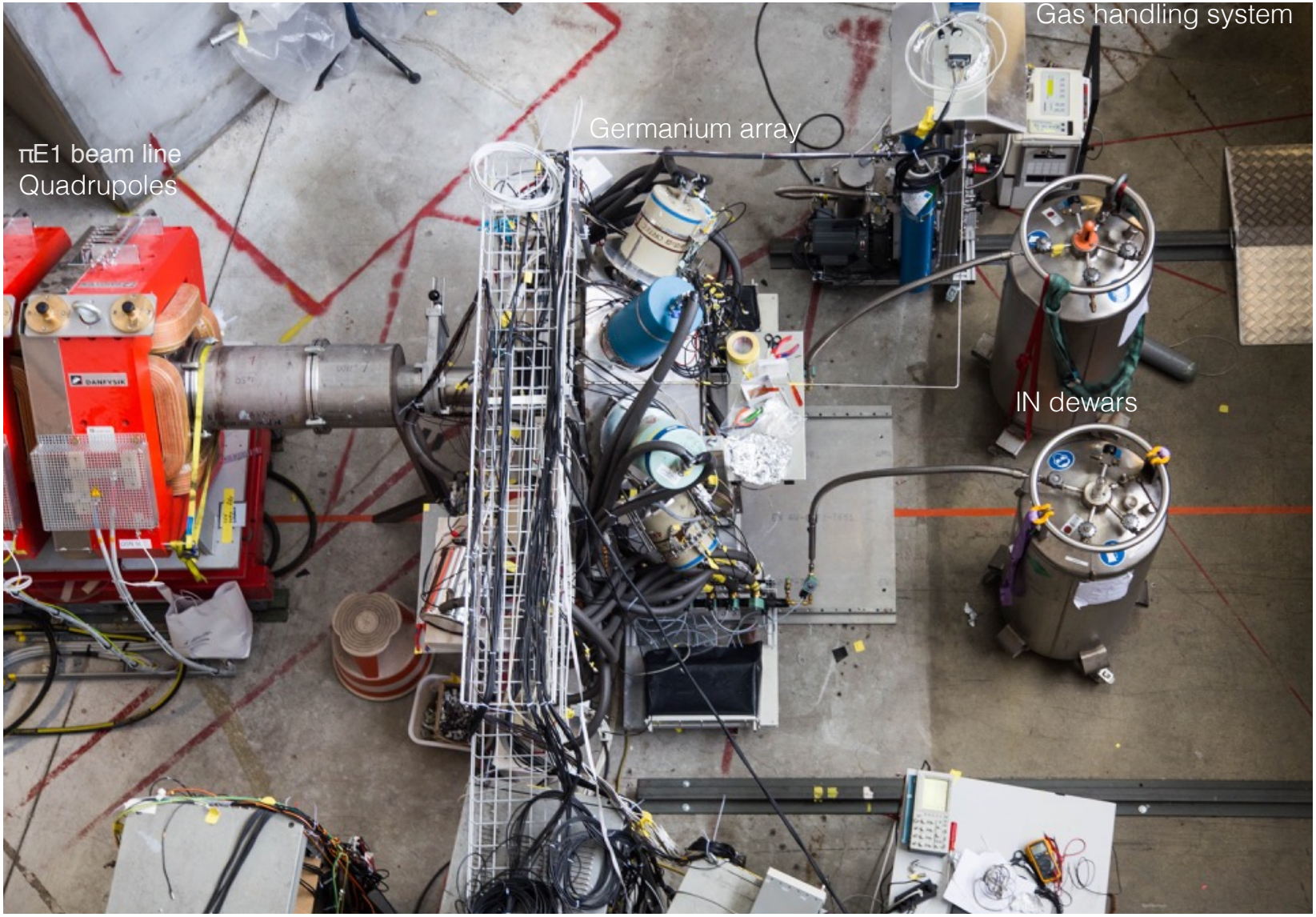


Germanium array

- 11 germanium detectors in an array from French/ UK loan pool, Leuven, PSI
- First time a large array is used for muonic atom spectroscopy



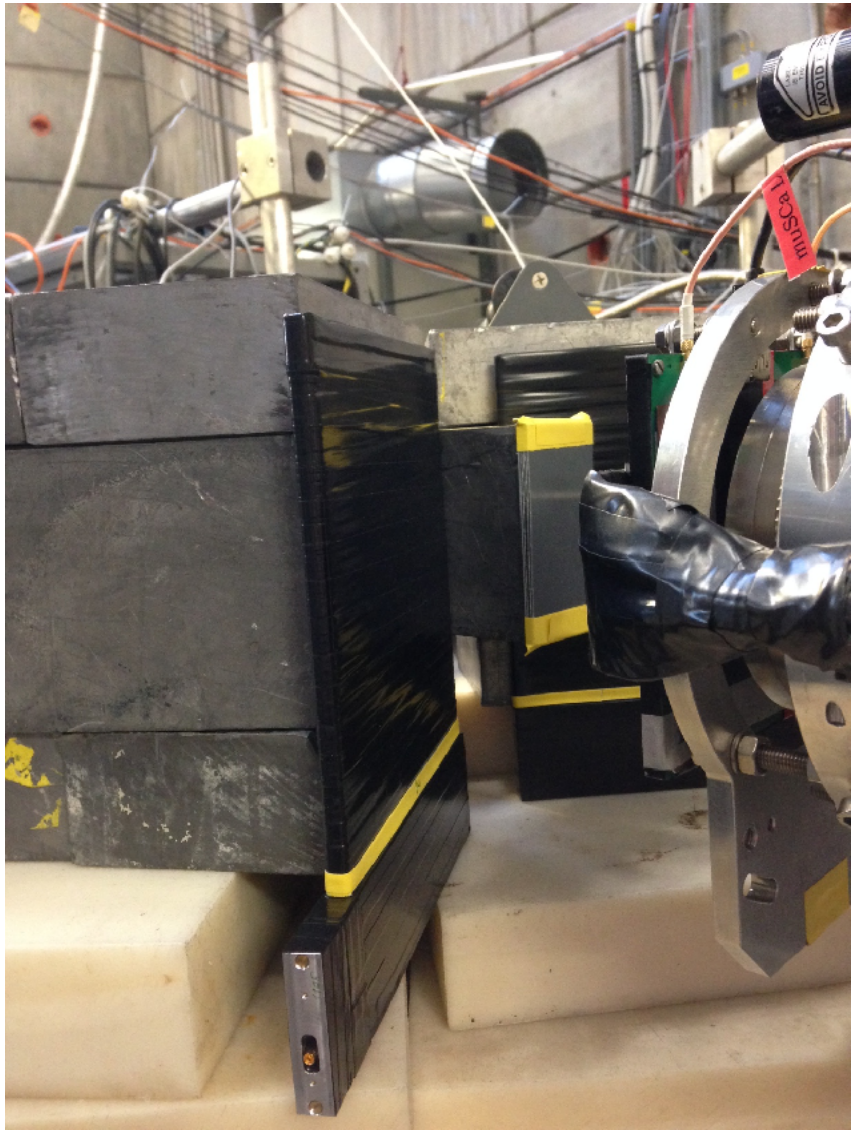
Experimental setup 2017/2018



History muX: 2015

- Using the Alcap DAQ and setup
- 25 and 75% Ge detectors

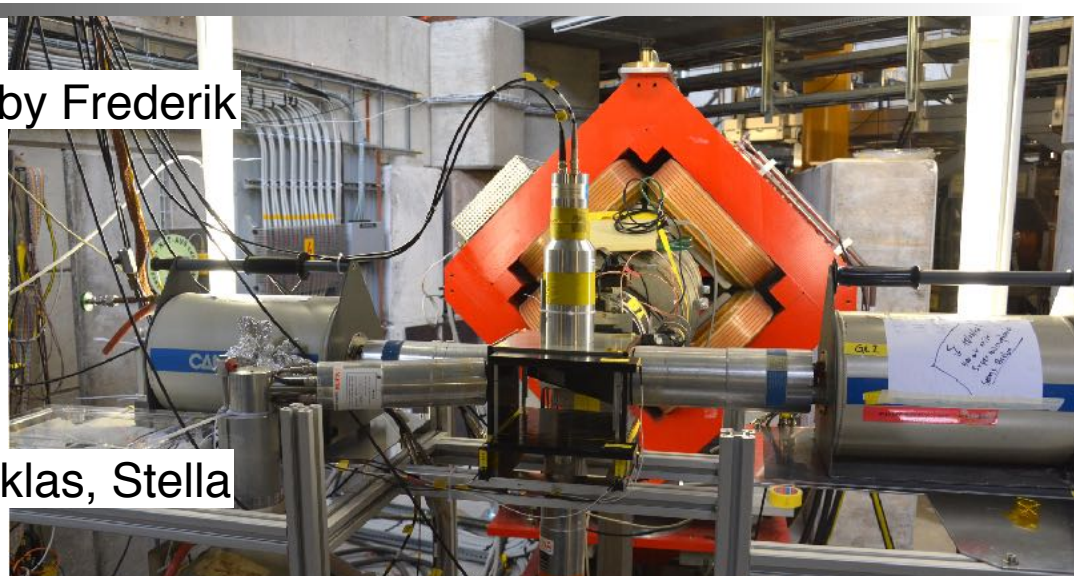
- Taking first spectra with
  - ^{nat}Pb
  - ^{nat}Re
  - ^{nat}Zn

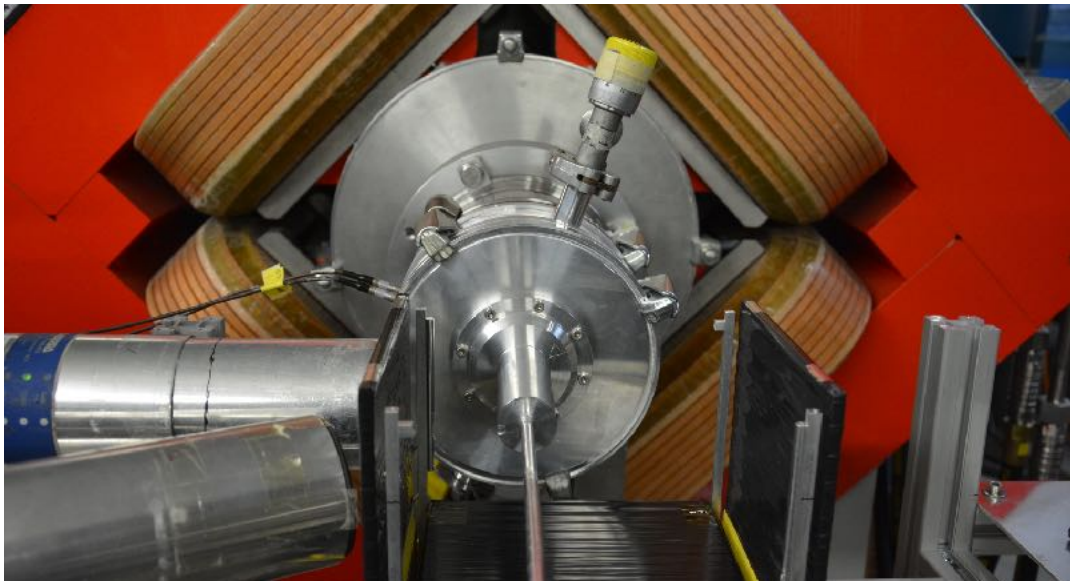


History muX: 2016

- Own DAQ based on Struck digitiser ⇨ Talk by Frederik
- 4 Ge detectors (but only two working)

- Measurement of
  - ^{185}Re, ^{187}Re ⇨ Talk by Niklas, Stella
  - ^{208}Pb for calibration
  - ^{nat}Zn
  - First gold transfers (in 2nd attempt)





History muX: 2017

- 11 Ge detectors in an array

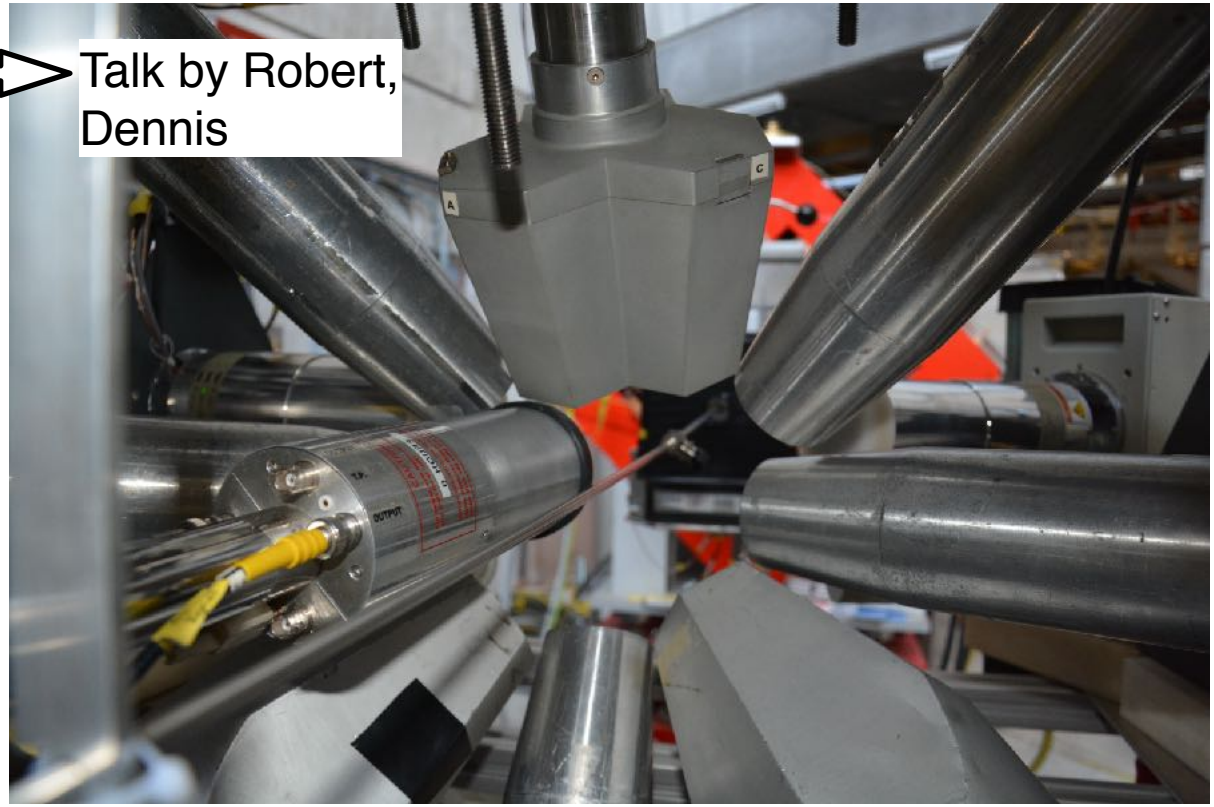
- Measurement of
  - Transfer to 5 µg Au ⇨ Talk by Alex
  - Transfer to ^{238}U
  - Transfer to Ar/Kr/Xe
  - ^{65}Zn ⇨ Talk by Frederik

History muX: 2018

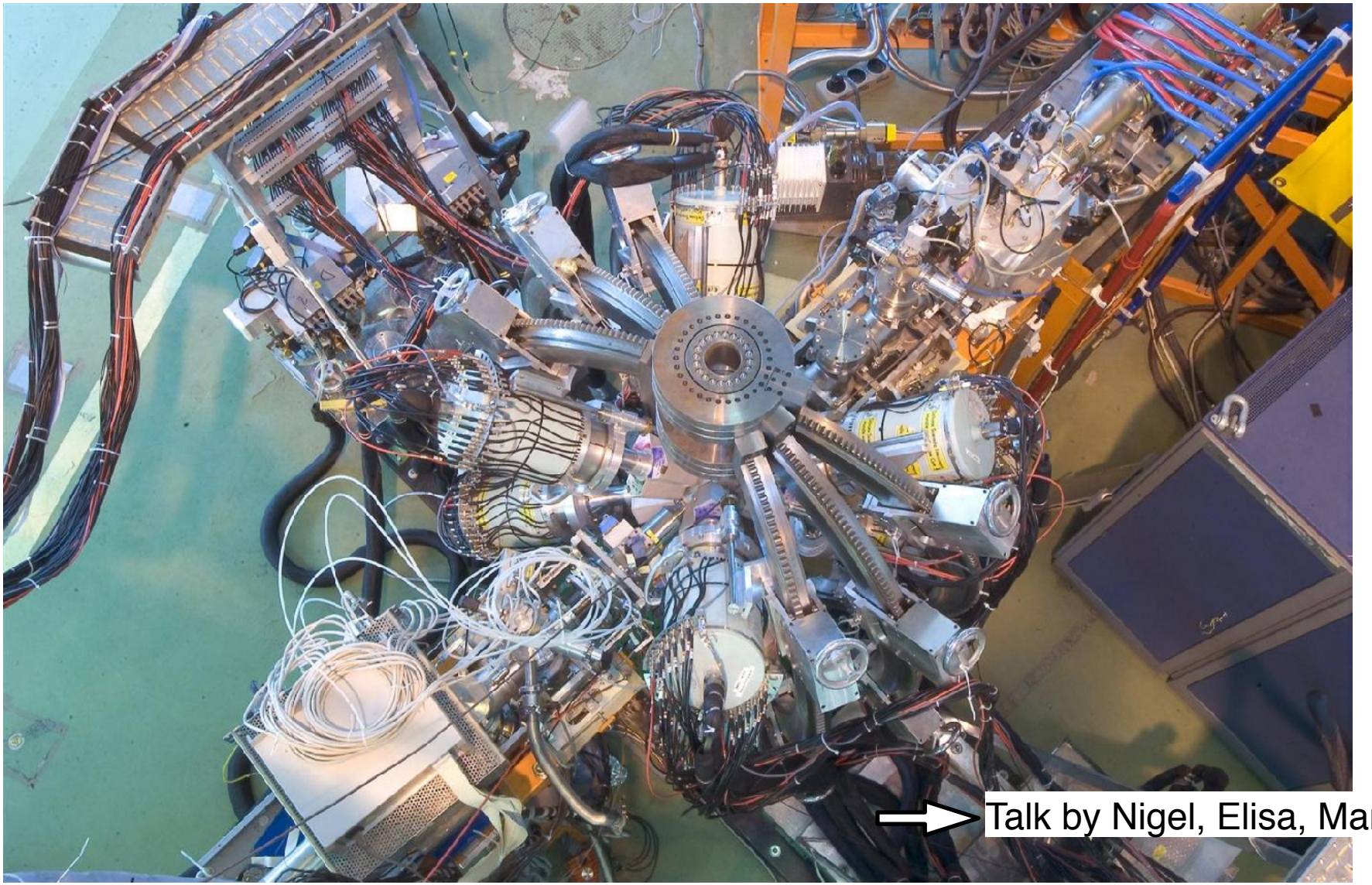
- 13 Ge detectors in an array (1 not working)

- Measurement of
  - Transfer to ^{226}Ra, ^{248}Cm
  - Transfer to Kr
  - ^{197}Au, ^{178}Hf, ^{159}Tb

⇨ Talk by Robert, Dennis



Miniball at PSI: 2019?



muX collaboration

A. Adamczak[1], A. Antognini[2,3], N. Berger[4], T. Cocolios[5], R. Dressler[2], C. Düllmann[4], R. Eichler[2], P. Indelicato[6], K. Jungmann[7], K. Kirch[2,3], A. Knecht[2], J. Krauth[4], J. Nuber[2], A. Papa[2], R. Pohl[4], M. Pospelov[8,9], E. Rapisarda[2], D. Renisch[4], P. Reiter[10], N. Ritjoho[2,3], S. Roccia[11], N. Severijns[5], A. Skawran[2,3], S. Vogiatzi[2], F. Wauters[4], and L. Willmann[7]

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[11]CSNSM, Université Paris Sud, CNRS/IN2P3, Orsay Campus, France



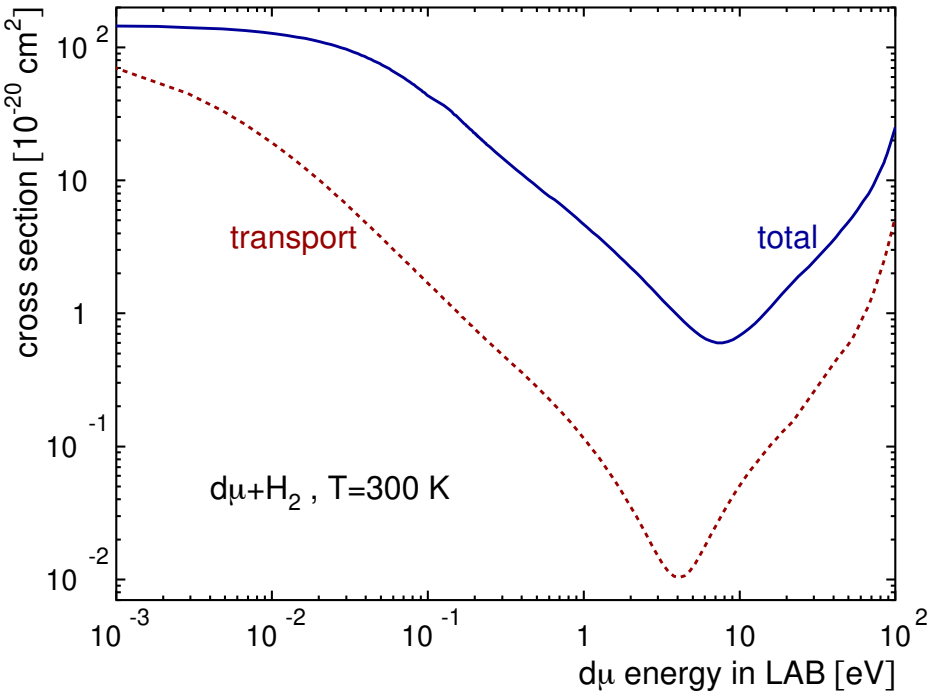


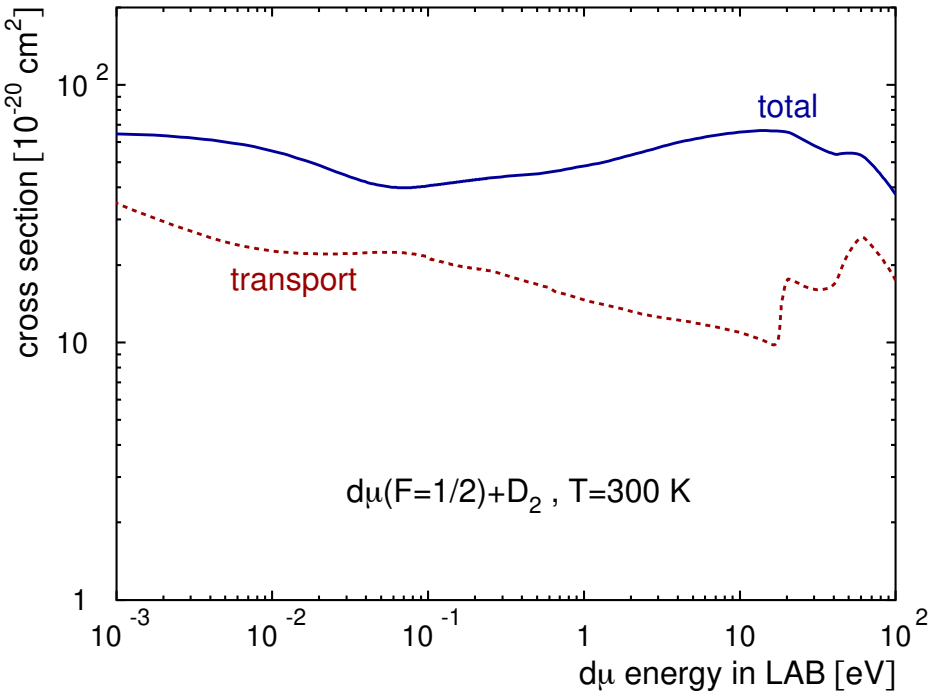




Backup

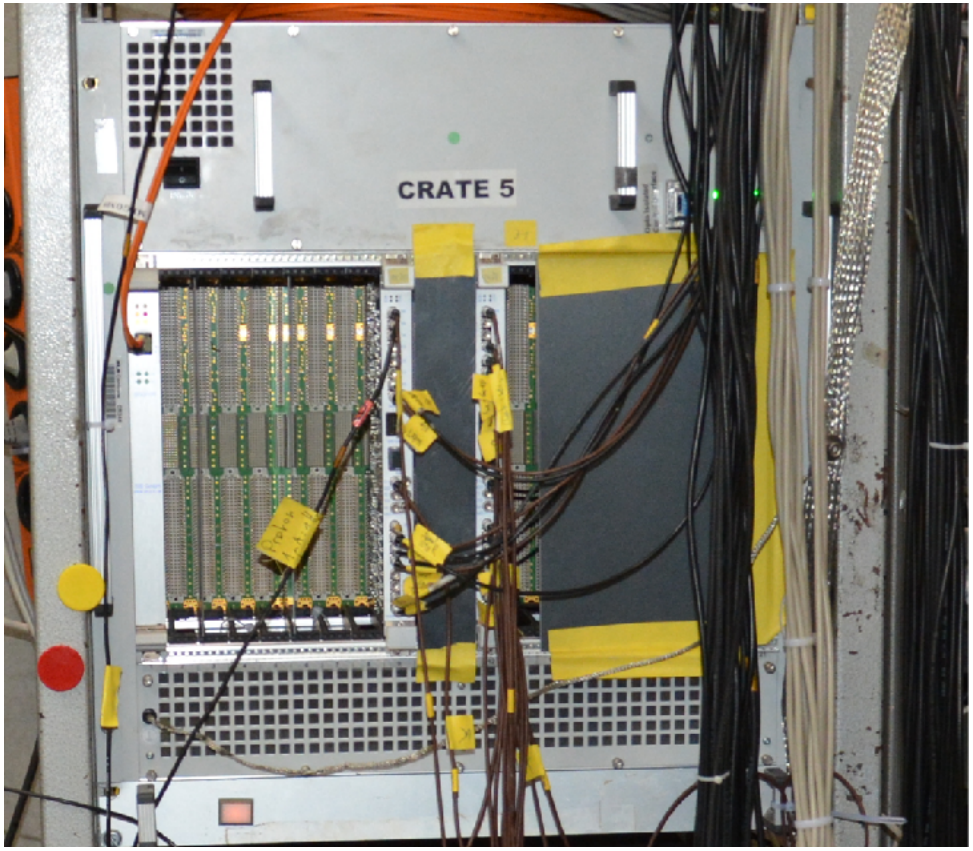
Scattering cross sections





- Scattering on deuterium does not show a Ramsauer-Townsend minimum
- Need to be careful to not have too much deuterium in the gas mixture

DAQ

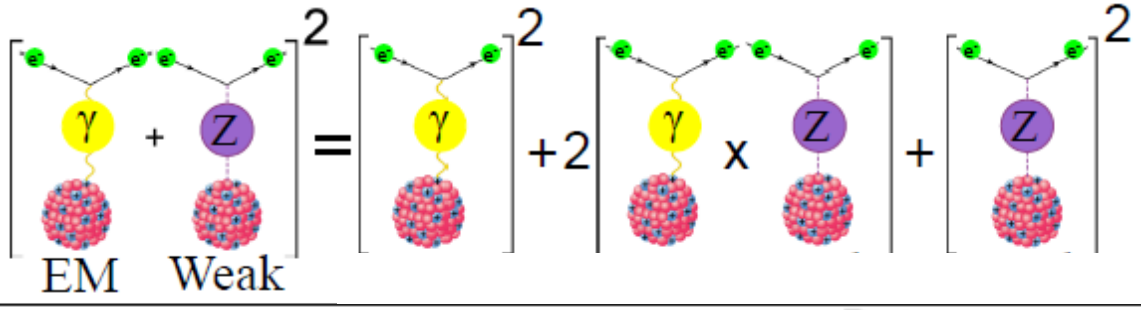


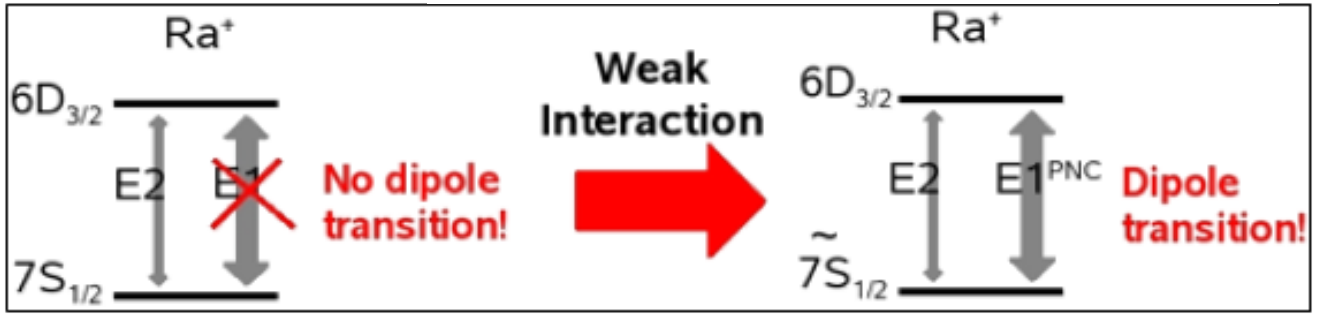
http://www.struck.de/sis3316.html

- Struck SIS3316 digitizer: 16 channel, 14 bit, 250 MHz
- Firmware for online pulse processing

Weak Interaction in Atoms

Interference of EM and Weak interactions





$$E1_{PNC} = K_r \; Z^3 \; Q_w = K_r \; Z^3 \; (-N + Z\,(1-4\sin^2\theta_W))$$

Measurement — **Atomic Theory** — **Heavy System**

K. Jungmann, L. Willmann, Workshop on Muonic Atom Spectroscopy (2016)

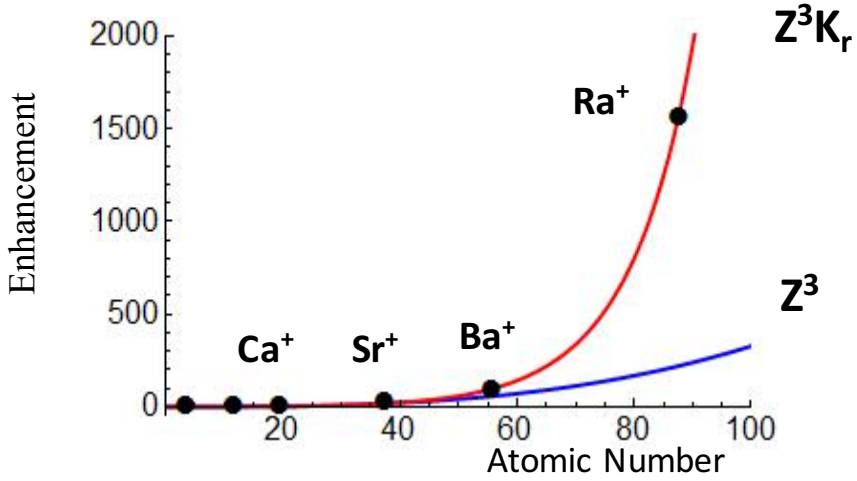
Benefit of Ra

Scaling of the APV

increase faster than Z^3 (Bouchiat & Bouchiat, 1974)

$$\left\langle nS_{1/2}\left|H_W\right|nP_{1/2}\right\rangle \propto K_r Z^3$$

K_r relativistic enhancement factor



Ra⁺ effects larger by:

20 (Ba^+)

50 (*Cs*)

L.W. Wansbeek *et al.*, Phys. Rev. A **78**, 050501 (2008)

→ 5-fold improvement over *Cs* feasible in 1day

Relativistic coupled-cluster (CC) calculation of $E1_{APV}$ in Ra^+

$$\mathbf{E1_{APV} = 46.4(1.4)\cdot 10^{-11}\, iea_0\,(-Q_w/N)} \quad \textbf{(3\% accuracy)}$$

K. Jungmann, L. Willmann, Workshop on Muonic Atom Spectroscopy (2016)

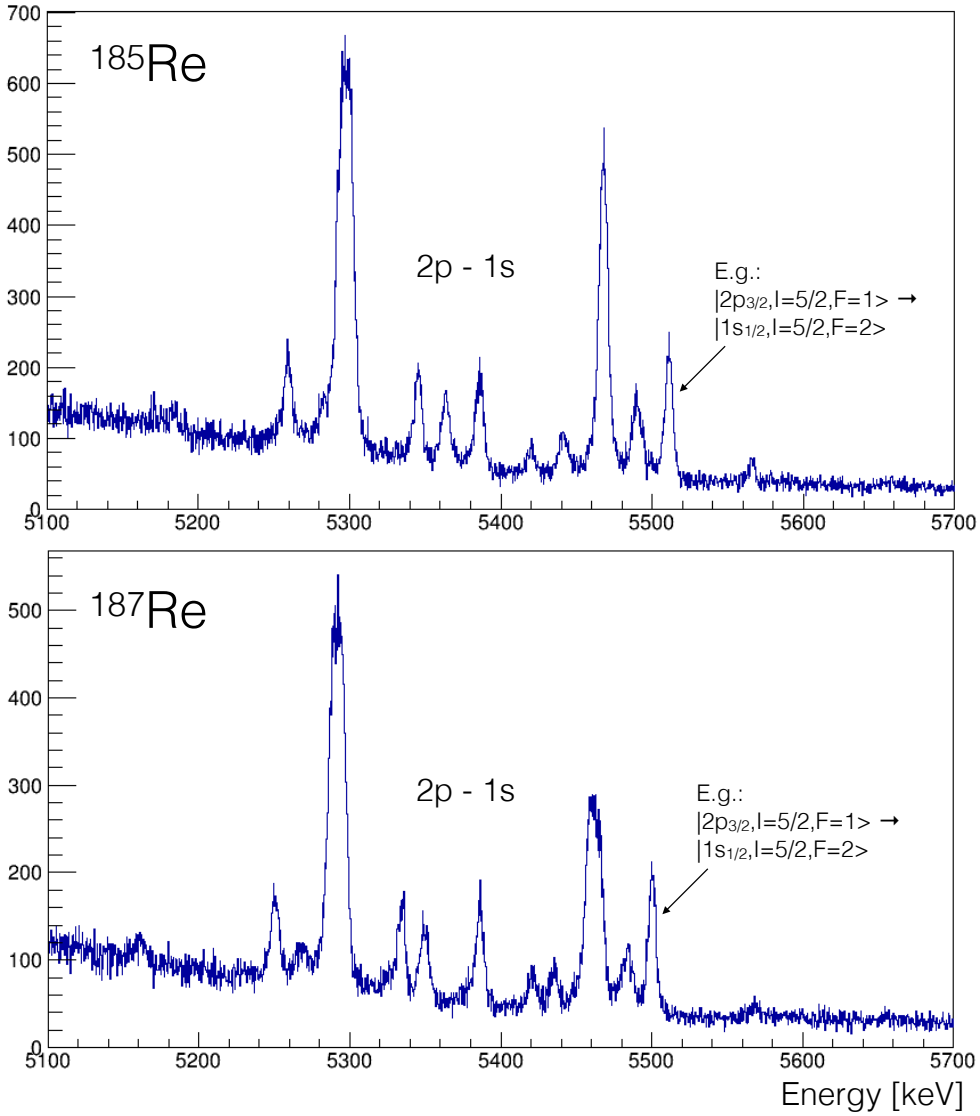
Other results:

$45.9\cdot 10^{-11}\, iea_0\,(-Q_w/N)$ (R. Pal *et al.*, Phys. Rev. A **79**, 062505 (2009), Dzuba *et al.*, Phys Rev. A **63**, 062101 (2001).)

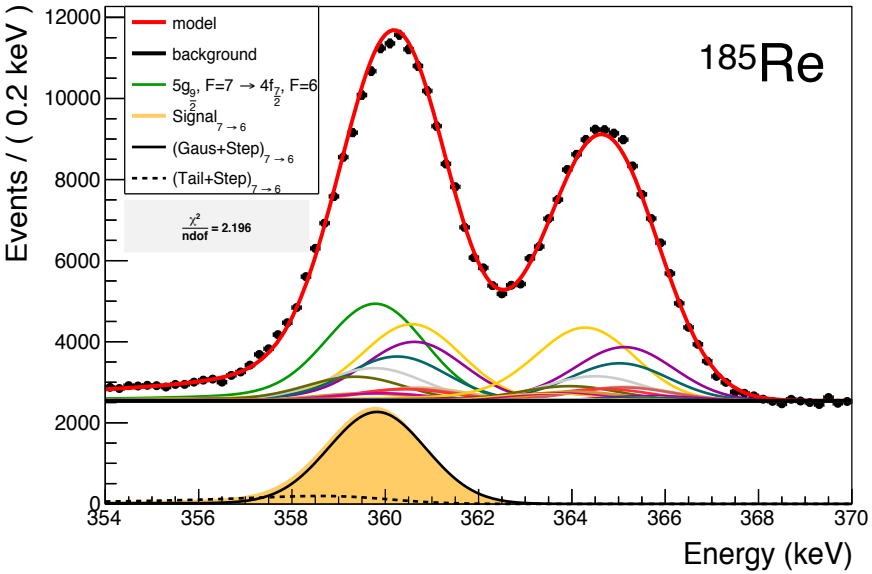
- Need reliable charge radius at <0.2% accuracy for atomic theory

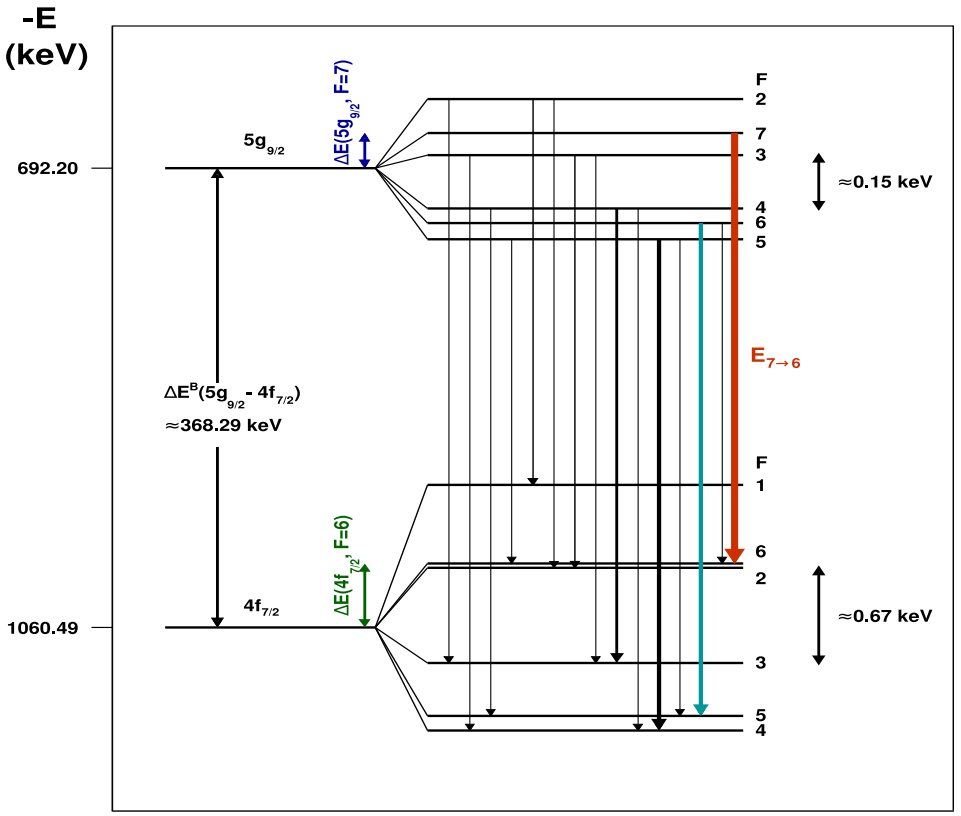
^{185}Re & ^{187}Re spectra

- Hyperfine structure + low-lying nuclear levels
- Highly complicated spectra
- Need very detailed theoretical calculations to extract nuclear properties

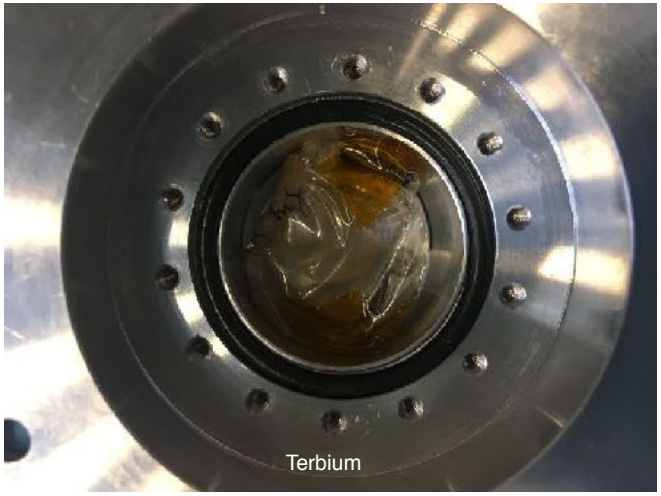


Extraction of quadrupole moments



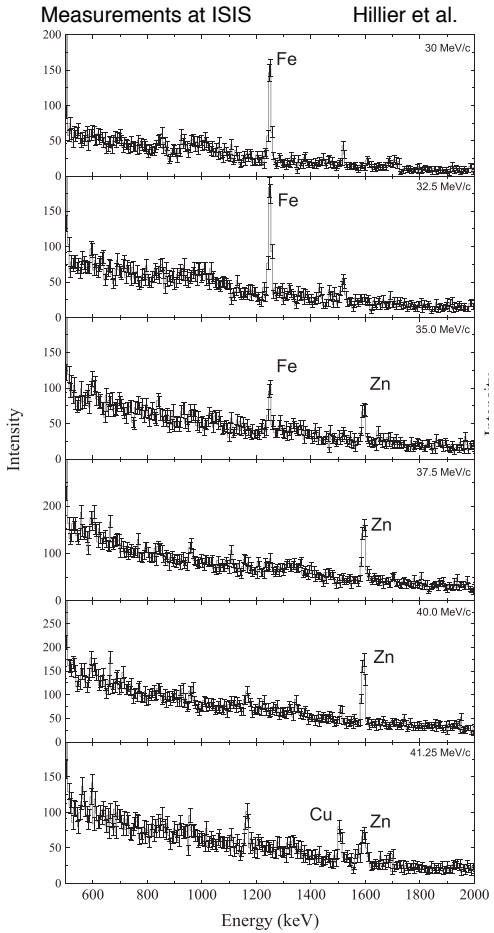


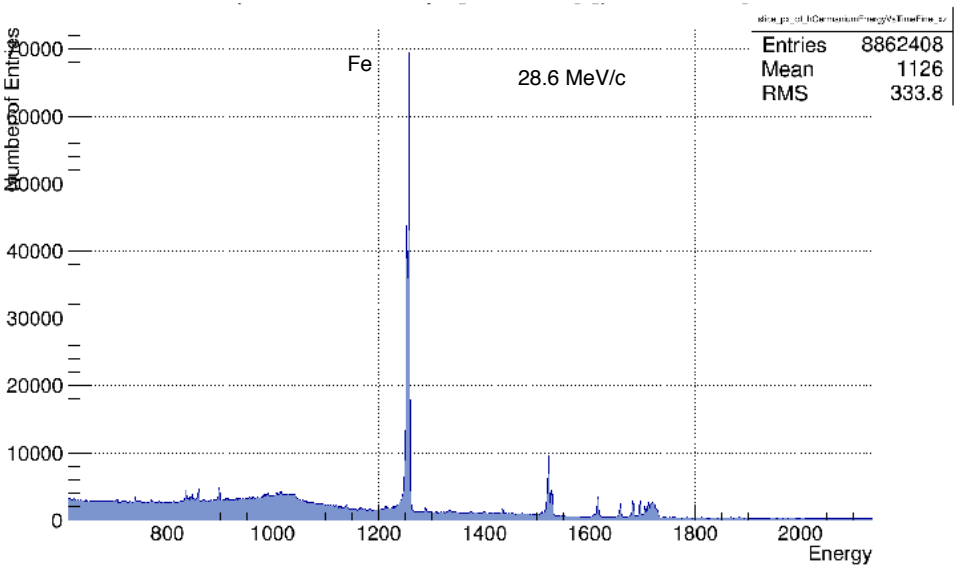
Measuring some other targets

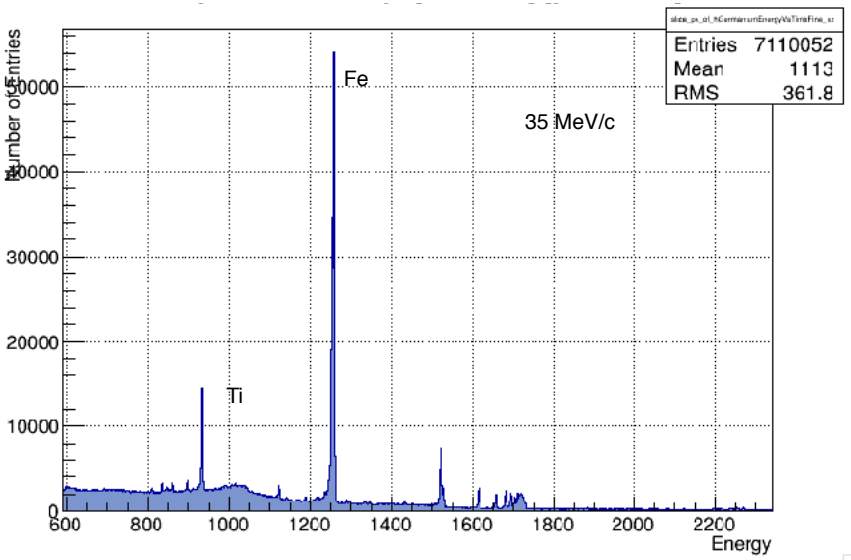


- Decided to measure some samples that are useful:
  - Gold: Has never been properly measured & published
  - Terbium/hafnium: Ideal test cases to extract quadrupole moments from 5-4 transitions
- Gold coin was a present to Finn ;-), Klaus brought terbium and hafnium from Cologne

Elemental analysis with negative muons

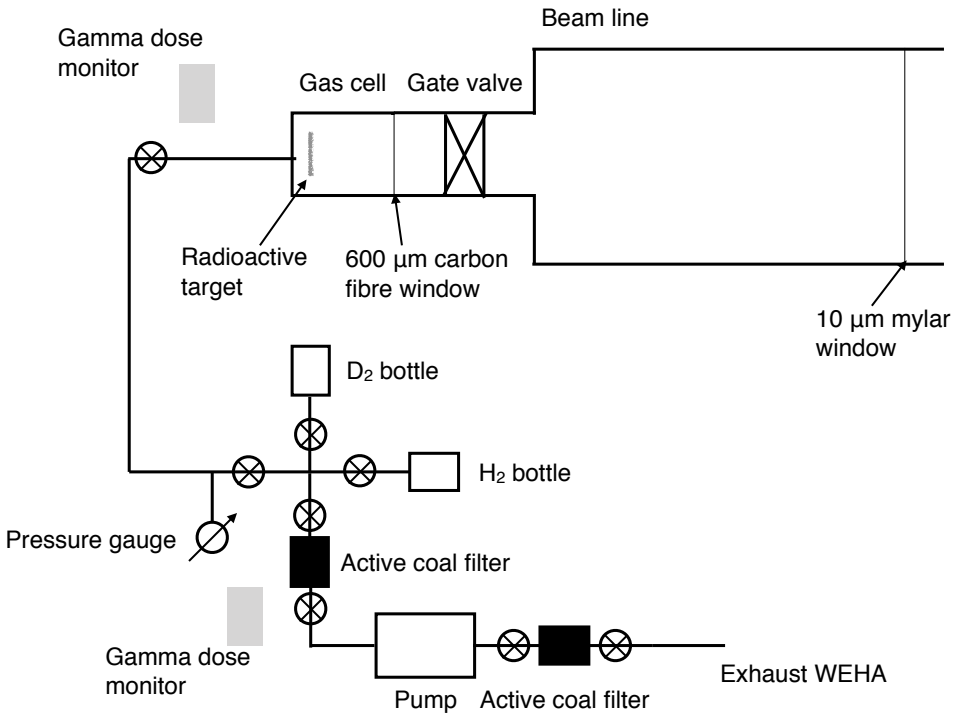






- Elemental analysis with muonic x-rays
- Depth profiling as a function of momentum
- Proof-of-principle with stacks of foils

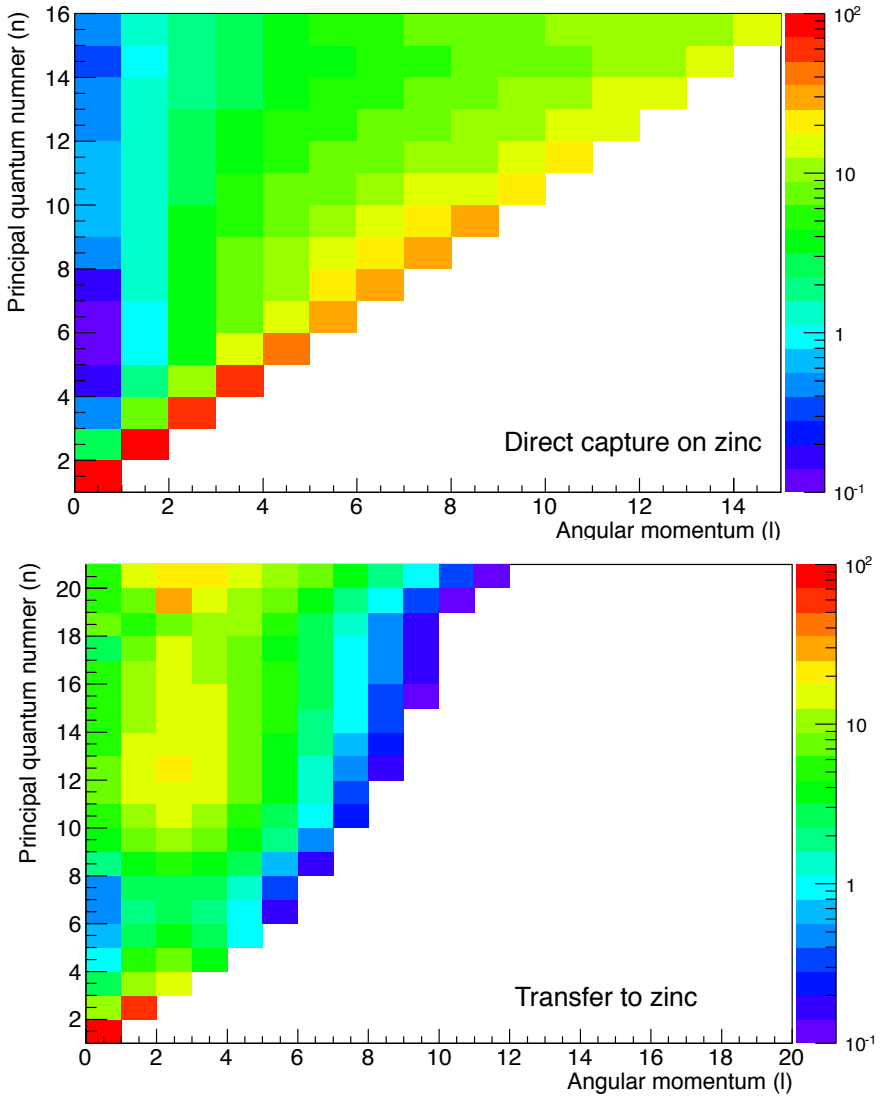
Safety



- Implemented full safety features for handling radioactive targets

Muonic cascade

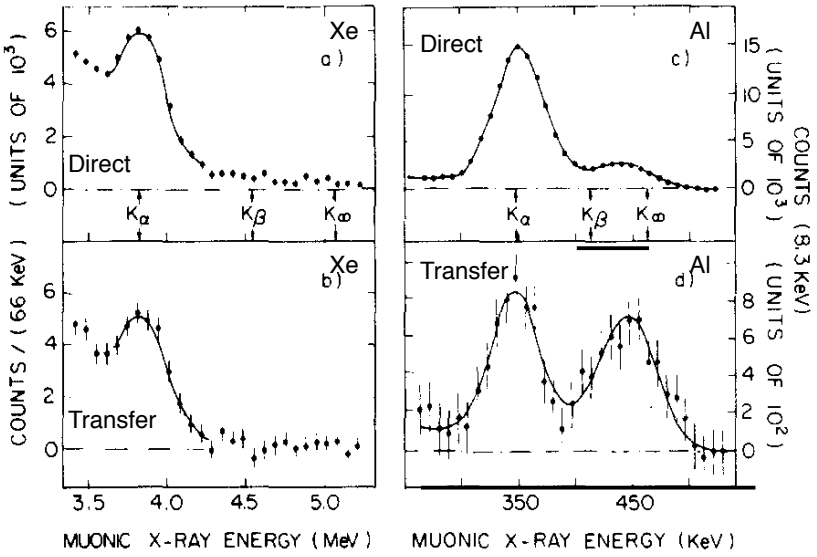
- Muonic cascade after transfer favors higher np-1s transitions
- Experimentally confirmed for many low- and medium-Z atoms



Muonic cascade

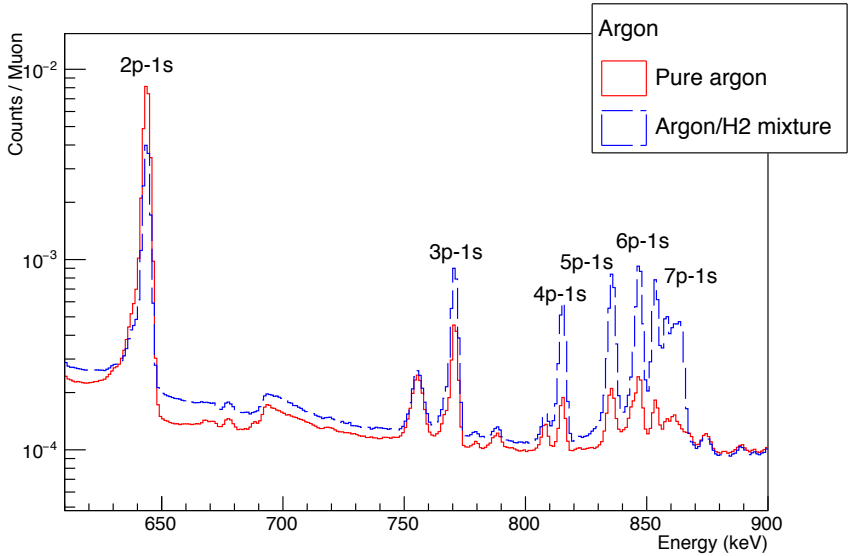
- One publication that claims that enhancement is not seen in high-Z atoms
- Troubling as would like to predict our yields
- Additionally need to do a cascade calculation to predict the relative strengths of all the HFS states

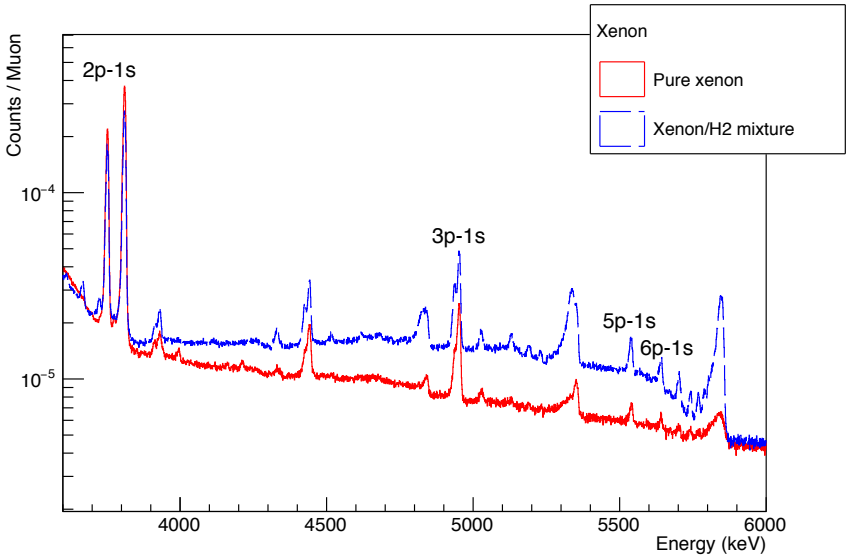
Bertin et al., Phys. Lett. **74A**, 39 (1979)



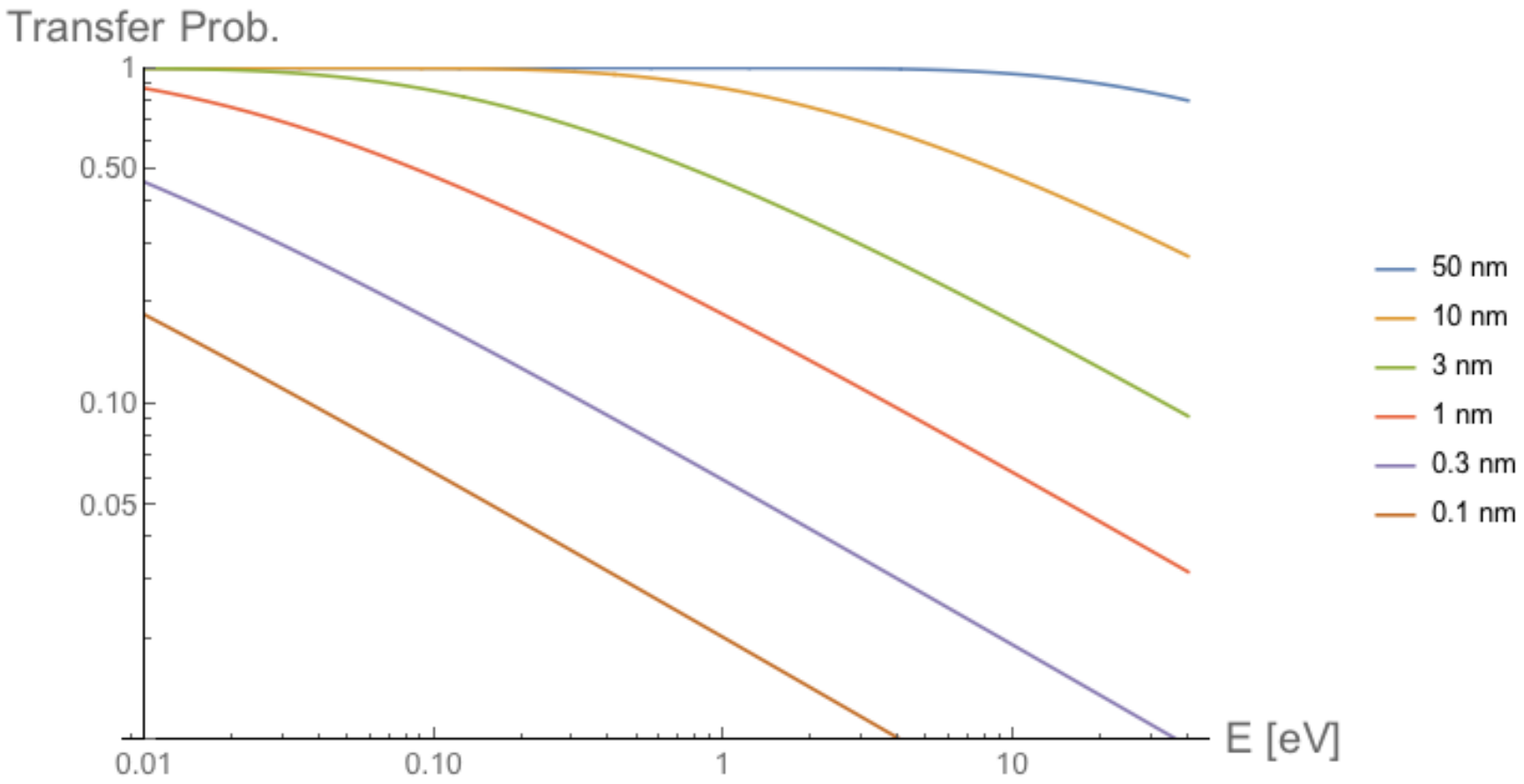
Measurements with noble gases

- Performed measurements in pure Ar, Kr, Xe and corresponding mixtures with H_2
- Effect of enhanced np-1s clearly seen also in Xe
- Detailed yields under investigation

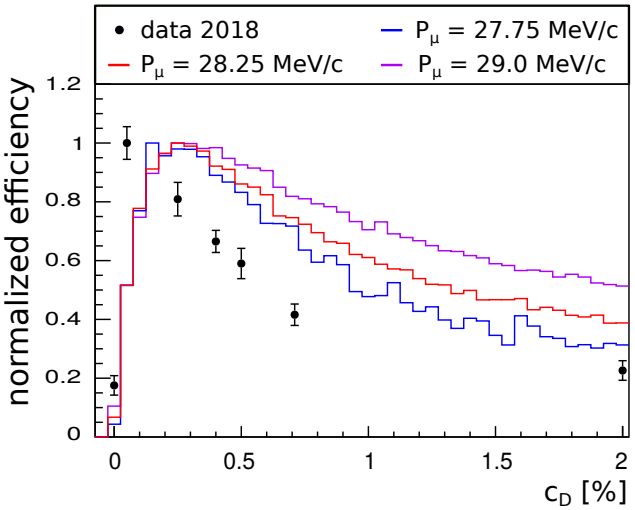




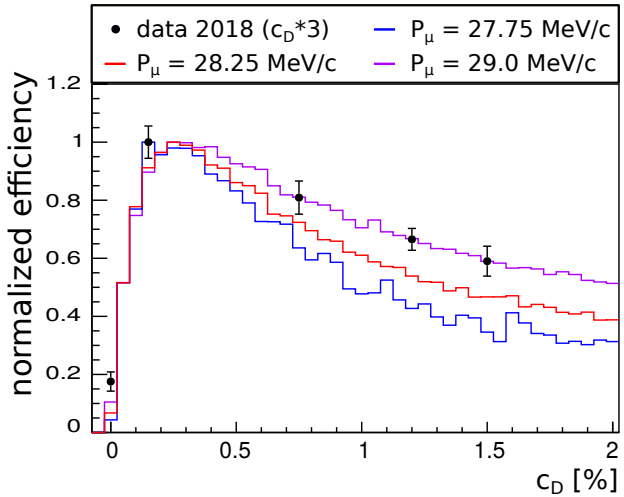
Transfer Probability in Gold



Puzzle of deuterium concentration



b) c_D scan (P_μ=28.6 MeV/c)



c) c_D scan, modified data