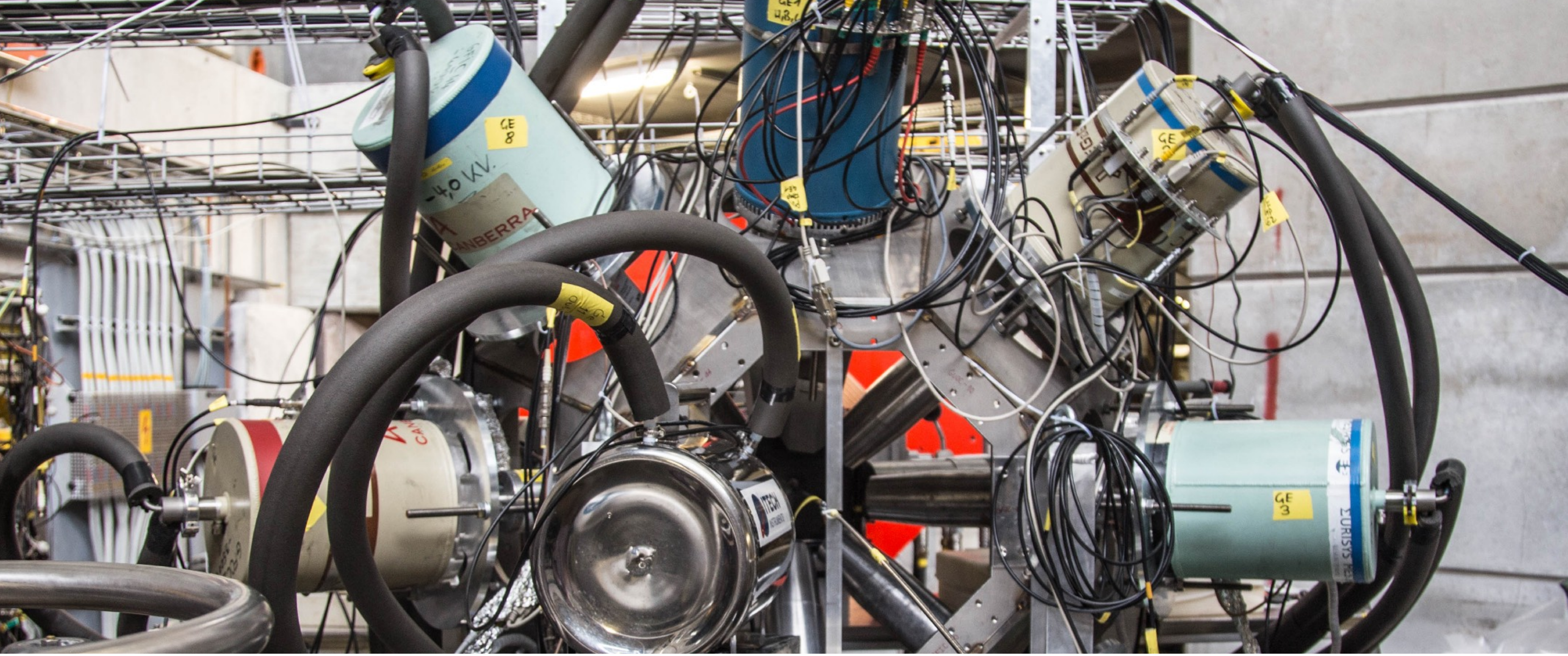

THE NUCLEAR CHARGE RADIUS OF RADIOACTIVE ISOTOPES BY MUONIC X-RAYS MEASUREMENTS

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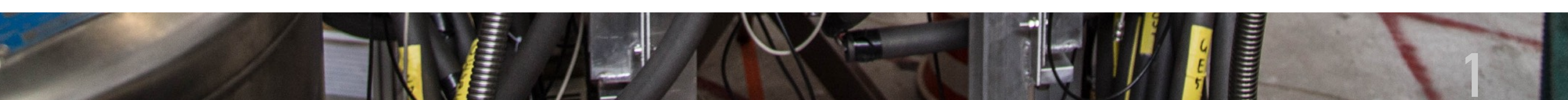
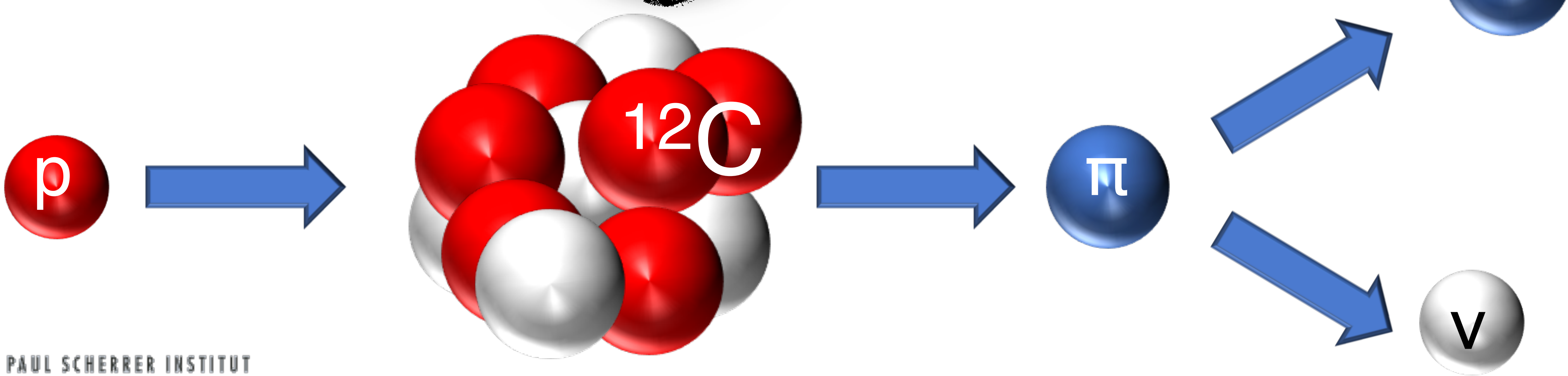
Alexander Albert Skawran, PSI
For the muX Collaboration



MUON

- “Big brother” of the electron
- 200 times heavier than an electron
- Lifetime of 2.2 μs
- Same electric charge as electrons
- Pion decay is used for muon creation at PSI



Scheme of pion production at PSI

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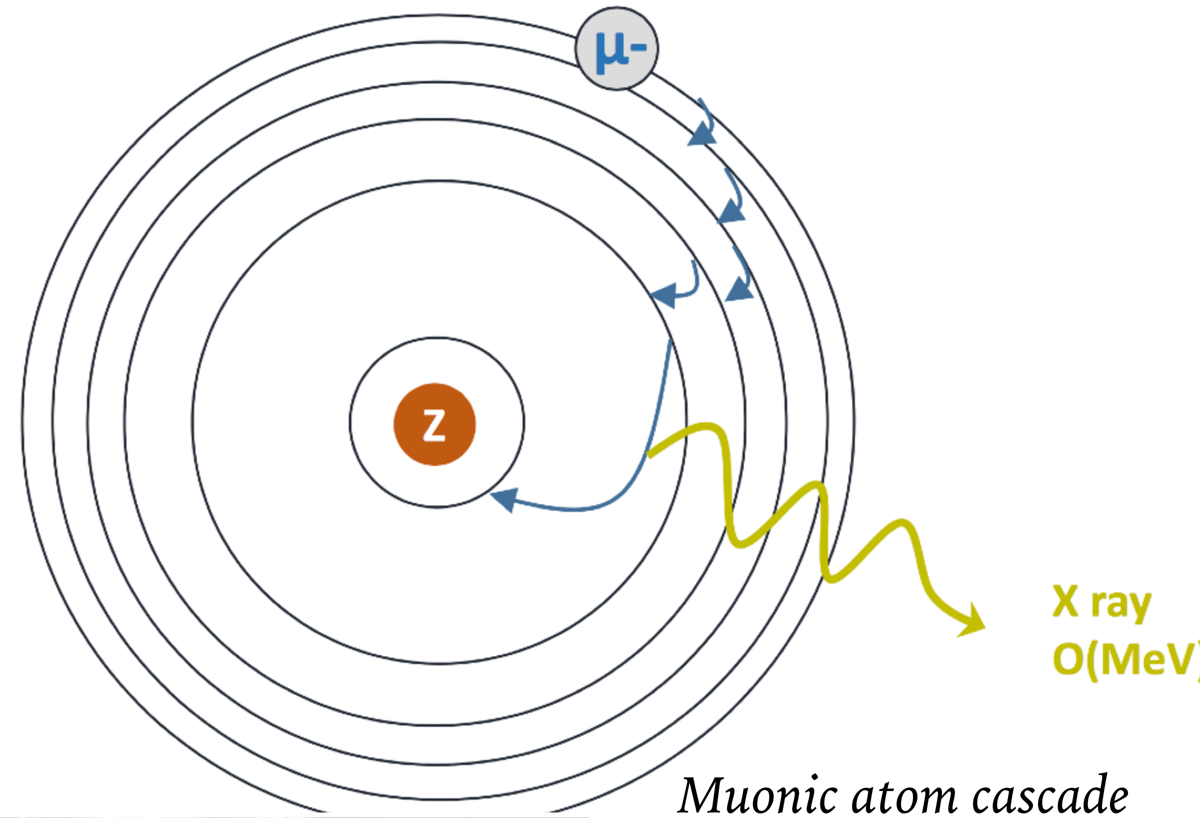
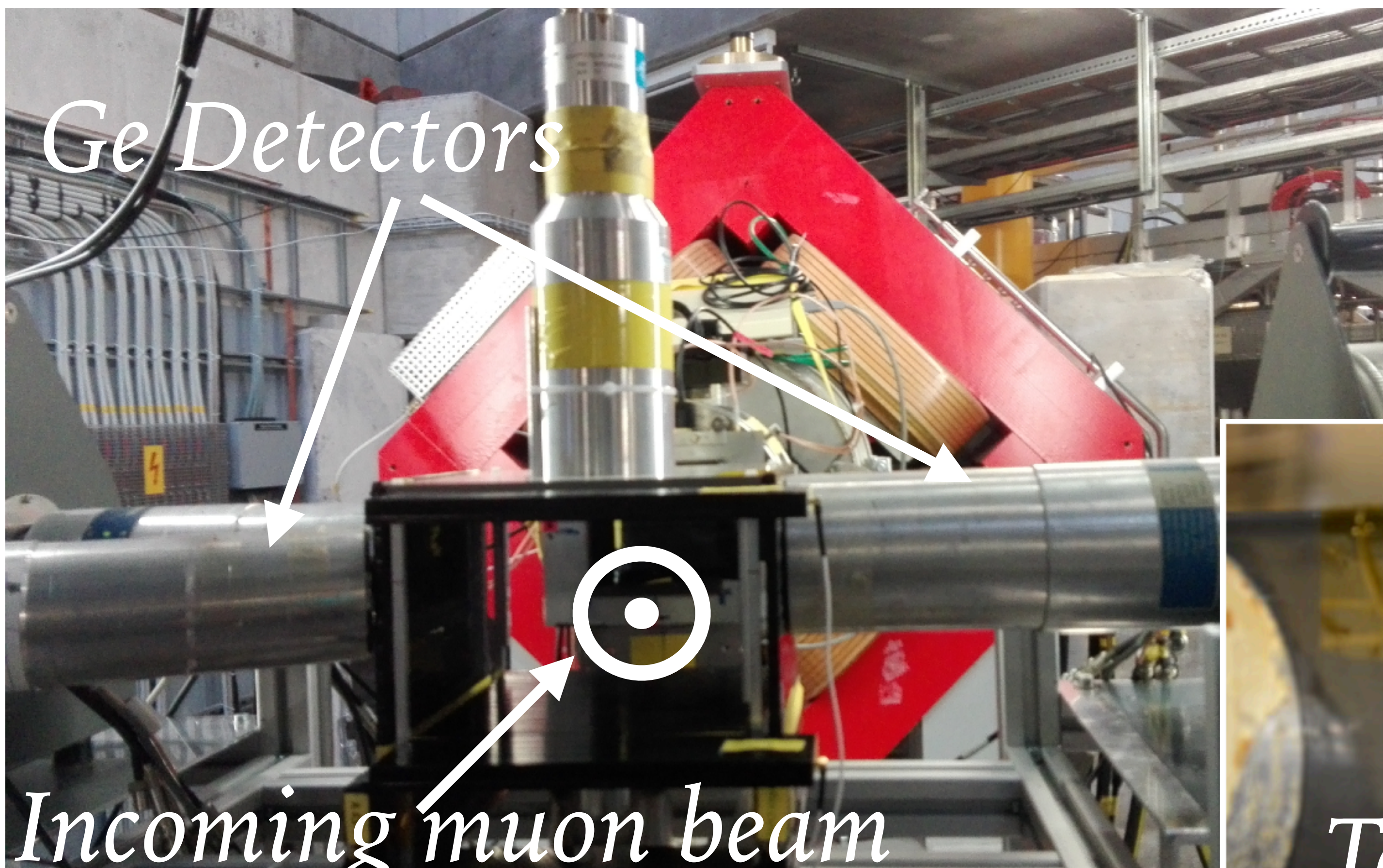
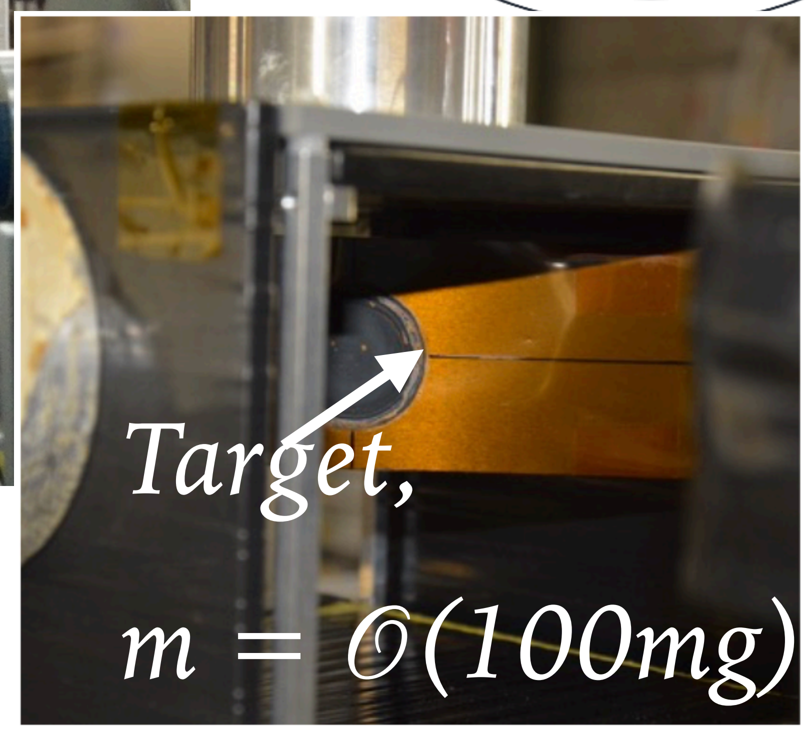
"TRADITIONAL" MUONIC ATOM SPECTROSCOPY



Muonic atom cascade



Example of standard setup for muonic atom spectroscopy



Simple target setup for unlimited target amount

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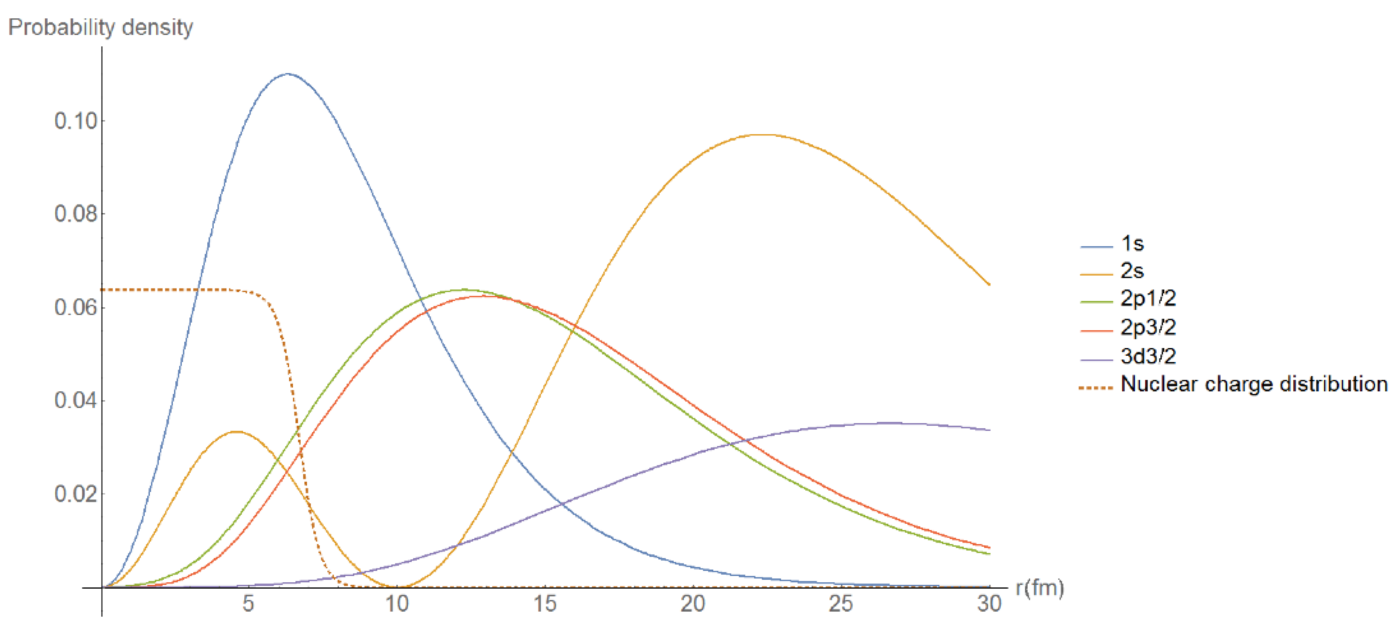
NUCLEAR CHARGE RADII



Muon and nuclear charge distribution lead-208

$$E_{1s}\ (Z=82) \sim 19\ \text{MeV (point nucleus)}$$

$$10.6\ \text{MeV (finite size)}$$

Kessler et al., PRC **11**, 1719 (1975)

- Muonic atom energy spectrum is highly sensitive to nuclear charge distribution due to larger overlap
- Charge radius is extracted by QED calculations and model for nuclear charge distribution
- Precise radius extractions are possible
- Example: For ^{208}Pb was achieved a RMS radius of 5.5031(11) fm with 2x10^{-4} relative precision

(Bergem et al., Physical Review C 37.6 (1988): 2821)

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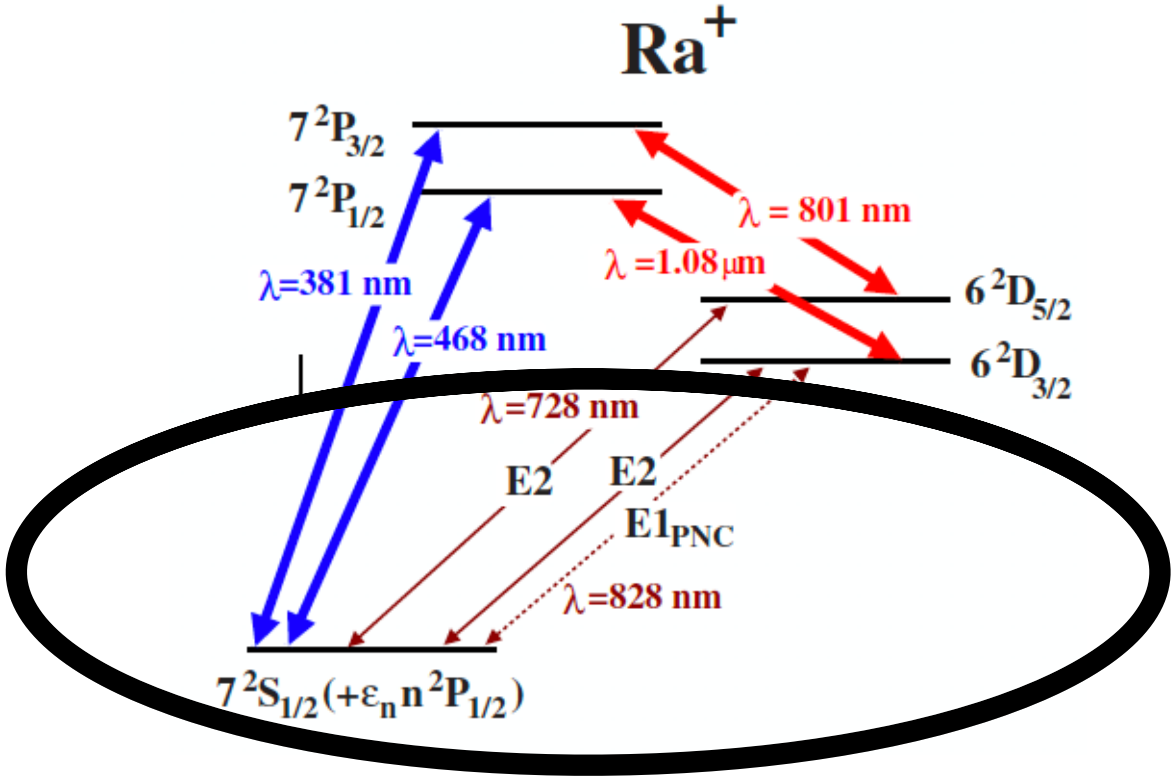
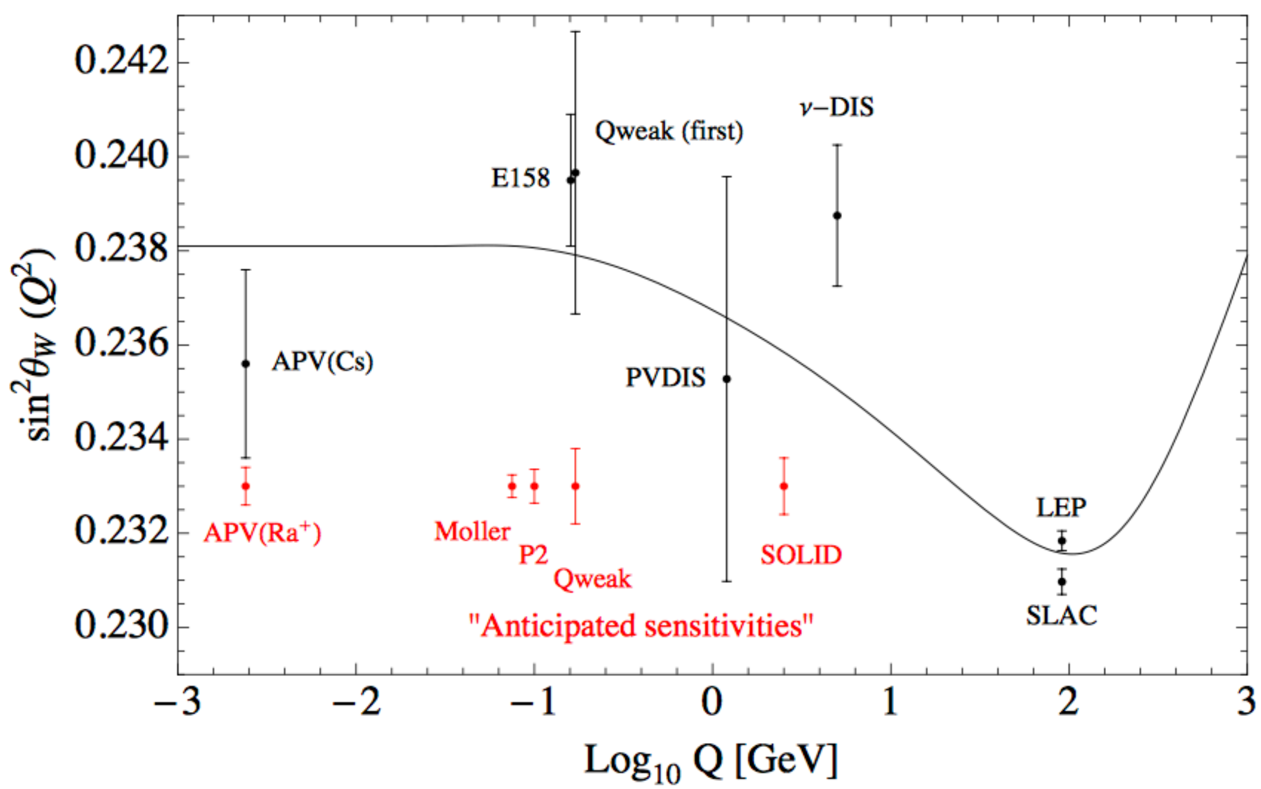


Parity non conserving transition in Ra-226



Wansbeek et al., PRA **78**, 050501 (2008)
Wood et al., Science **275**, 1759 (1997)
Lee, arXiv:1511.03783 (2015)

NUCLEAR CHARGE RADIUS OF ^{226}RA

- A planned atom parity violation experiment requires the radium charge radius with 0.2% accuracy
- E1 transition between $6^2D_{3/2}$ and $7^2S_{1/2}$ is forbidden
- Due to weak interaction a small admixture of E1 in E2 is possible
- Using precise calculations the admixture can be used to extract weak charge

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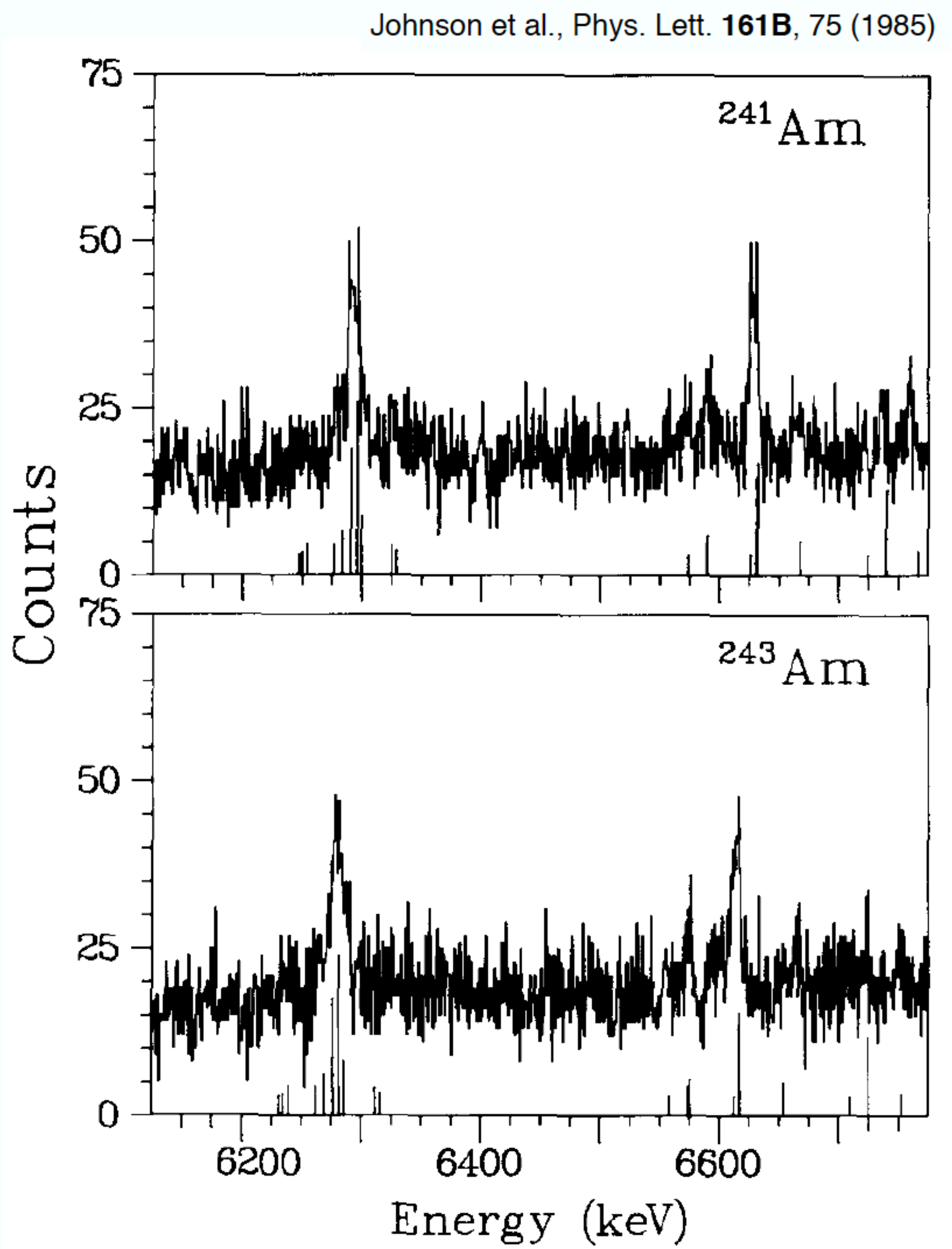
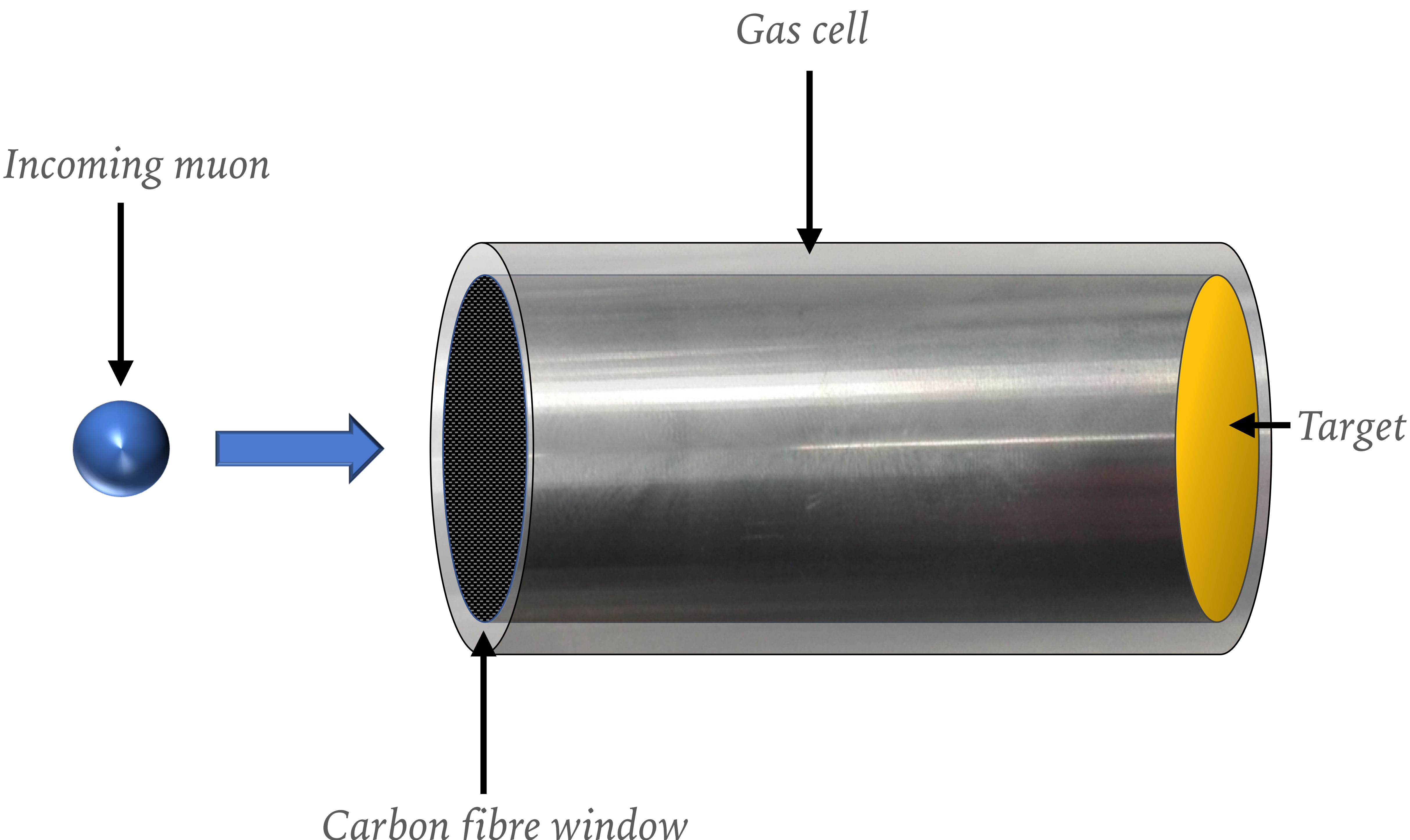


Energy spectrum of Americium-241 and -243

RADIUM TARGET

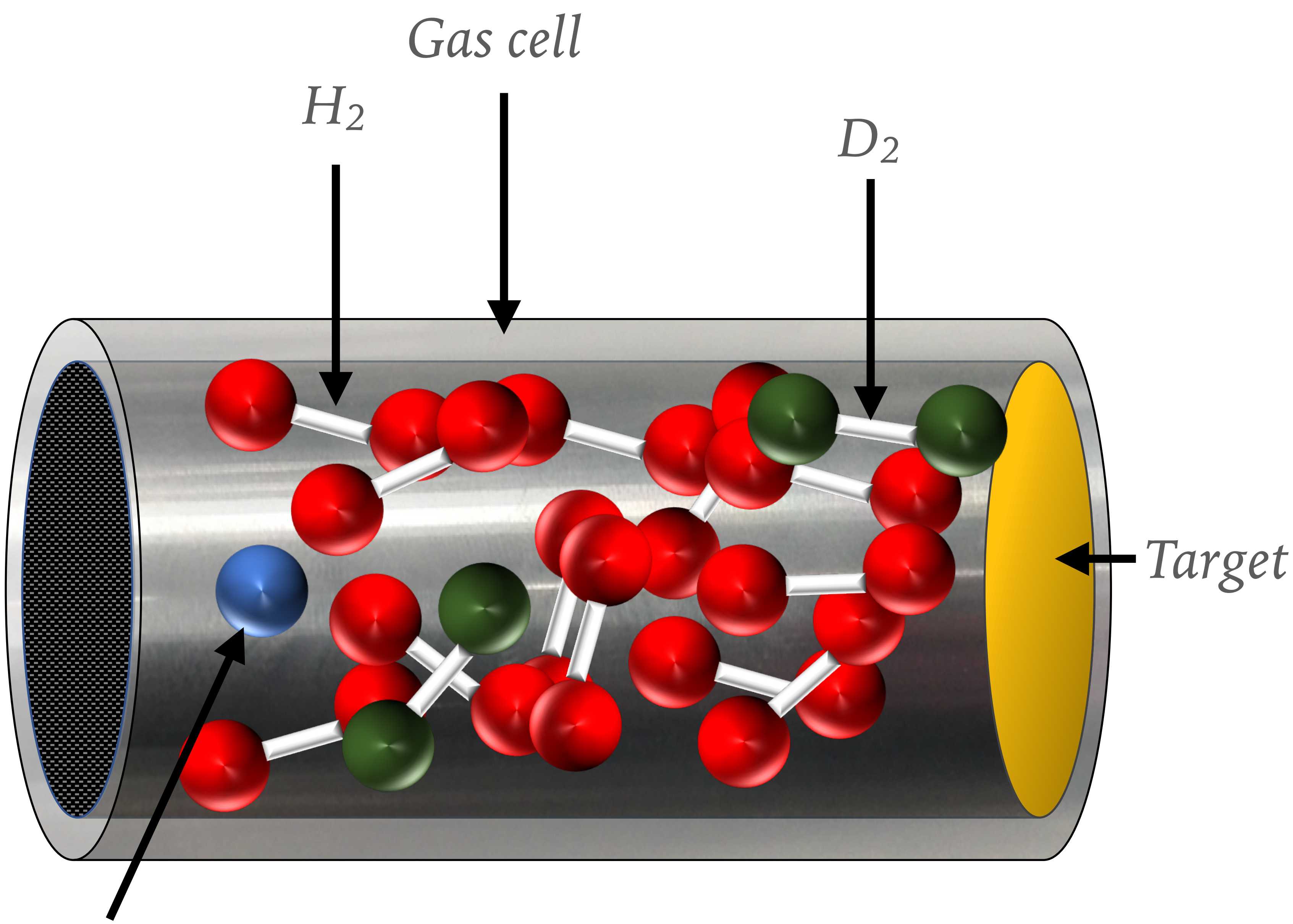
- So far only a few radioactive isotopes measured with muonic atom spectroscopy
- In the paper they describe the target weight as "modest weight of 1 g"
- The radium-226 target is allowed to have only several μg due to radioactivity safety regulations
- To stop enough muons O(100 mg) of radium are required
- New target set up required to increase event rate

SKETCH GAS CELL TARGET



SKETCH GAS CELL TARGET

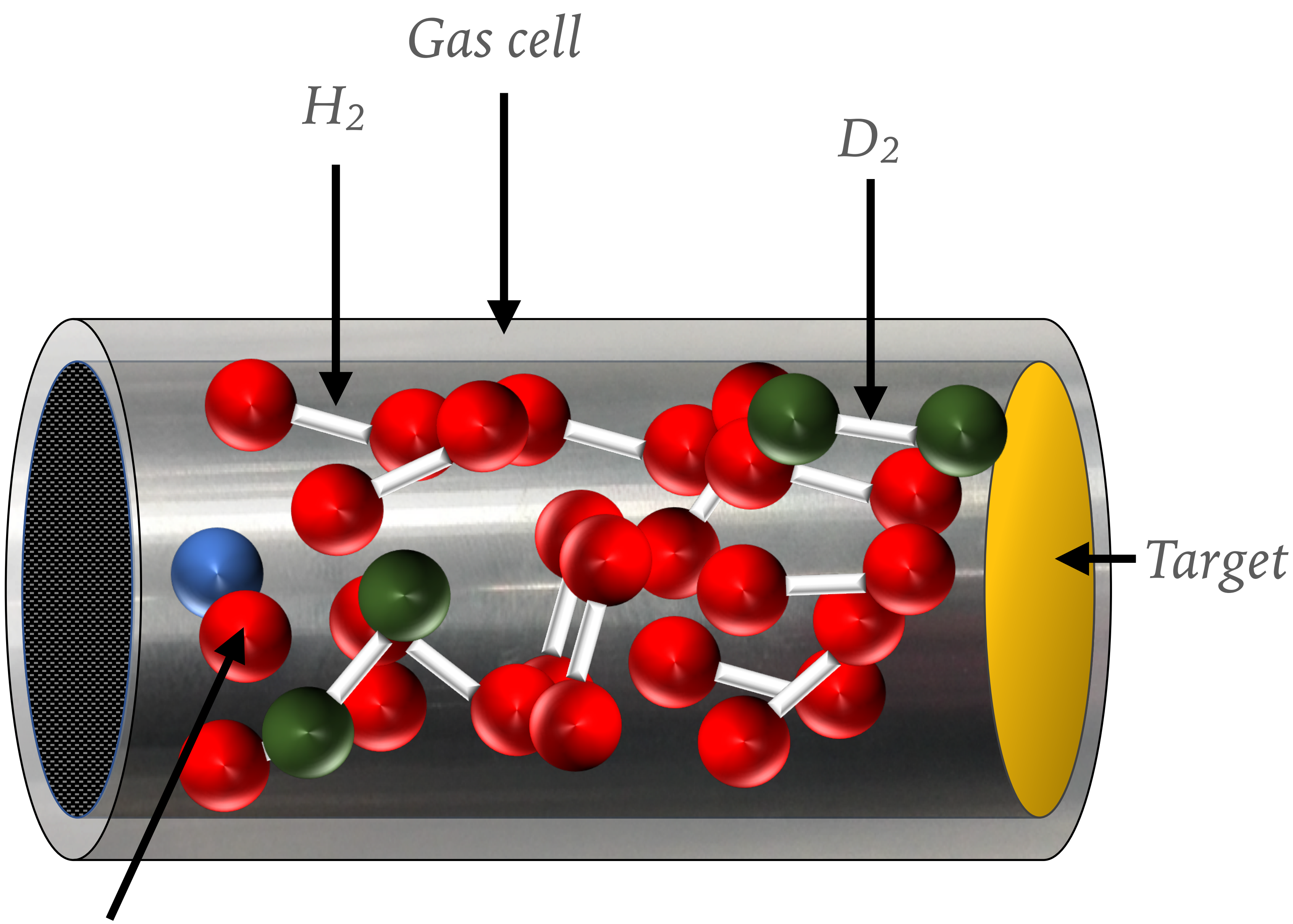
- *Gas cell is filled with 100 bar hydrogen and 0.25% deuterium admixture*



Muon collides with H_2 molecules in gas cell

SKETCH GAS CELL TARGET

- *Gas cell is filled with 100 bar hydrogen and 0.25% deuterium admixture*



Muon in gas cell is captured by a proton of a H_2 molecule.

Muonic hydrogen μp is produced.

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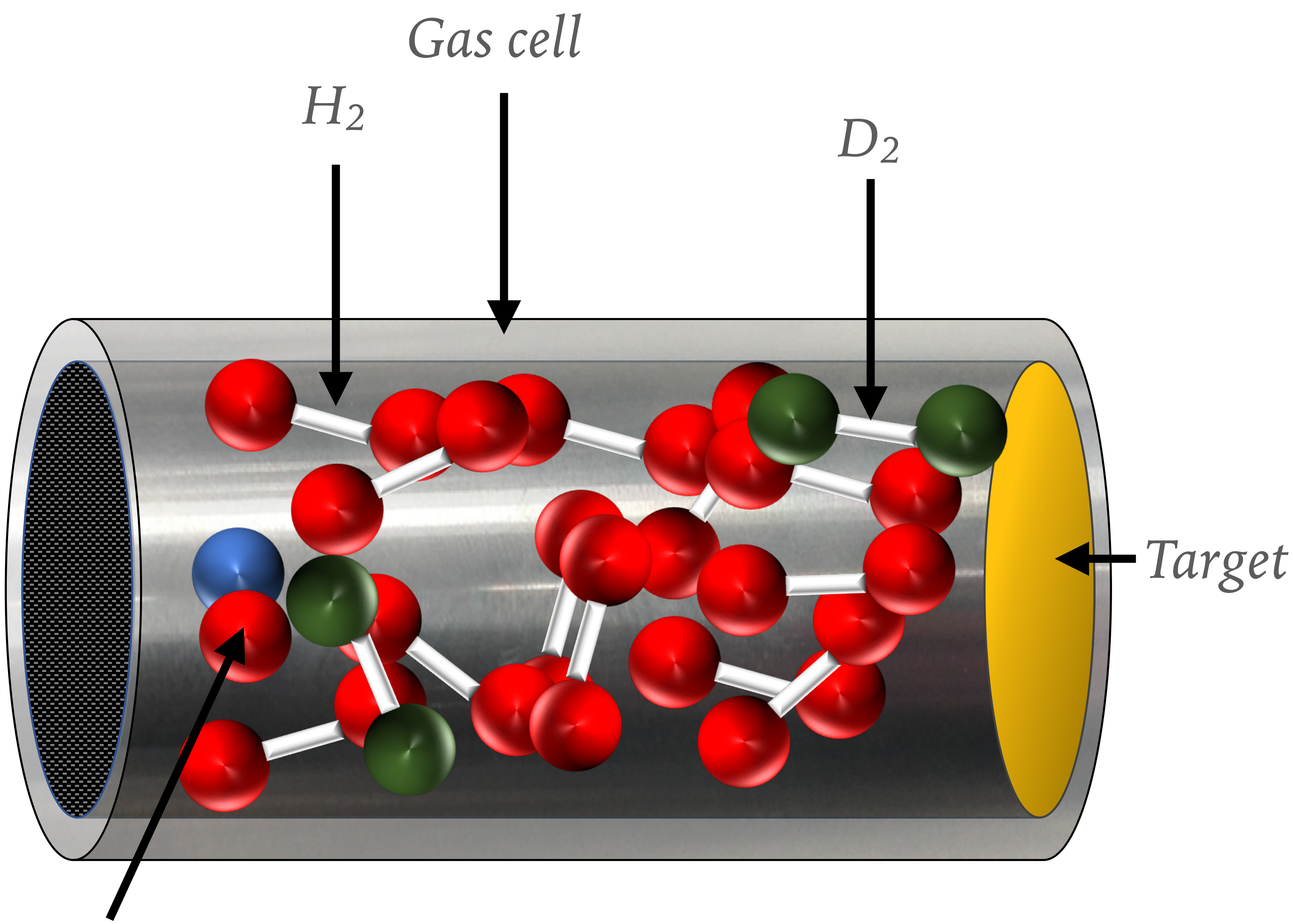
SKETCH GAS CELL TARGET

- *Gas cell is filled with 100 bar hydrogen and 0.25% deuterium admixture*



Muonic hydrogen collides with D_2. The muon is transferred to a deuteron. The transfer results in μd with a kinetic energy boost of several eV.

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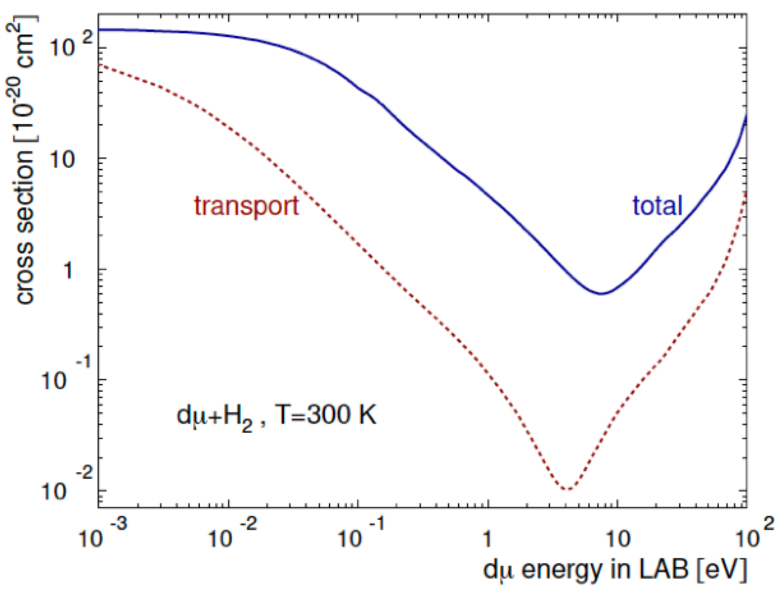
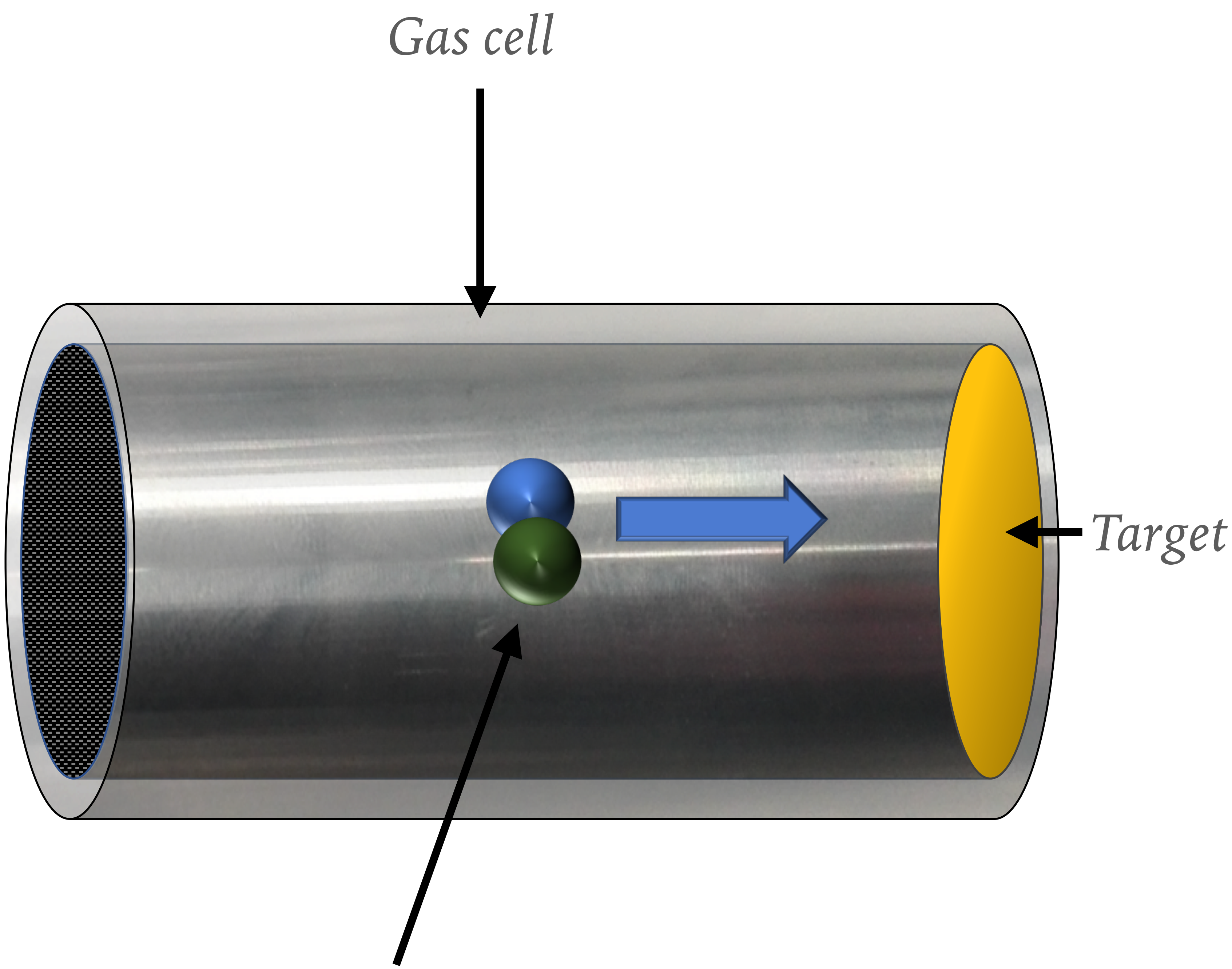
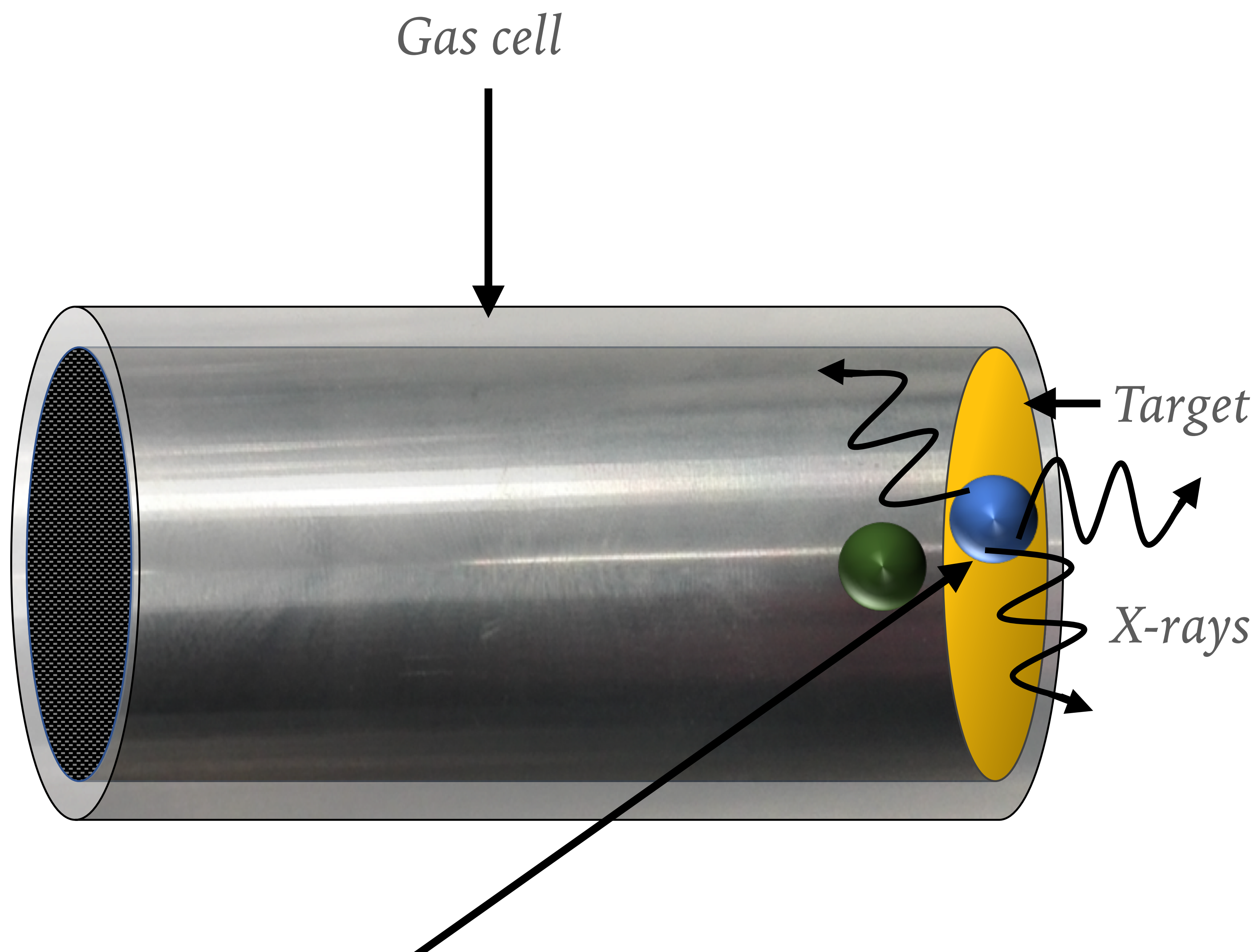
SKETCH GAS CELL TARGET





The gas is almost transparent to the μd atom due to the Ramsauer-Townsend effect. μd can move to target.

SKETCH GAS CELL TARGET



The μd atom transfers the muon to the target. Muonic X-rays are emitted.

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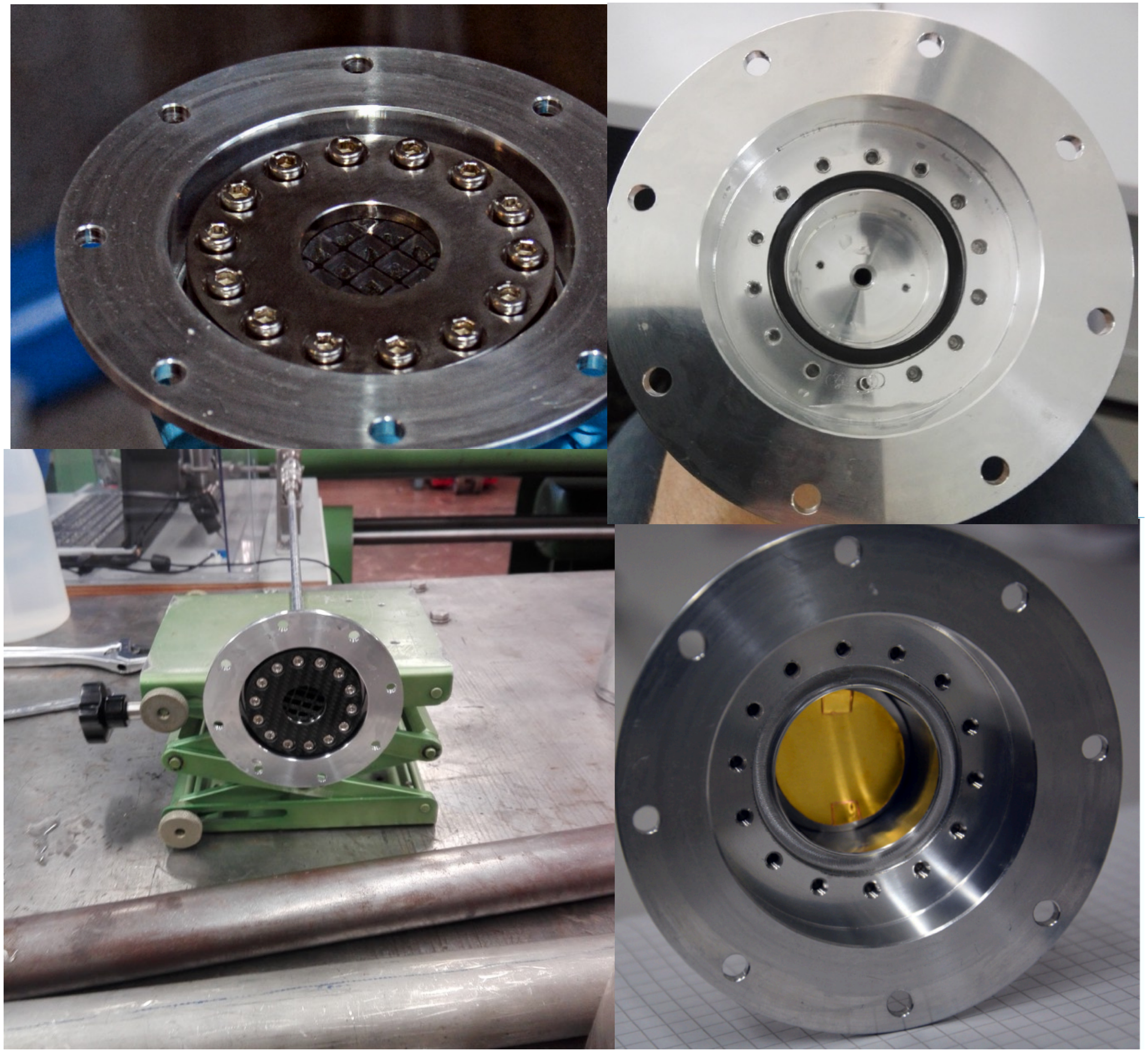
PRESSURE TEST GAS CELL



- Gas cell has to resist a pressure of 100 bar
- Tested different setups
- Final set up includes a carbon fibre window with two support grid layers containing carbon fibre and titanium
- Window withstands a pressure of more than 350 bar, some screw threads could not take the increasing pressure

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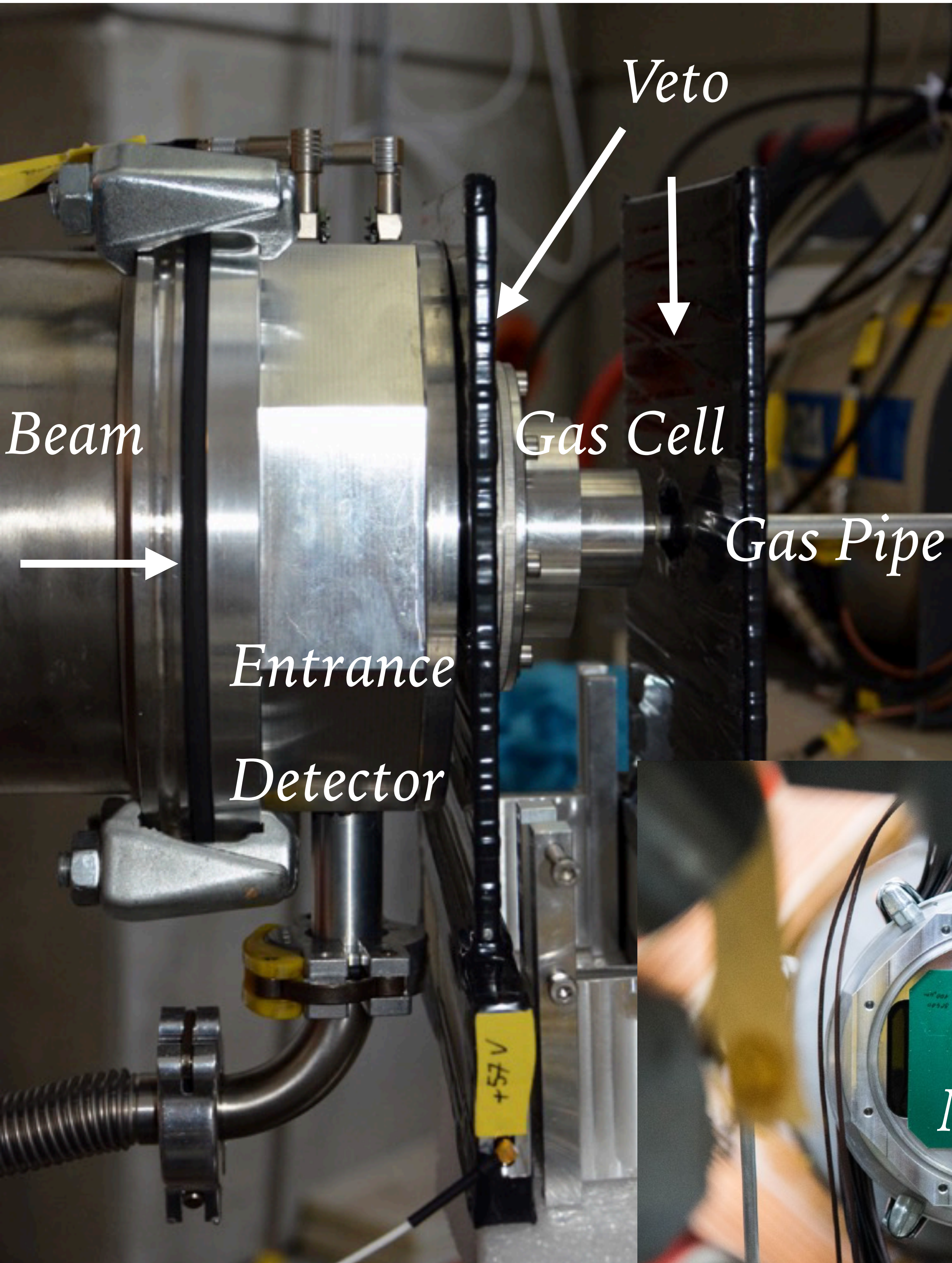
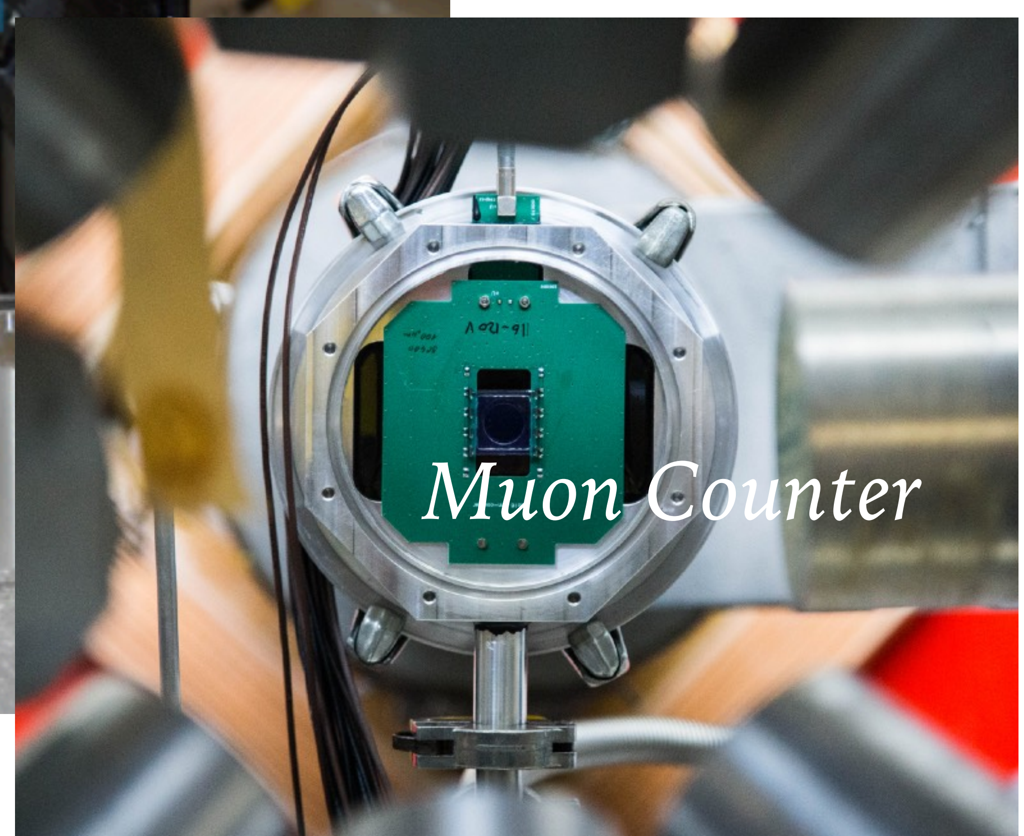
MUON COUNTER

- To estimate the efficiency of the muon transfer to the target and to detect coincidences a thin scintillator is used to detect incoming muons.
- Other scintillators are used as veto detectors for anti-coincidence with decay electron.





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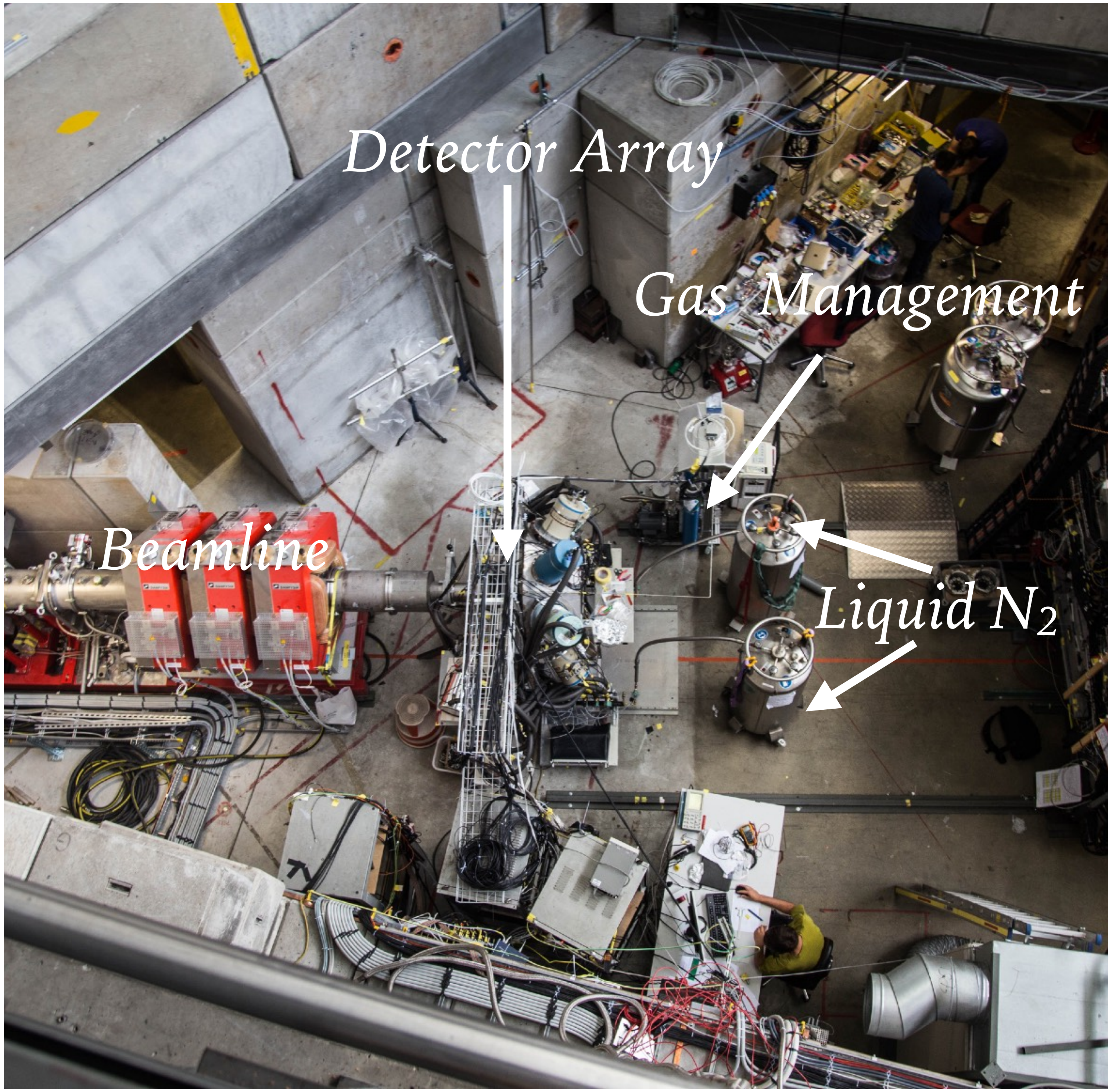
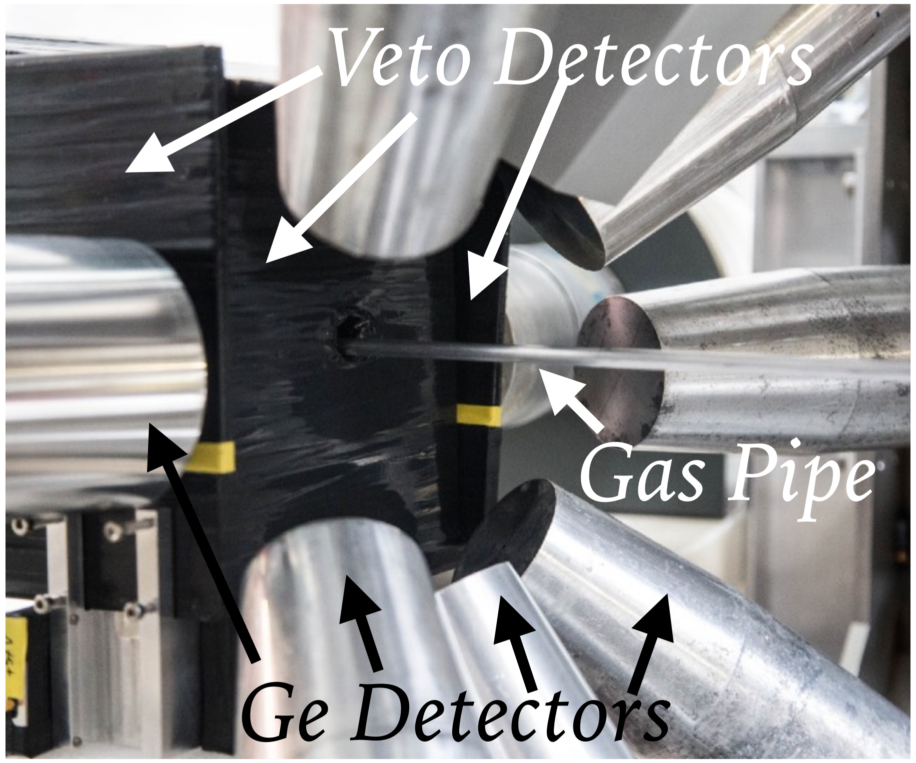
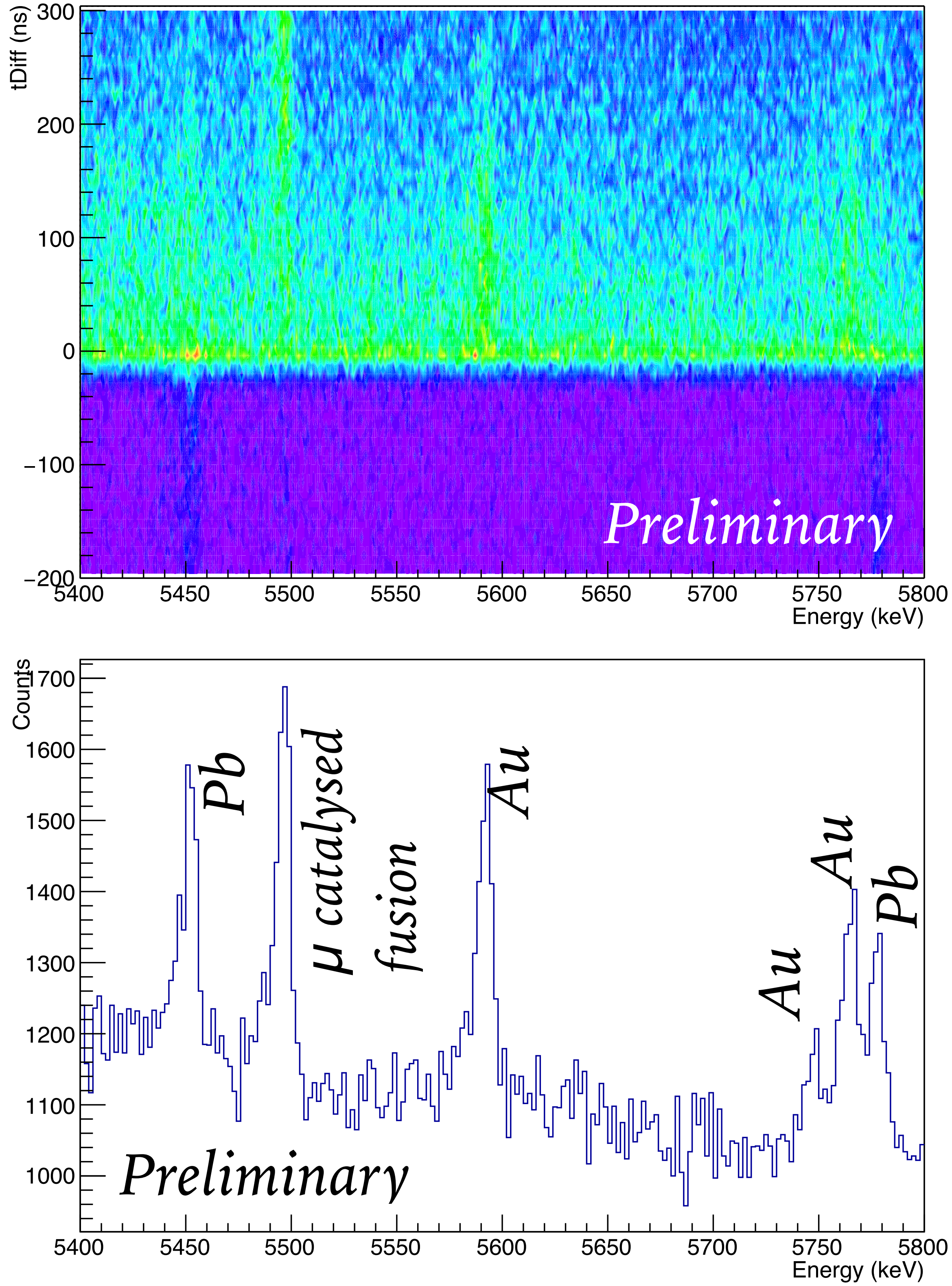
SET UP GOLD TARGET TEST



- During 2017 an array of 11 Ge detectors were used
- It was the first time that an array was used for muonic atom spectroscopy





Energy spectrum of 5 μg gold target

GOLD SPECTRUM

- Used gold to test muon transfer
- Observed gold spectrum with 5 μg target
- Used lead for energy calibration
- Observed also muon catalysed fusion

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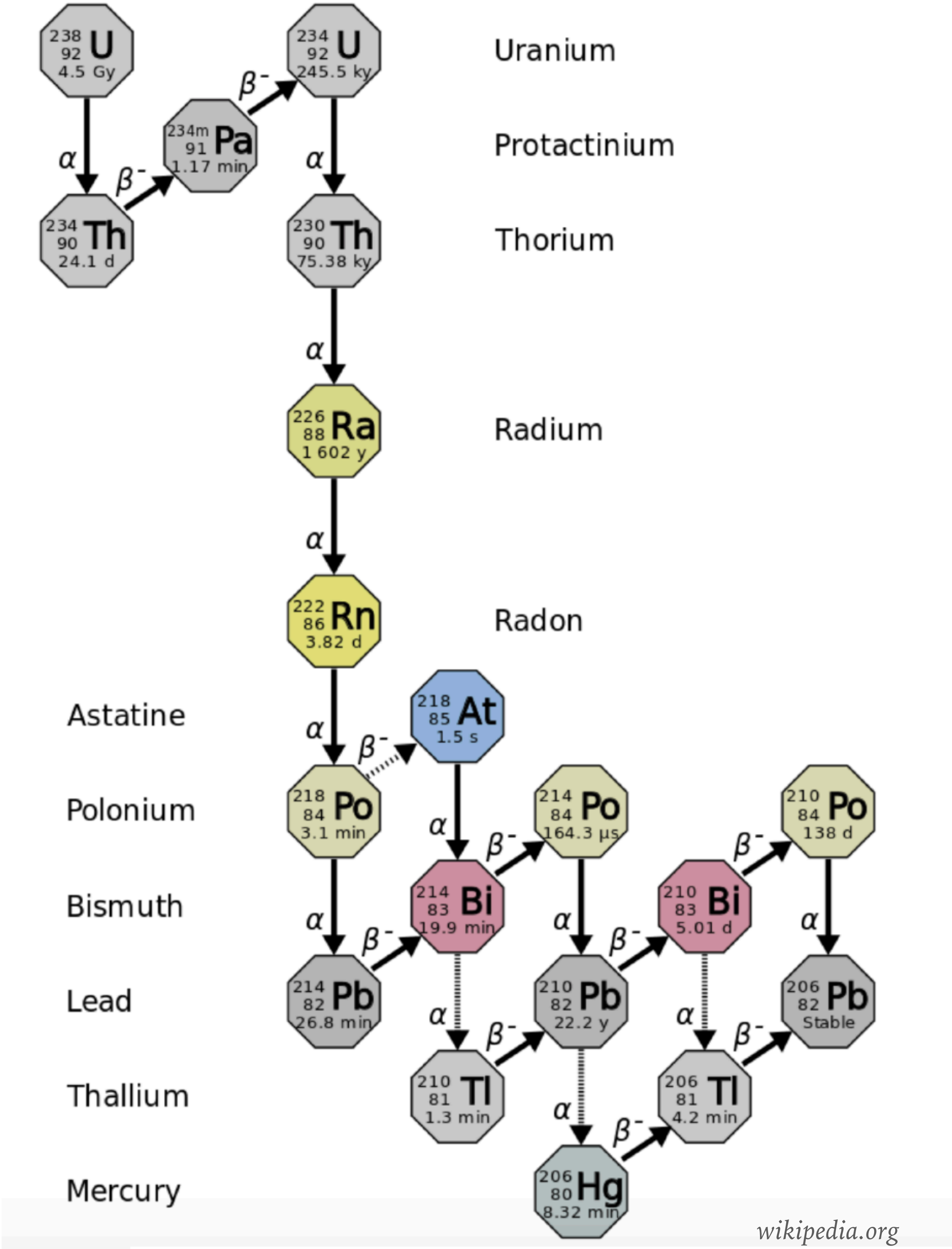
MUON TRANSFER EFFICIENCY

Target	Size	Backing	N_γ / N_μ	ϵ
50 nm Au	4.9 cm^2	Cu	$(10.9 \pm 0.3) \times 10^{-5}$	10.0%
10 nm Au	4.9 cm^2	Cu	$(6.9 \pm 0.2) \times 10^{-5}$	6.3%
3 nm Au	4.9 cm^2	Cu	$(3.6 \pm 0.1) \times 10^{-5}$	3.3%
3 nm Au	4.9 cm^2	kapton	$(3.2 \pm 0.1) \times 10^{-5}$	2.9%
3 nm Au	1 cm^2	Cu	$(1.3 \pm 0.1) \times 10^{-5}$	1.2%

Detected gammas per muon fraction in gold targets (preliminary)

- Detected 2p-1s gammas per incoming muon for various target sizes and amounts
- Type of backing layer seems to have negligible influence
- Even a sufficient number of photons is achieved in the 5 μg target

GAMMA, BETA BACKGROUND OF ^{226}RA SOURCE



Decay chain of Radium-226

- A 5 μg radium-226 target leads to 200 kBq of all daughter
- Highest gamma emitters are lead-214 and bismuth-214
- The corresponding gamma rate is about 400 kHz

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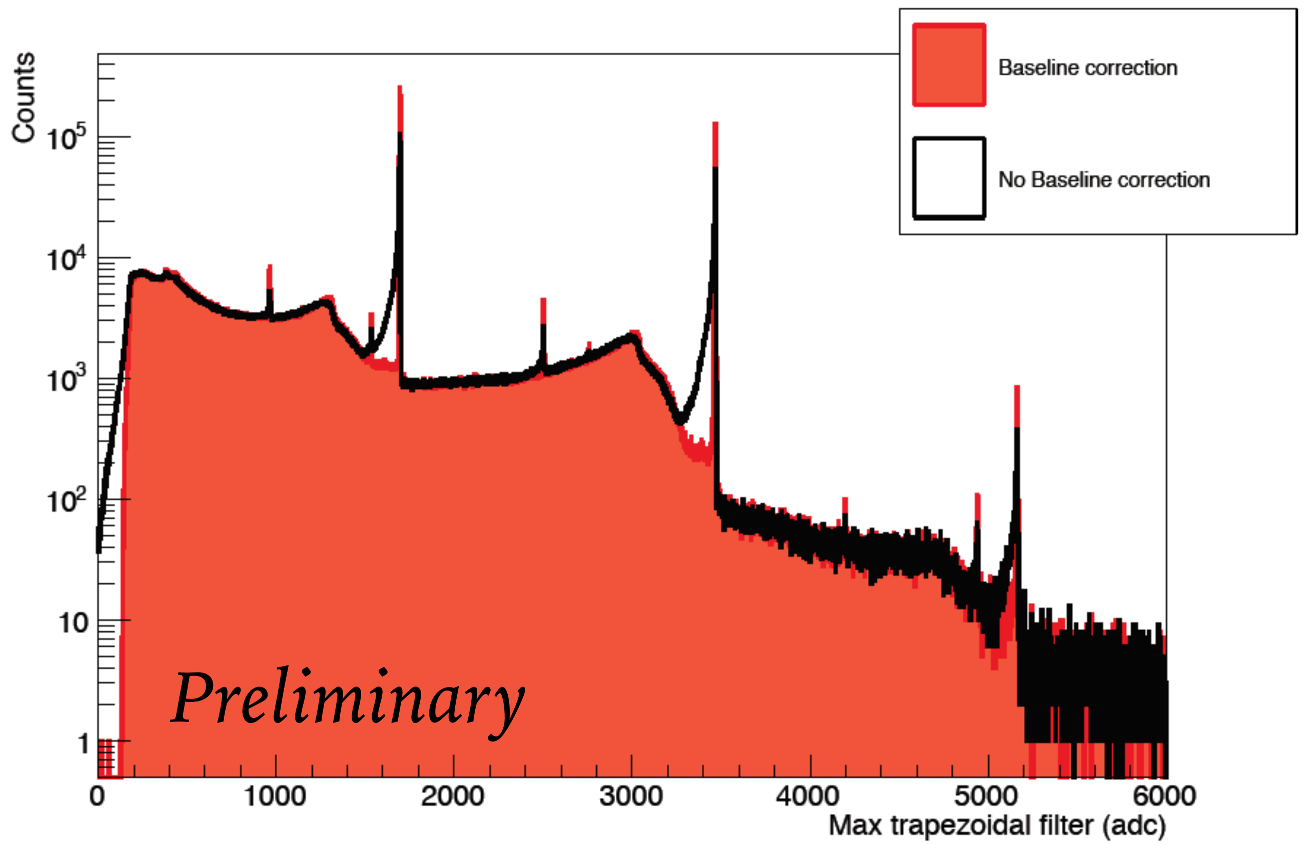
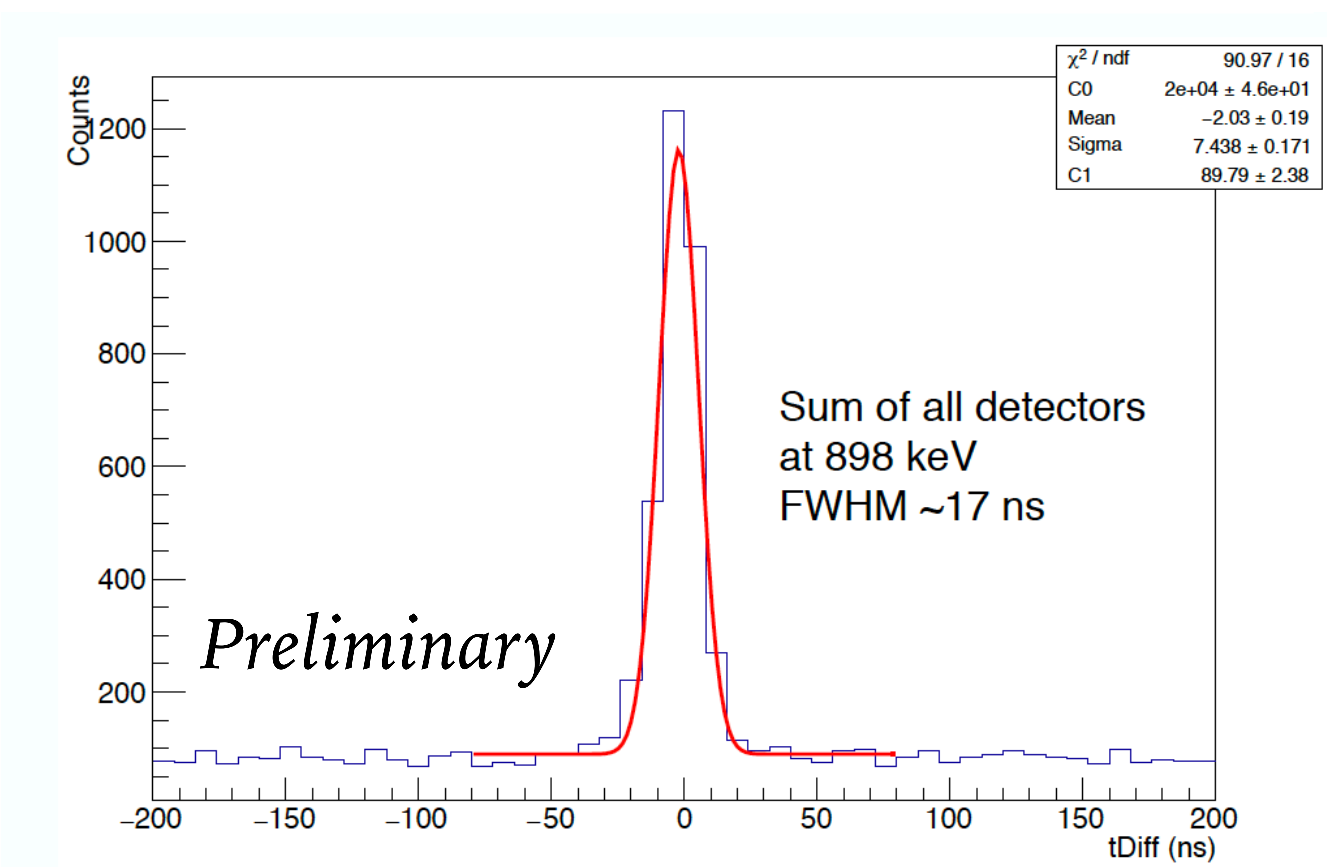
TIME AND ENERGY RESOLUTION RADIOACTIVE TARGETS



Effect of offline analysis on energy resolution

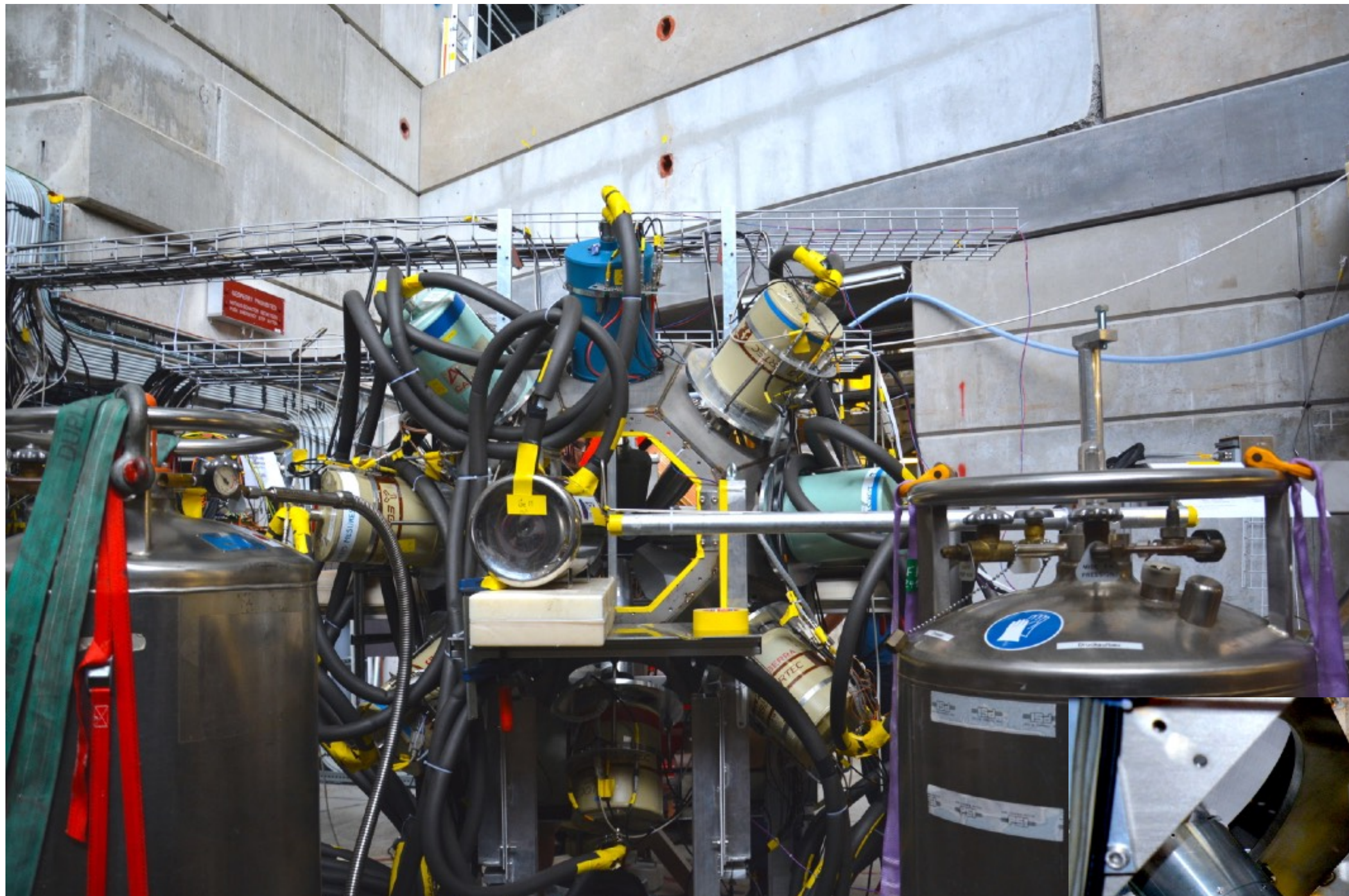


Time resolution of all Ge detectors at 898 keV

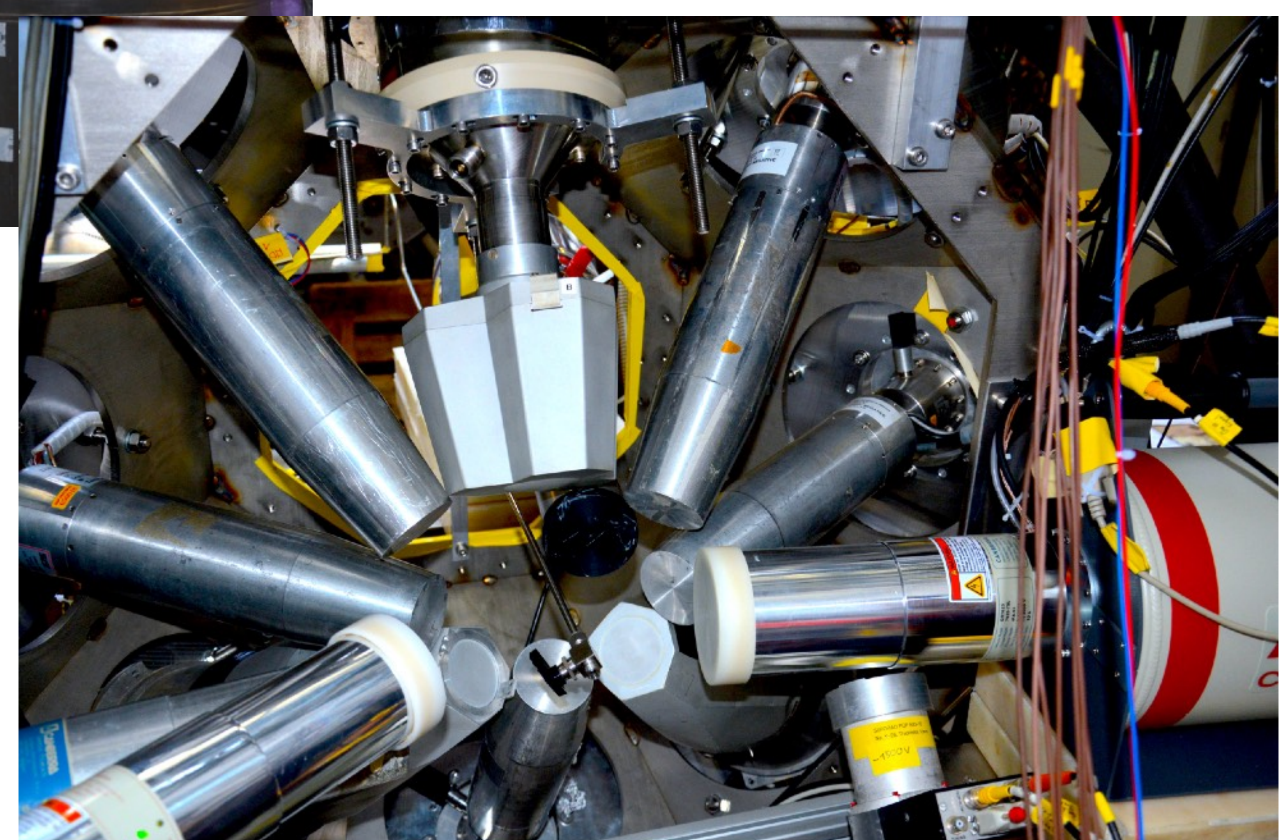
- Performed measurements of a high rate 420 kHz yttrium-88 gamma source
- The radium source has a similar activity
- Offline analysis improves time and energy resolution
- DAQ can handle high data rate

FIRST EXPERIENCES WITH CURIUM-248 AND RA-226 TARGETS

- During July 2018 the first attempt to observe muonic curium-248 and radium-226 happened
- The production of appropriate targets was unsuccessful



Detector setup radium-226 measurement



Detector array radium-226 measurement

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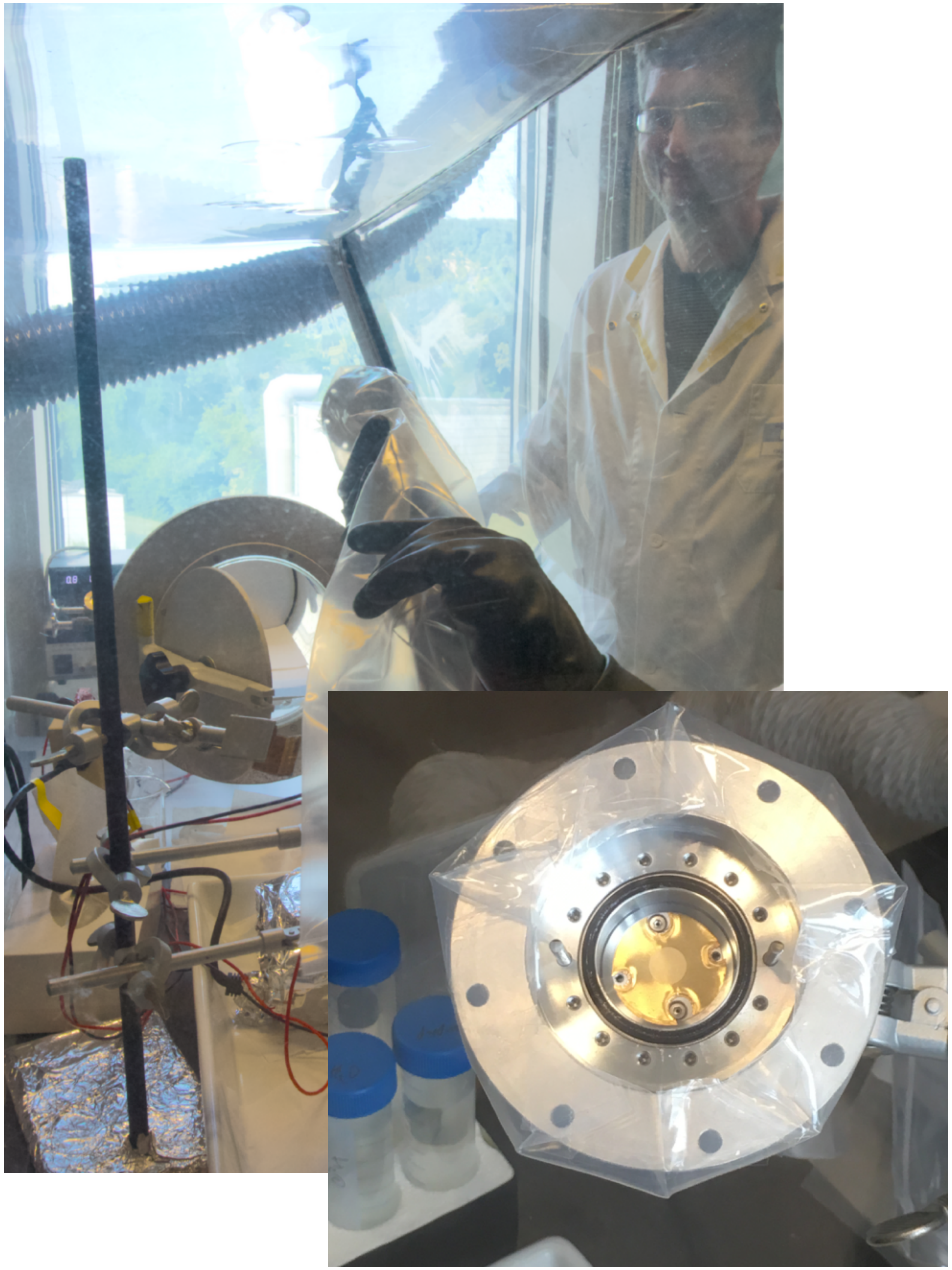
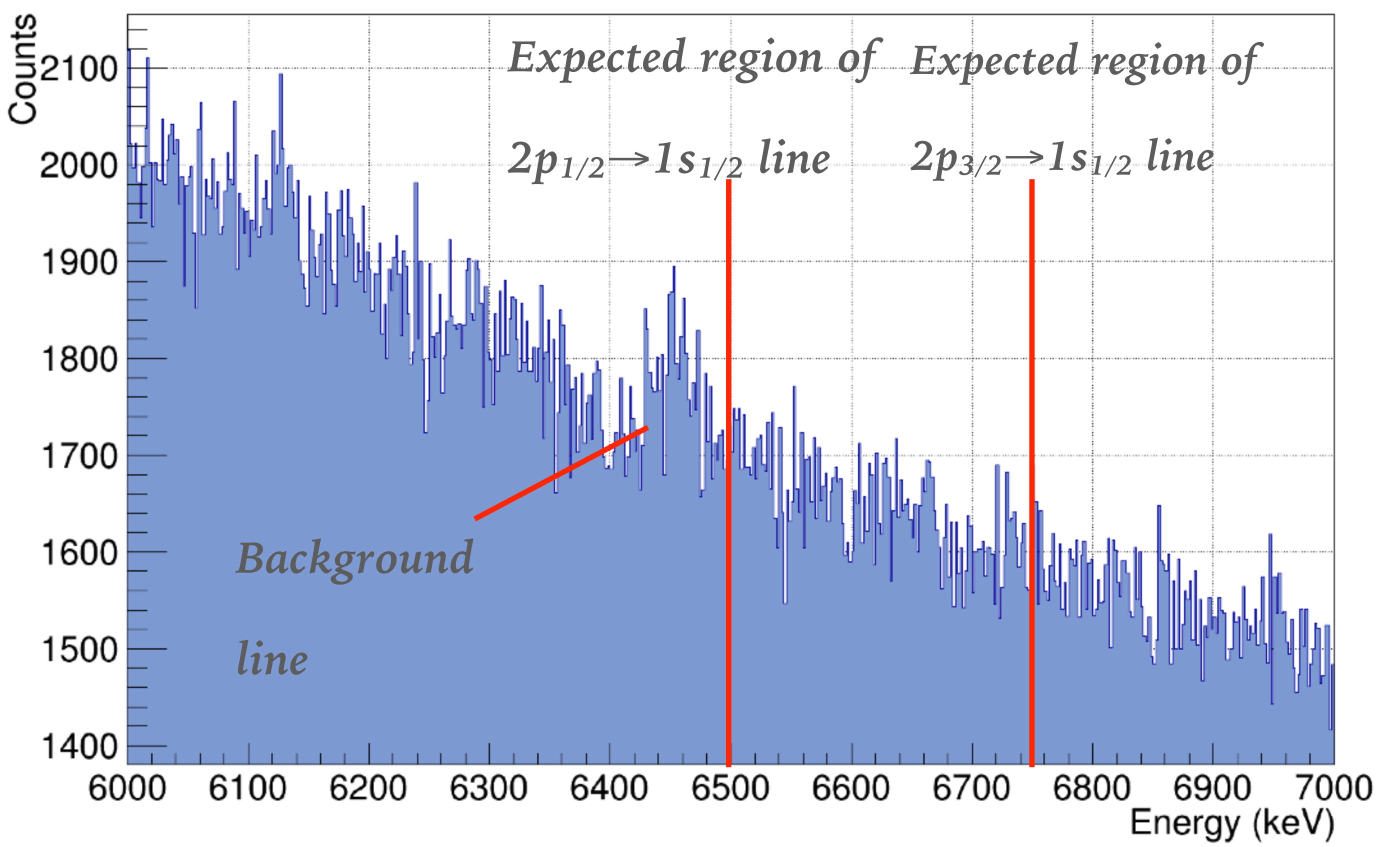
FIRST TRY WITH CURIUM-248



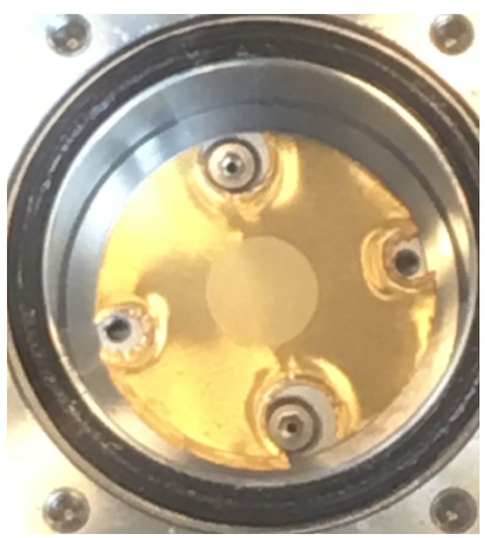
Curium gas cell prepared for sealing

- A ***100 µm copper*** plate is used as a substrate for curium-248. The copper is covered by a ***50 nm*** thin ***gold*** film to avoid unwanted oxidation
- Curium-248 was fixed on the gold layer by electrolysis
- The activity of the ***curium-248*** probe was ***2,448 kBq*** (~37 µg)
- The probe included an admixture of ***curium-246*** with an activity of ***8,978 kBq*** (~2 µg)

OBSERVED SPECTRUM CURIUM-248

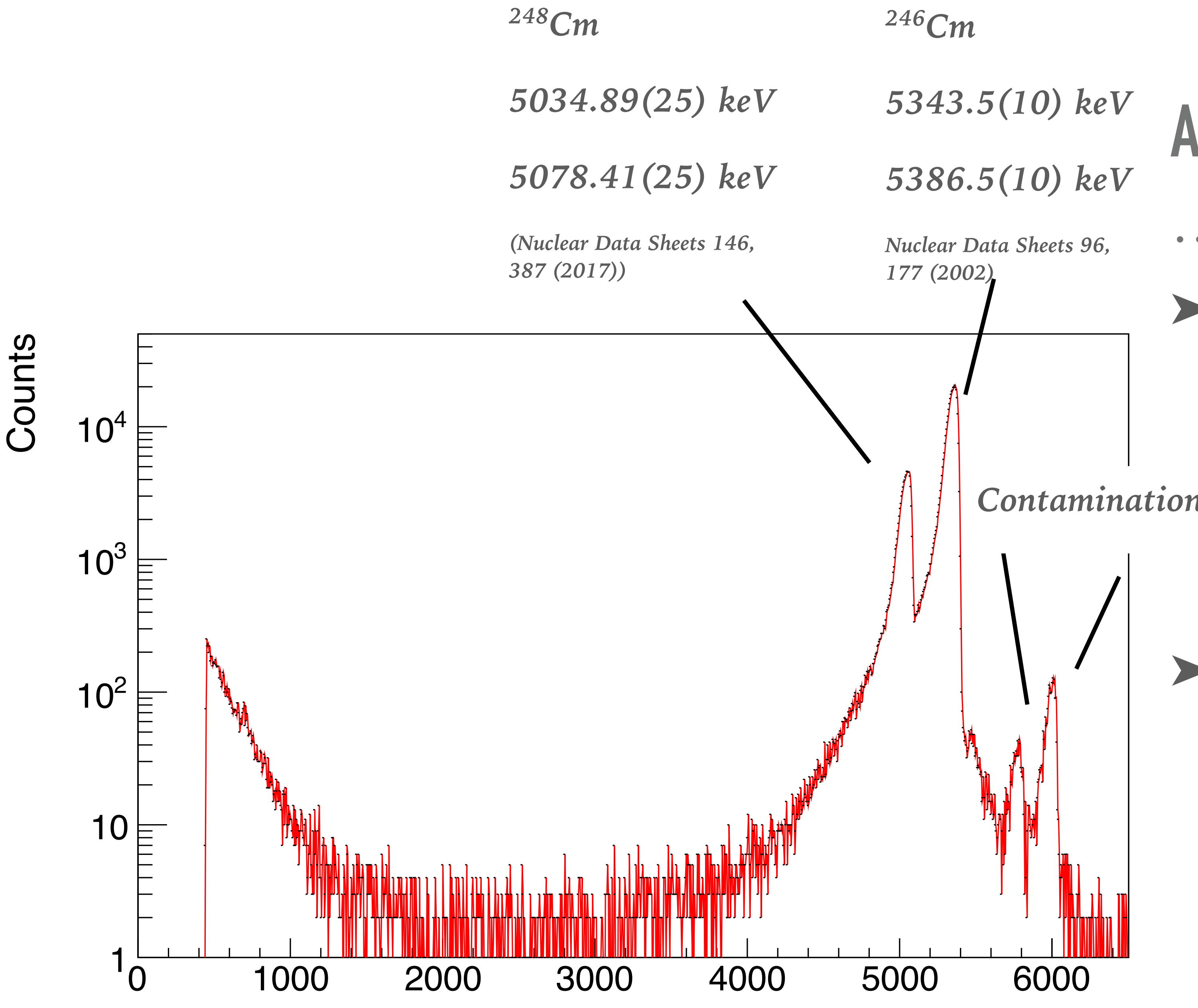


Observed energy spectrum of ^{248}Cm measurement in the expected 2p-1s region



^{248}Cm and organic compounds on the gold plate

- The estimated $2p \rightarrow 1s$ transitions for Cm-248 are:
  - $2p_{1/2}\rightarrow 1s_{1/2}$ ~6500 keV
  - $2p_{3/2}\rightarrow 1s_{1/2}$ ~6754 keV
- No Cm lines were observed
- Cm was plated on the Au-Cu plate. Hence, a disturbing organic layer could cover the Cm target
- A flame treatment was applied to reduce the thickness of the organic layer. This resulted in no improvement of the gamma spectrum

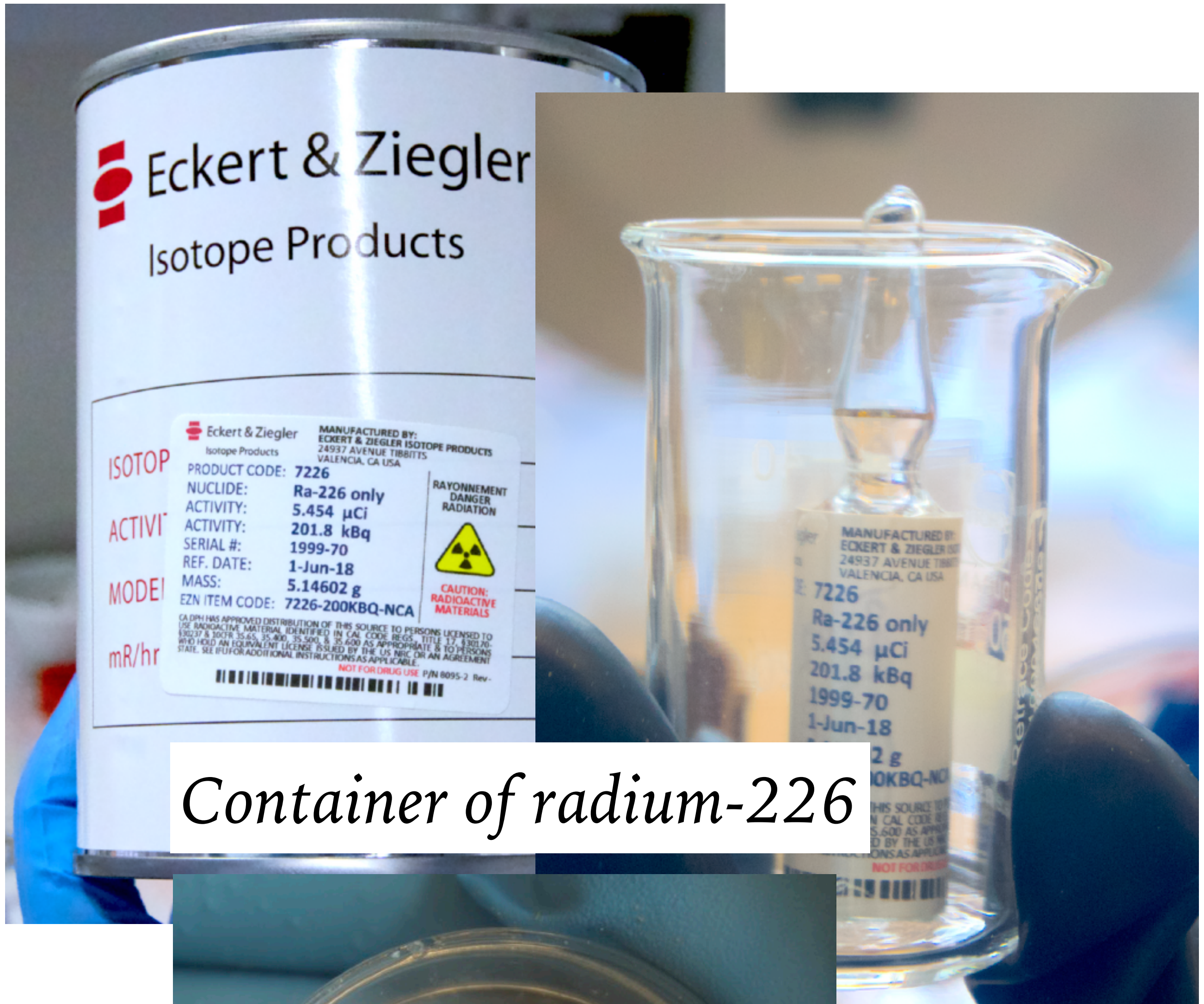


Alpha spectrum of ^{248}Cm and ^{246}Cm

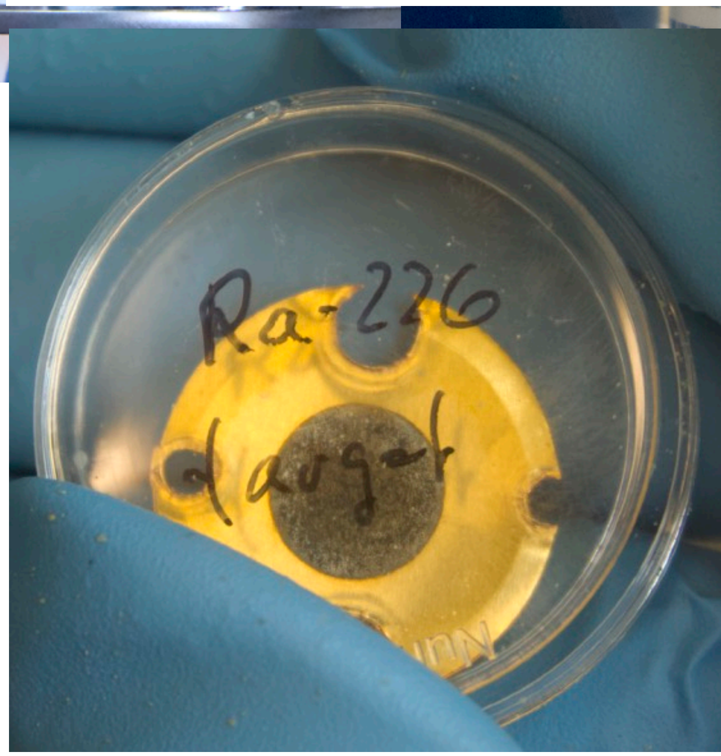
Carbon covered gold plate

ALPHA SPECTRUM CURIUM-248 TARGET

- The observed alpha spectrum of the target shows two lines corresponding to ^{248}Cm and ^{246}Cm
- Due to the organic layer:
  - The two lines of each isotope smear out
  - Peak shift of ~10 keV
  - Huge tails on the left side
- Tested effect of organic layer with carbon covered gold disks



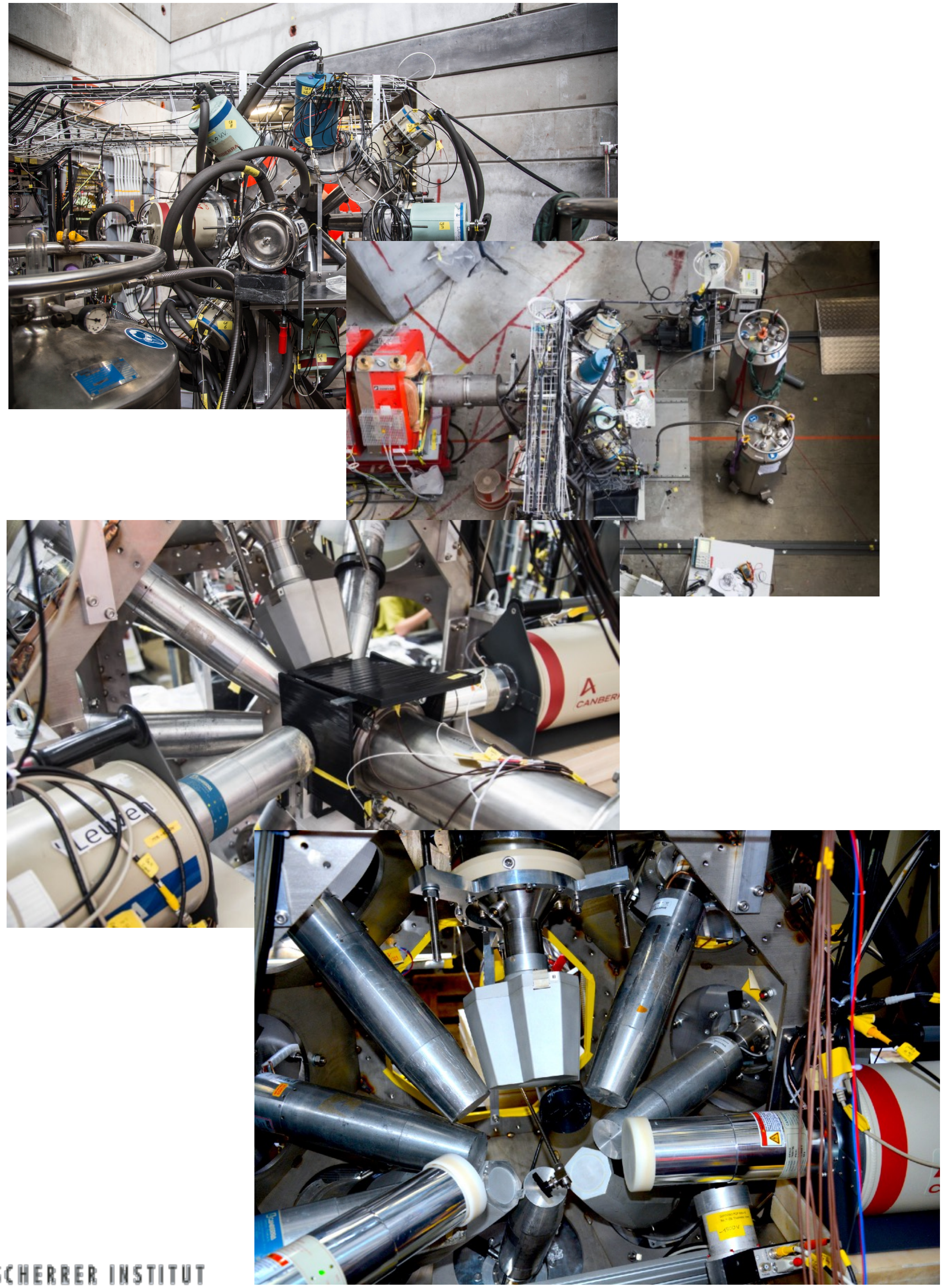
Container of radium-226



First try of radium-226 plating failed

FIRST TRY WITH RADIUM-226

- Ra-226 with an activity of 201.8 kBq is solved in acid
- During the first try it is plated on Cu-Au-Plate
- The plating destroyed the Au layer
- For a second plating the Ra-226 has to be removed from the Cu-Au-Plate
- During the separation occur many impurities in the solution
- The impurities have to be removed from the solution
- After all separations and the final plating only 1% of the original Ra-226 amount is left in the target
- A measurement in a reasonable time is not possible anymore

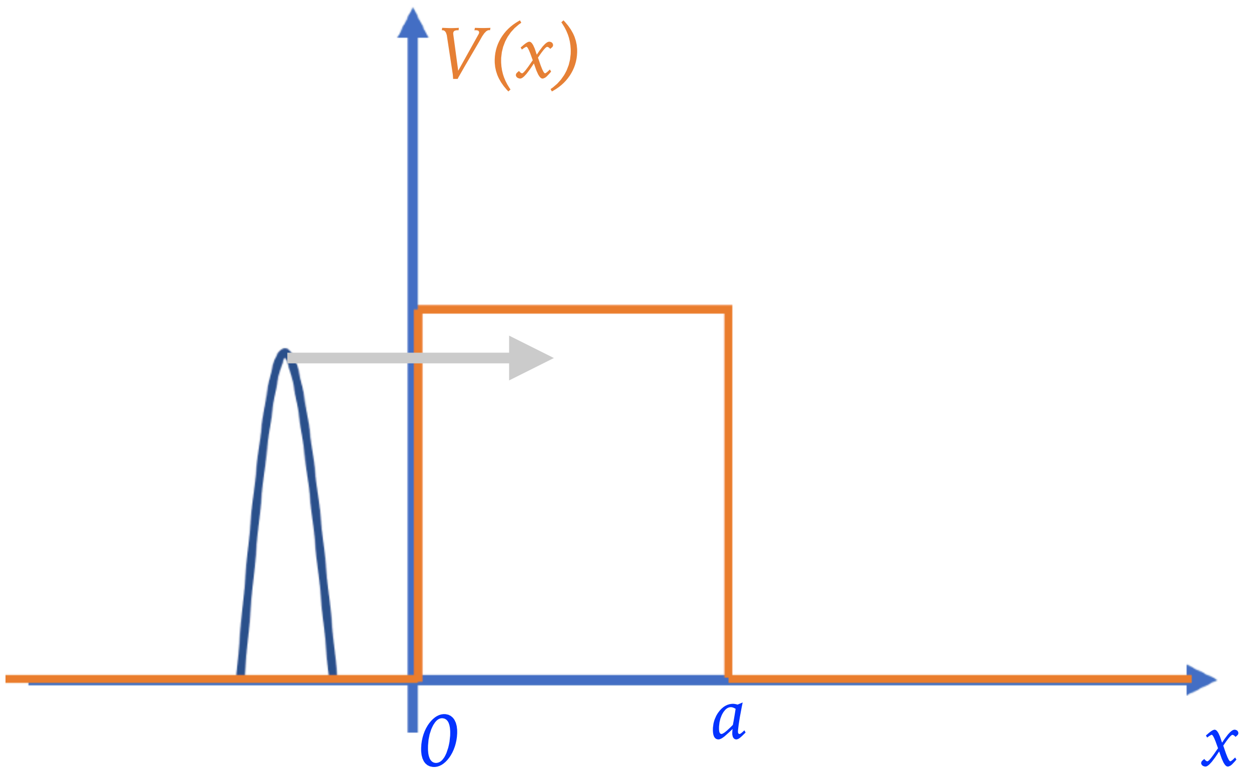


SUMMARY & OUTLOOK

- Muonic atom spectroscopy can be used for nuclear charge radius measurement
- Developed and tested a muon transfer method for tiny amount targets
- An improvement and quality assurance of the target production is required
- 2019 - Next try to observe muonic radium and curium X-rays

BACKUP SLIDES

RAMSAUER–TOWNSEND EFFECT

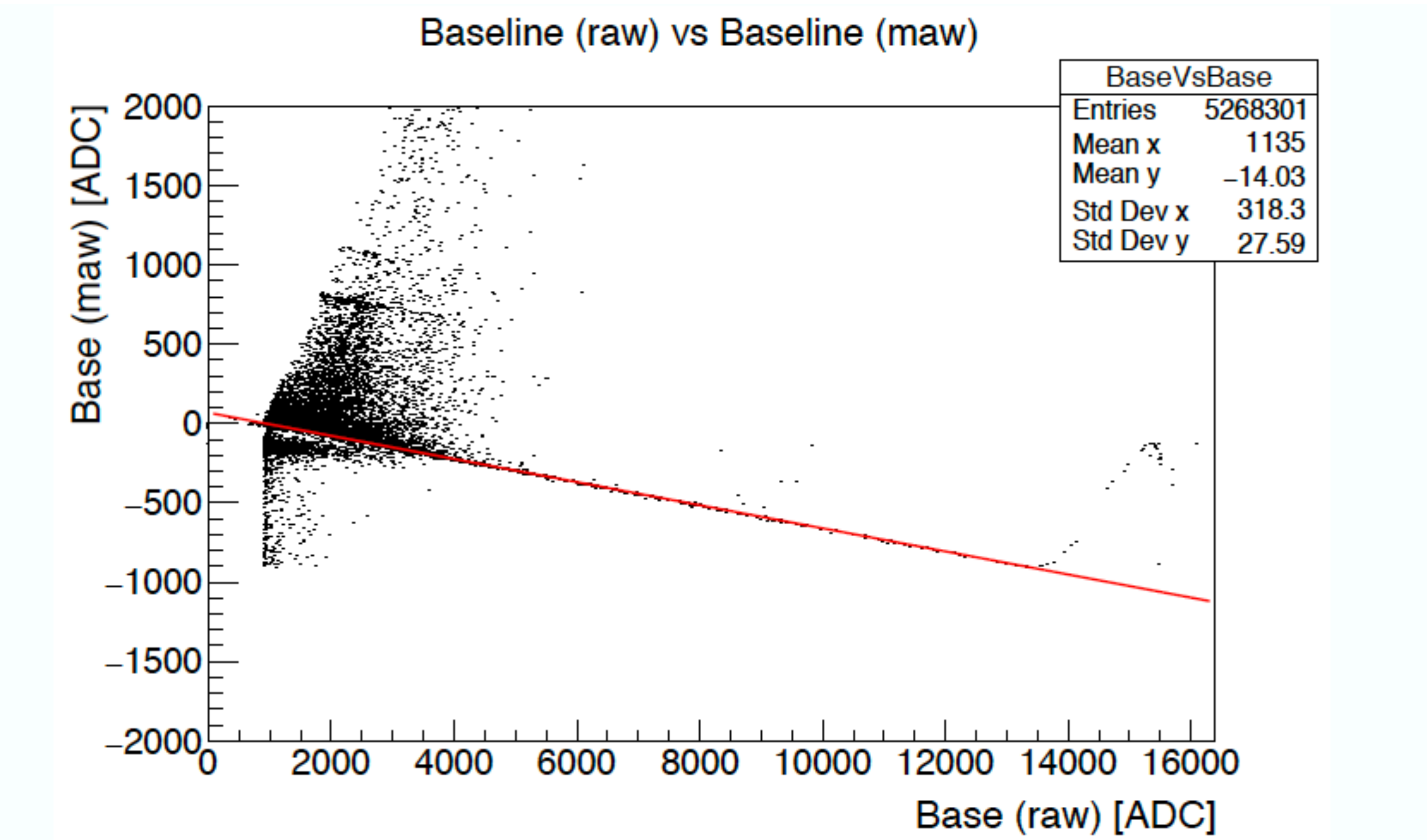


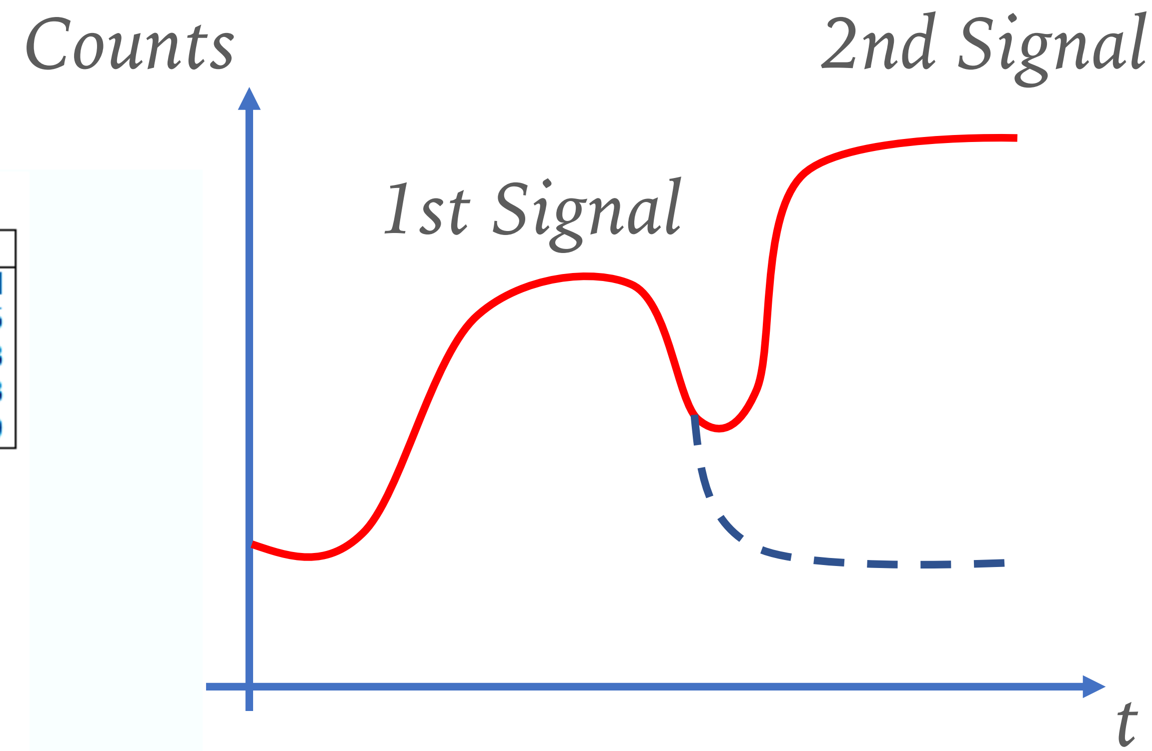
$$E\Psi = -\frac{1}{2m}\frac{\partial^2}{\partial x^2}\Psi + V\Psi$$

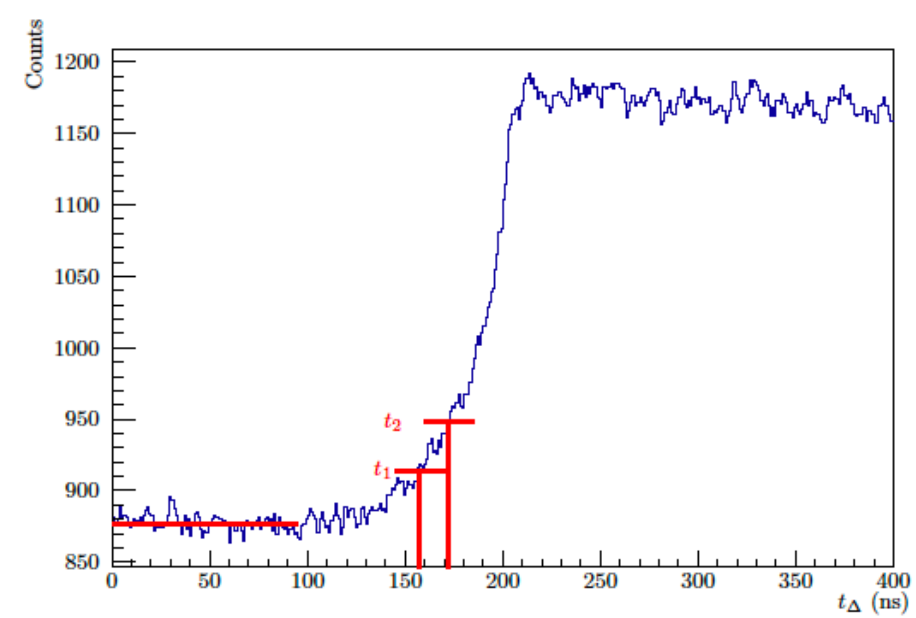
$$V(x) = \begin{cases} 0 & x < 0 \\ V_0 & 0 < x < a \\ 0 & x > a \end{cases} \qquad \Psi(x) = \begin{cases} e^{ikx} + Re^{-ikx} & x < 0 \\ Ae^{iKx} + Be^{-iKx} & 0 < x < a \\ Te^{-ikx} & x > a \end{cases}$$

$$\mathcal{T} = |T|^2 = \frac{1}{1 + \frac{V_0^2}{4E(E-V_0)}\sin^2 Ka} \qquad Ka = 2\pi\frac{a}{\lambda} = n\pi$$

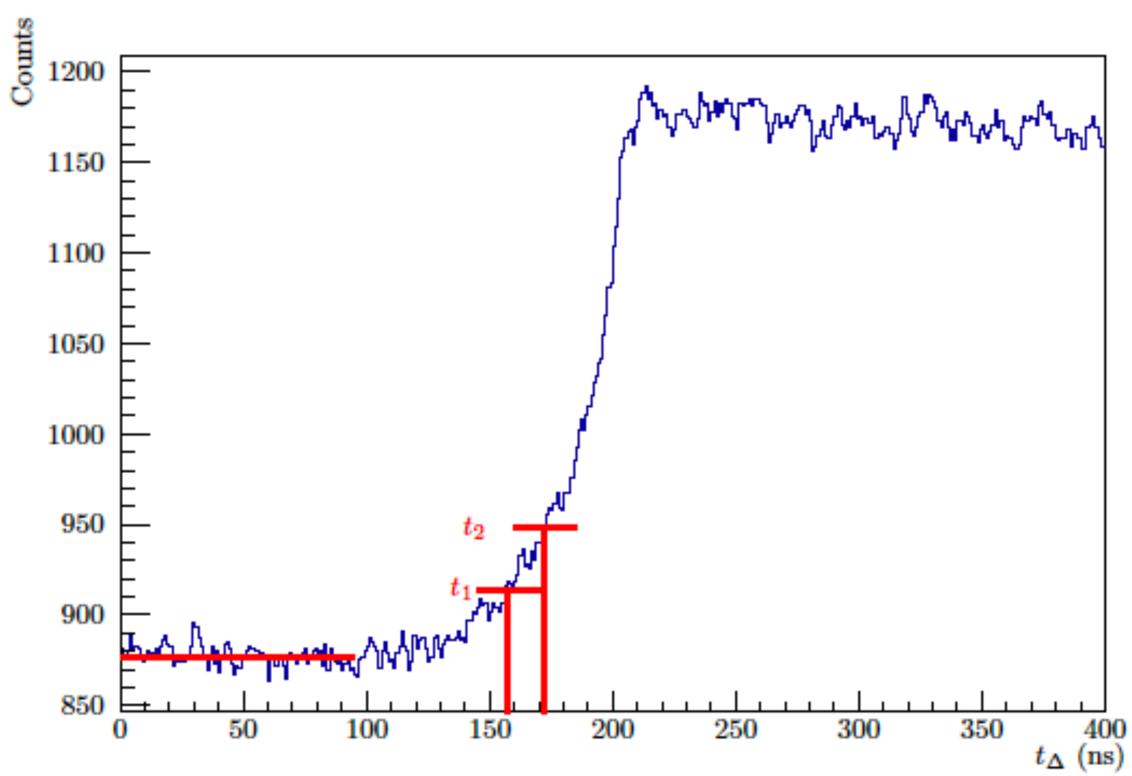
BASELINE CORRECTION







ELET TIME CORRECTION



- Avoid threshold activation due to noise (jitter effect)
- Avoid walk effect due to varying time signal shape
- Assume that rising slope is almost linear at the beginning

$$\Delta t = t_1 - t_0$$

$$\Delta t = t_2 - t_1$$

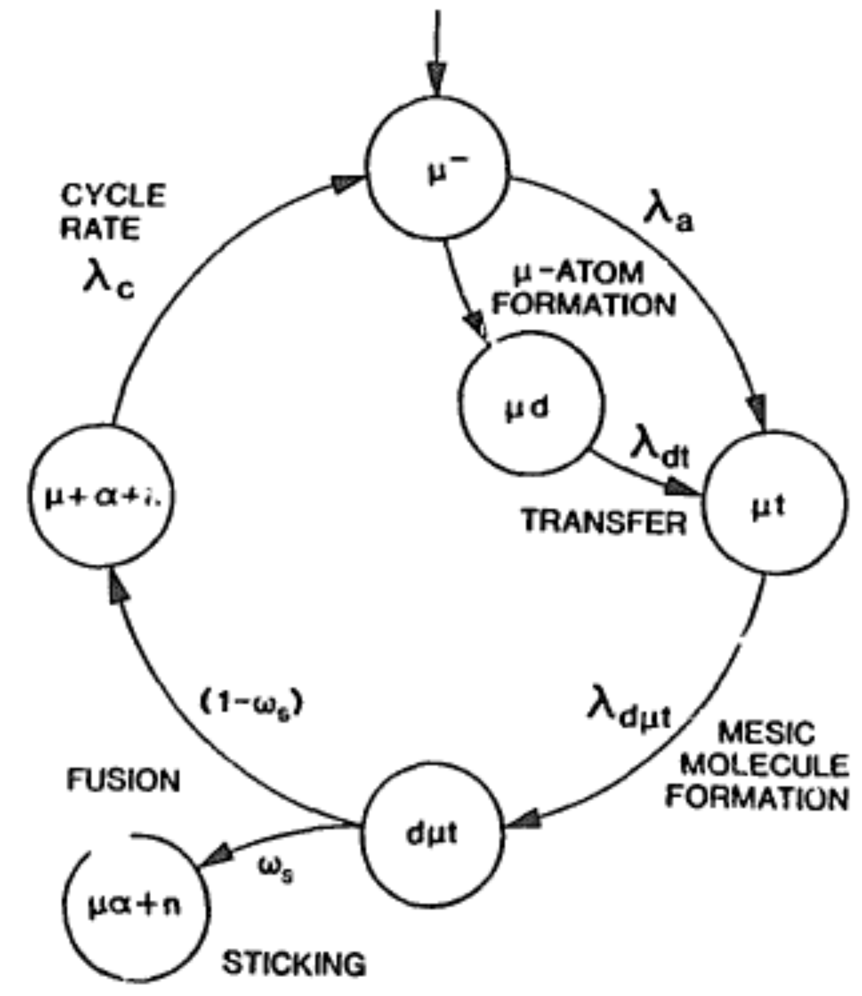
$$t_0 = 2t_1 - t_2$$

MUON CATALYSED FUSION

$$p\mu d \longrightarrow (\mu\,^3\mathrm{He})_{nl} + \gamma, \quad Q_{1s} = 5.502\ \mathrm{MeV},$$

$$d\mu d \longrightarrow (\mu\,^3\mathrm{He})_{nl} + n, \quad Q_{1s} = 3.277\ \mathrm{MeV},$$

$$d\mu t \longrightarrow (\mu\,^4\mathrm{He})_{nl} + n, \quad Q_{1s} = 17.598\ \mathrm{MeV}.$$



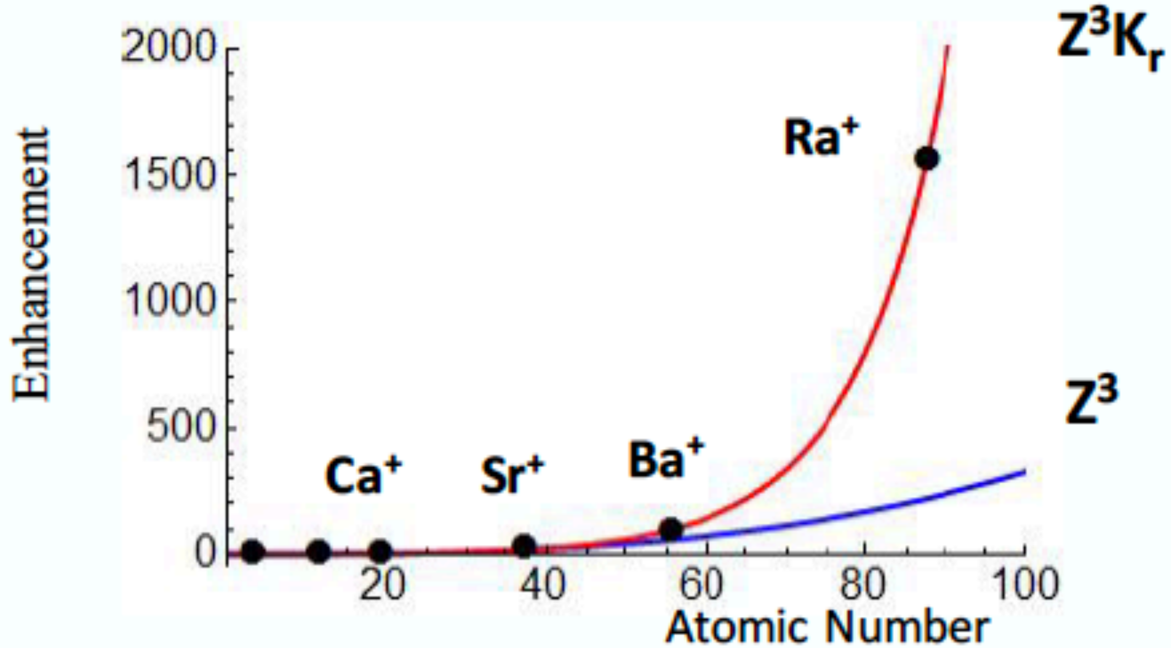
Petitjean, Nucl. Phys. **A543**, 79 (1992)

RADIUM APV

Scaling of the APV

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

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

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

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

ESTIMATION RADIUM PARAMETER

$$\rho(r) = \frac{\rho_0}{\left(1+\exp\left(\frac{r-c}{a}\right)\right)} = \frac{\rho_0}{\left(1+\exp\left(4\log(3)\frac{r-c}{t}\right)\right)}$$

$$r_{RMS} = \frac{\int \rho(r) r^2 dV}{\int \rho(r) dV}$$

t = 2.3 fm ≈ const

rms = 5.6841 fm
I.Angeli/
Atomic Data and Nuclear Data Tables 87 (2004) 185\
[Dash]206