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Implantation of ^{226}Ra for the measurement of its absolute nuclear charge radius

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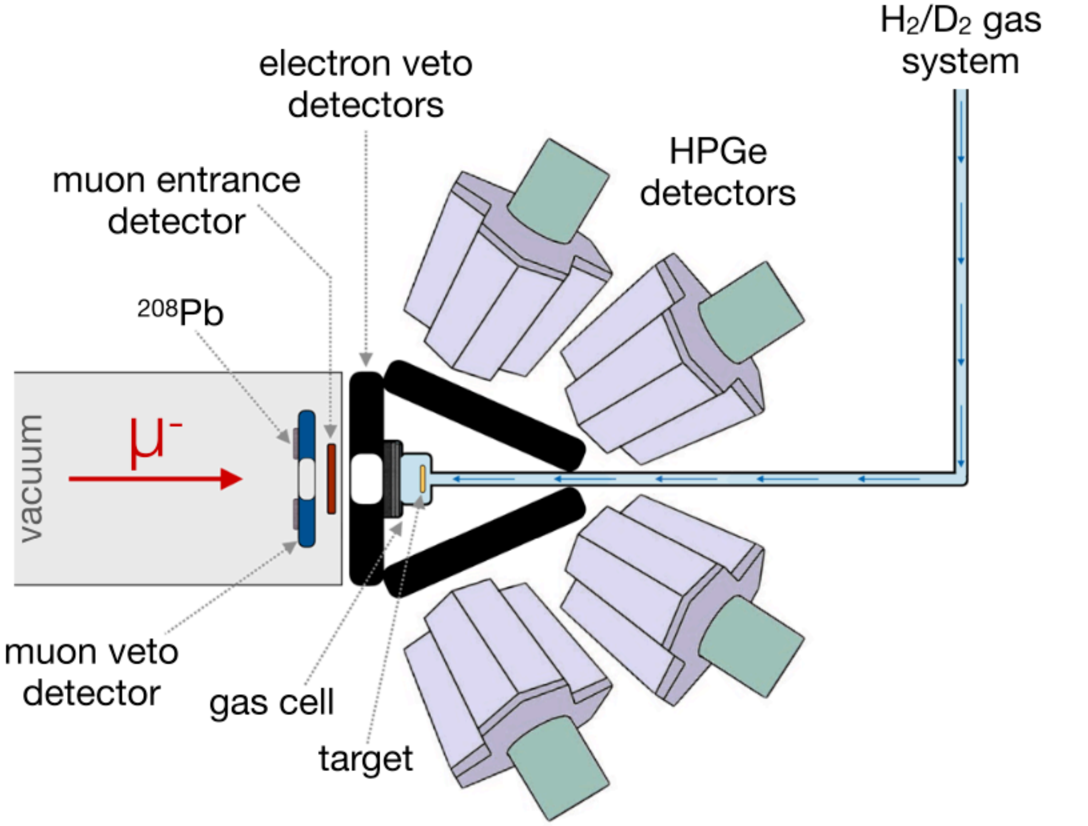
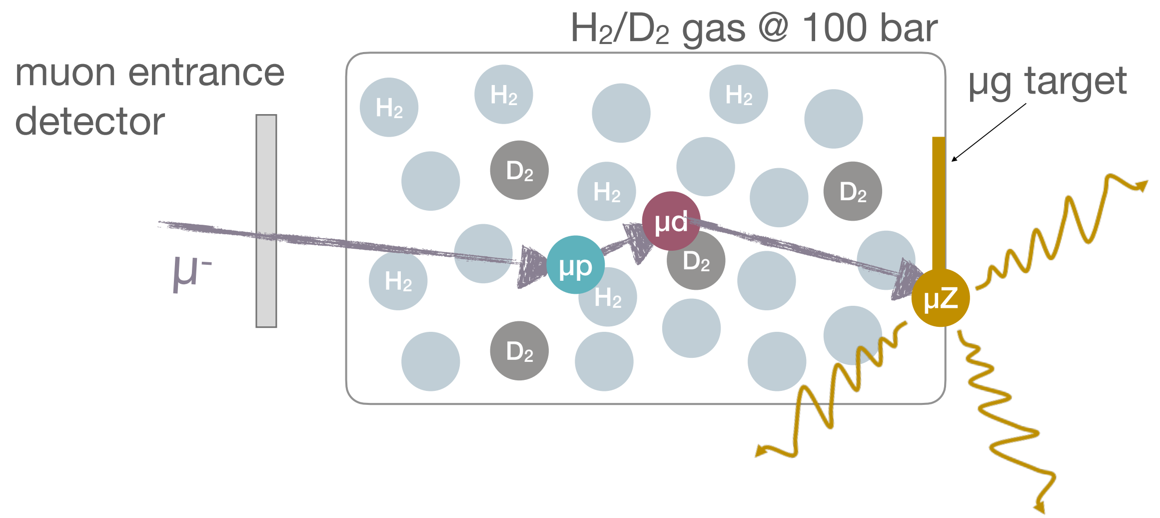
muX experiment

- Measurement of missing absolute charge radii for high-Z radioactive targets
- muX is a fully approved experiment at PSI with regular beam times to develop method and perform first measurements of radioactive targets
- Main goal: ^{226}Ra as a candidate for an APV experiment
- Transfer reactions in high-pressure H2/D2 gas mixture to measure microgram quantities





A. Adamczak et al., Eur. Phys. J. A 59, 15 (2023)

How to extract nuclear charge parameters

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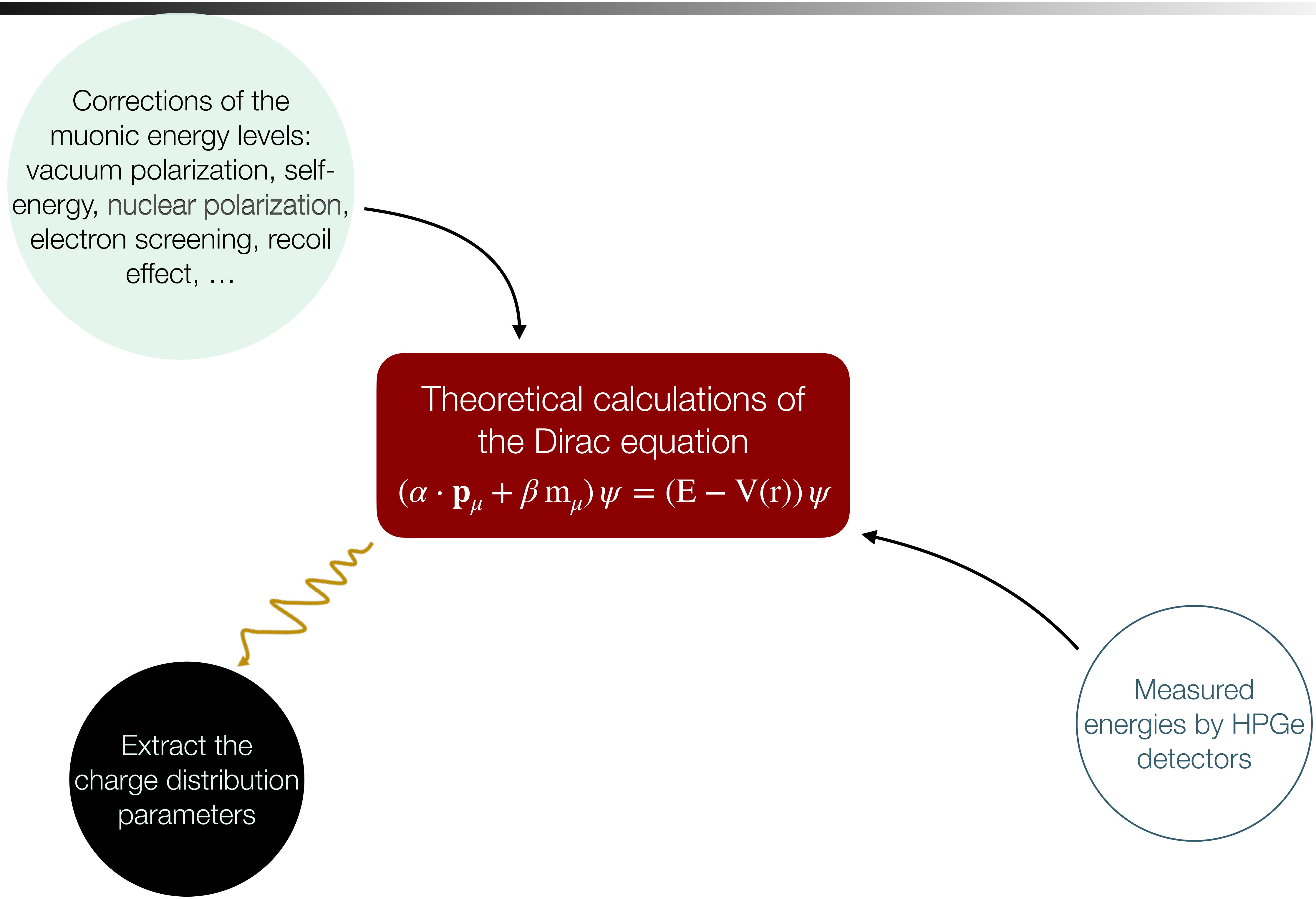
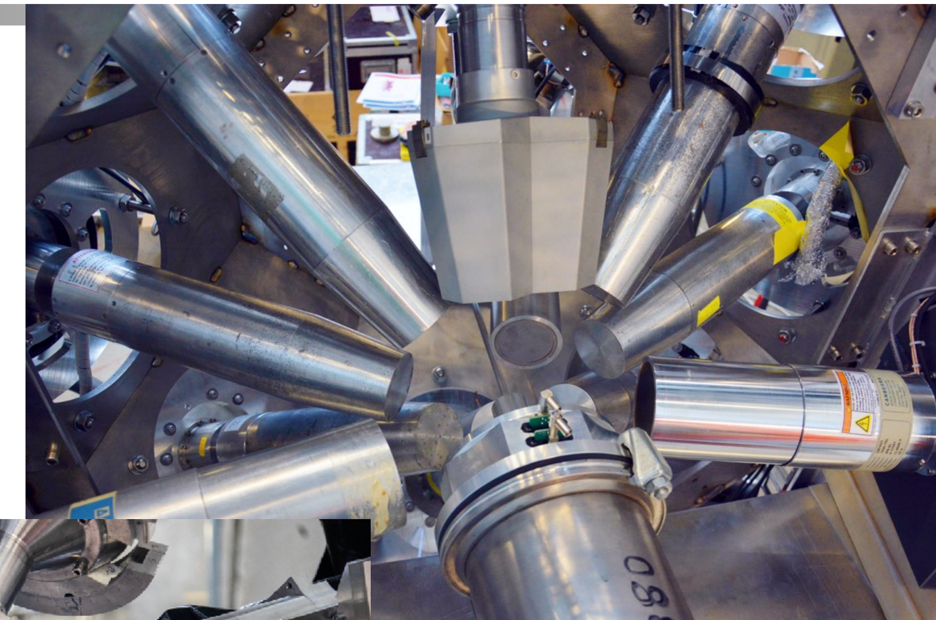
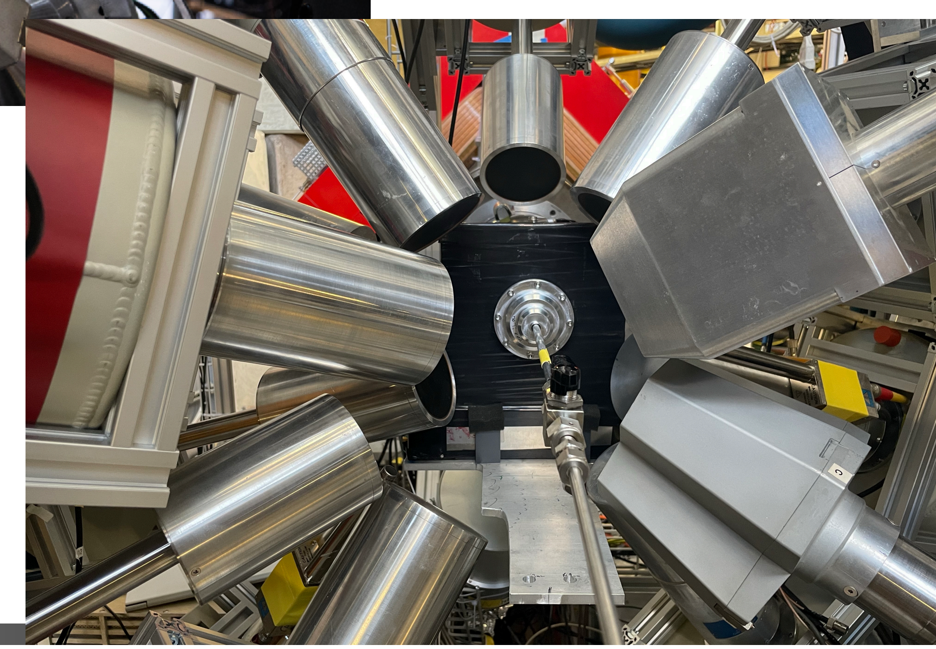


Germanium array

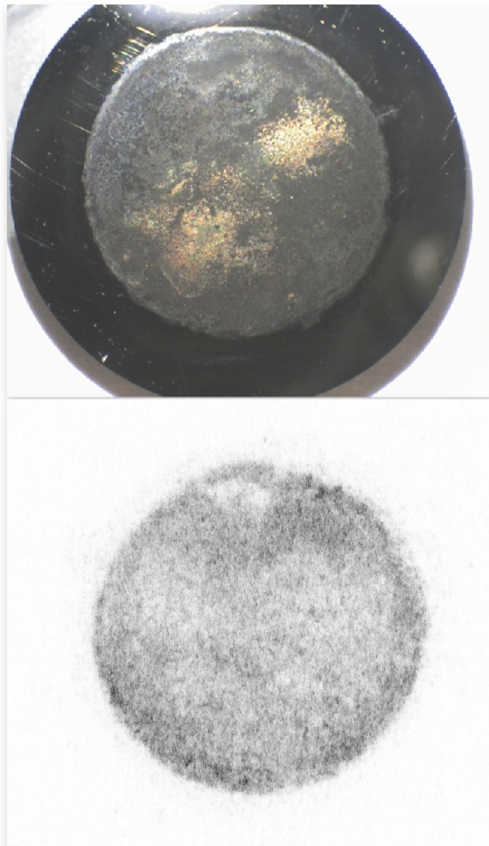
- 2017/2018
  - 11 germanium detectors in an array from French/UK loan pool, Leuven, PSI
  - First time a large array is used for muonic atom spectroscopy
- 2019
  - Miniball germanium detector array from CERN
  - 26 germanium crystals in total
- Since 2020: mixture of various detectors contributed from various collaborating institutions; common array with MIXE



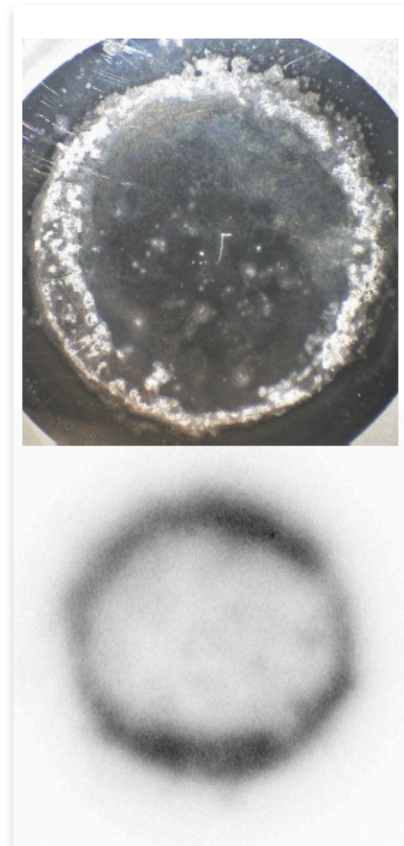


N. Warr et al., Eur. Phys. J. A 49, 40 (2013)
L. Gerchow et al., Rev. Sci. Instrum. 94, 045106 (2023)

Radioactive targets



15.5 μg ^{248}Cm target



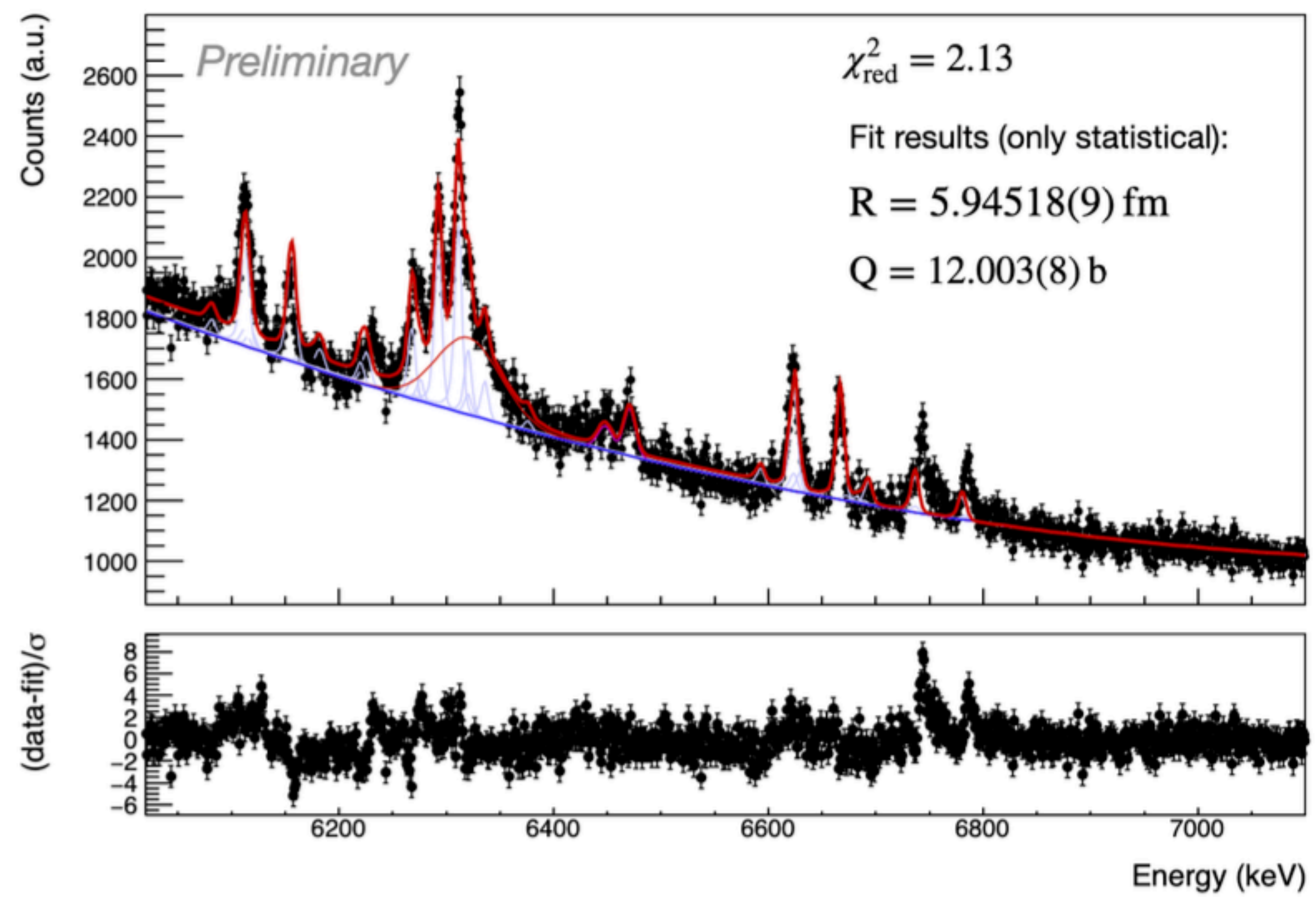
4.4 μg ^{226}Ra target

1.4 μg ^{226}Ra target

- Made by a combination of electroplating and printing in the Nuclear Chemistry unit at JGU Mainz
- Difficult to make thin targets that have only very little organic contamination
- We did not observe anything significant from the two radium targets
- For both curium and radium target we suffered from palladium contamination —> only about 1/3 of muons went to target material

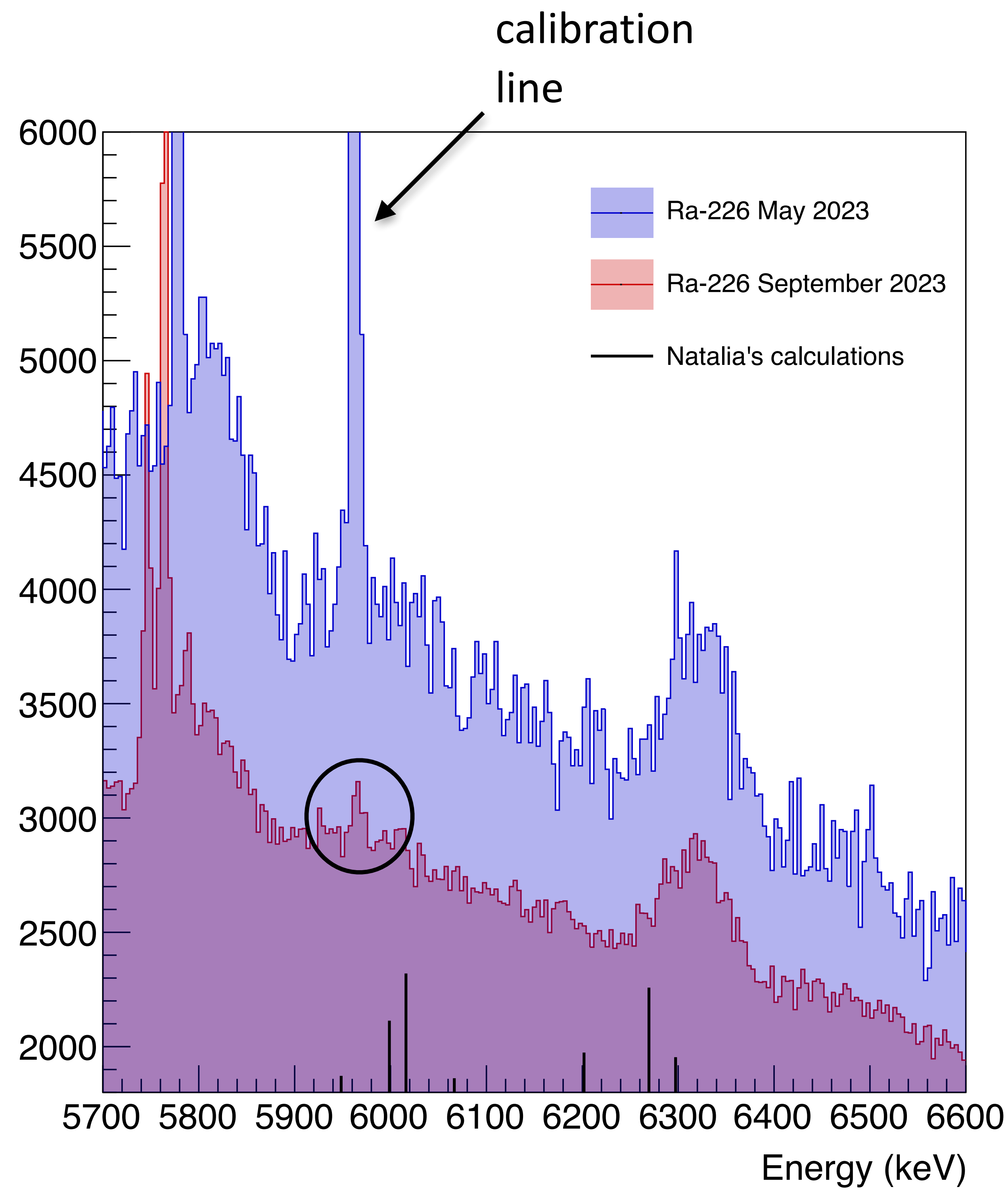
Muonic curium spectrum

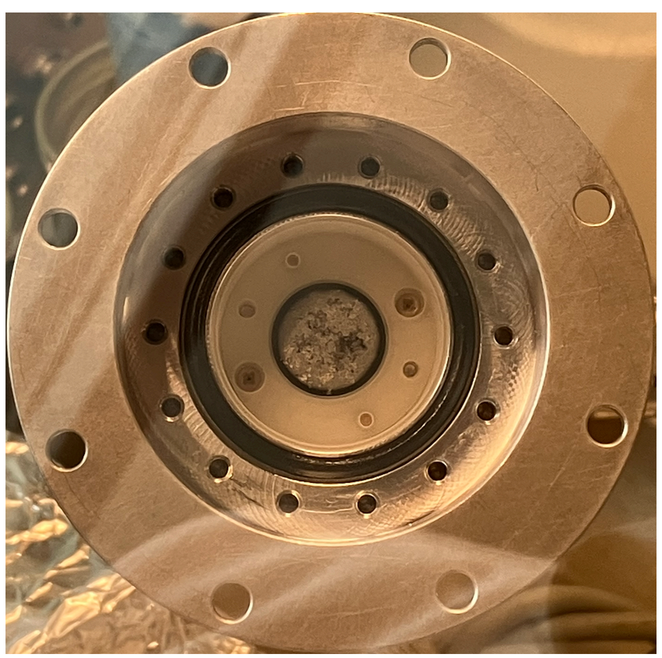
- Succeeded to measure muonic curium for the first time
- Effectively a 5 µg target
- Excellent statistical accuracy, but final result will be limited by systematics



First hints of muonic radium

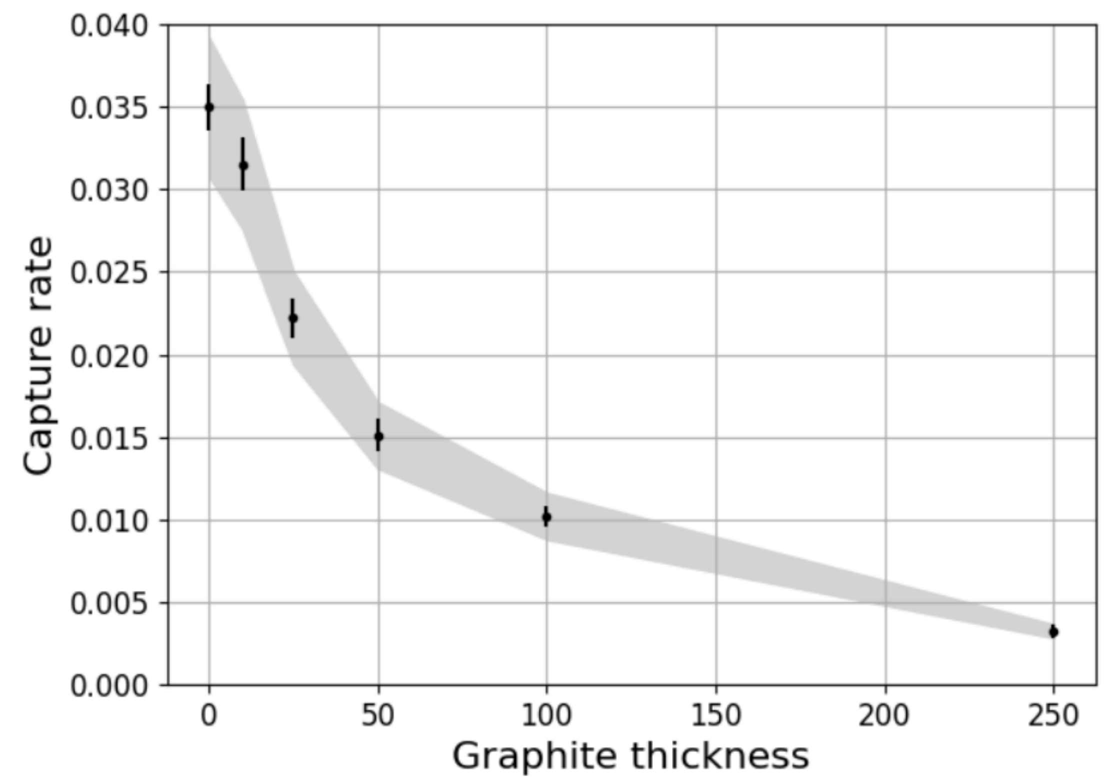
- After intense analysis of curium measurements and a lot of work on the target preparation using barium, we were ready again for radium
- We are confident that we see for the first time evidence of muonic radium x rays
- Not quite enough for a high-statistics measurement, hard to unambiguously assign hyperfine transitions





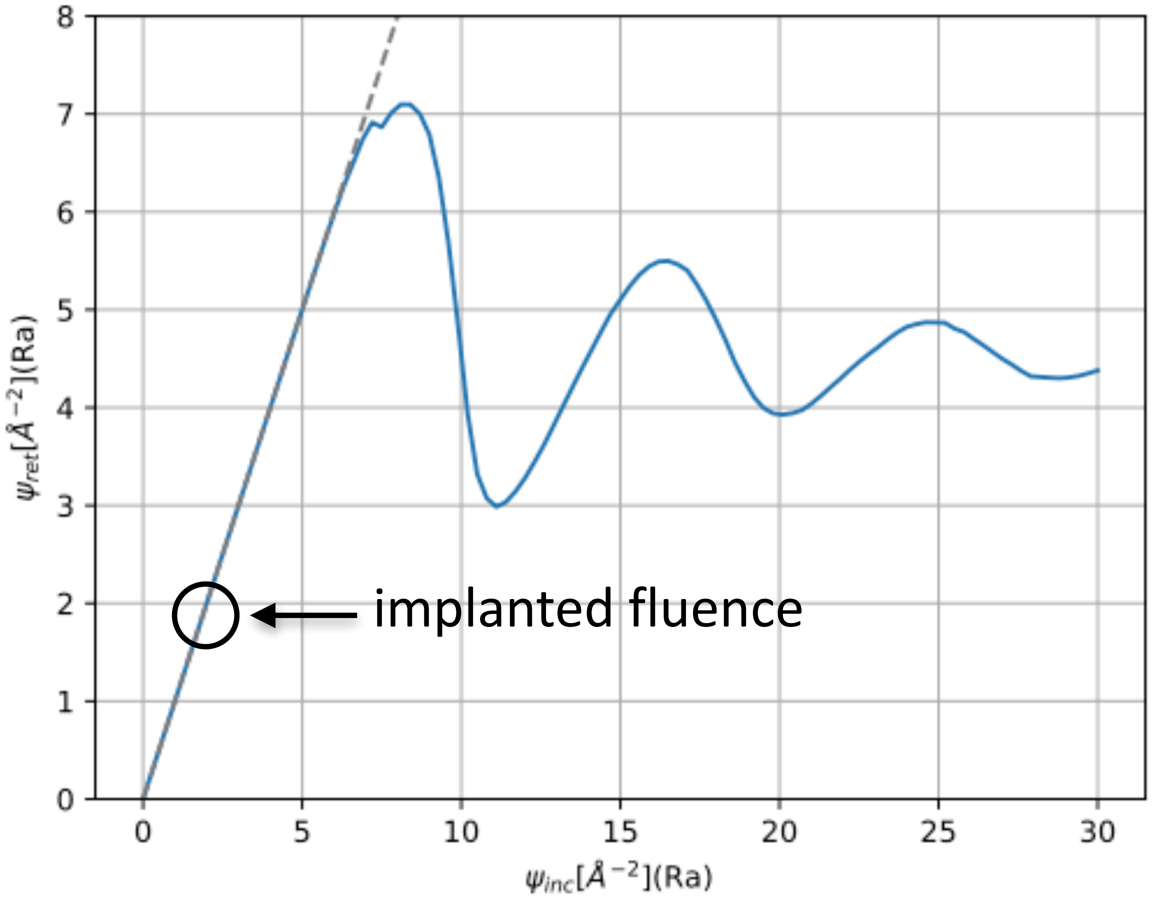
Can we prepare targets differently?

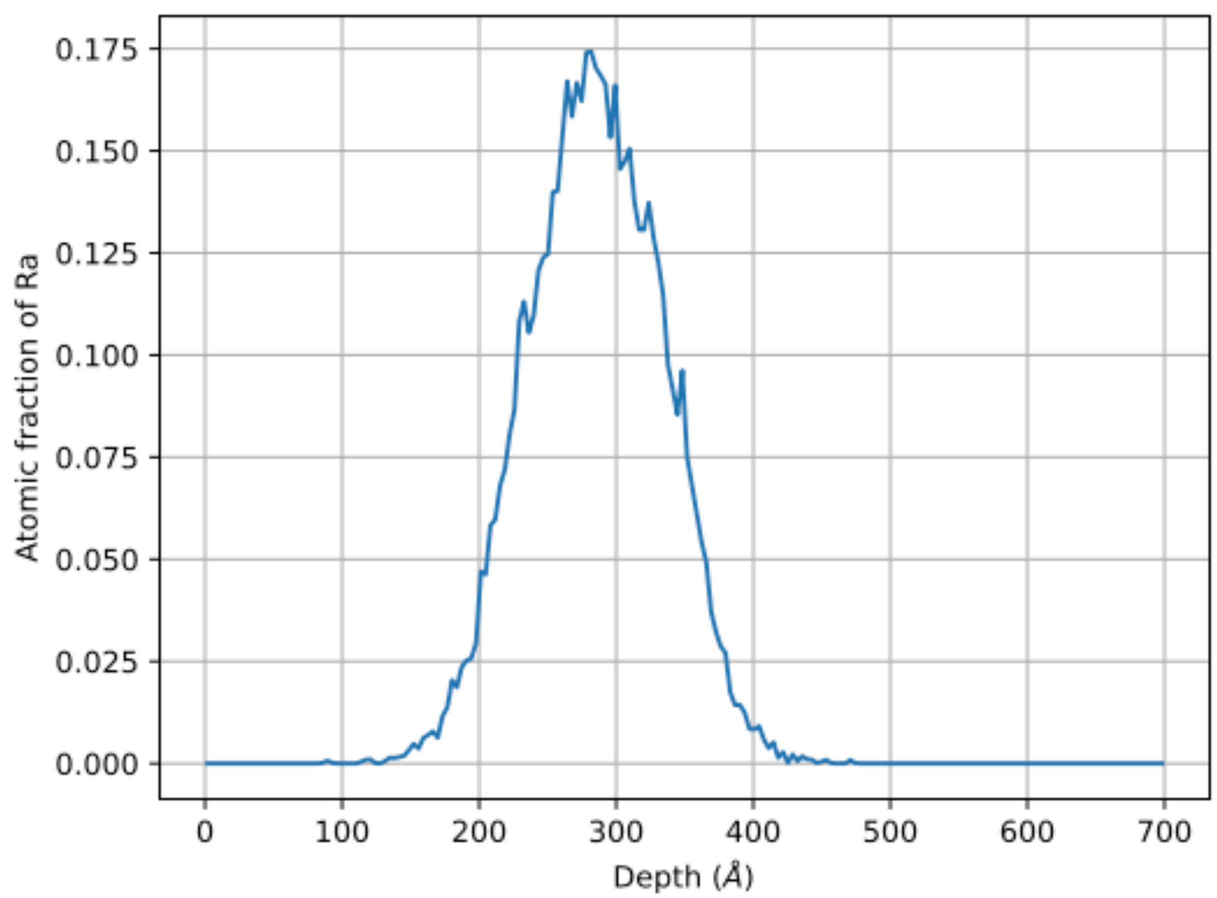
- Started looking at implanted targets using ion beams
- Checked effect of graphite layer on top of gold to characterise attenuation
- Can afford a layer of a few 10 nm
- Performed measurements with implanted gold targets and compared to surface targets
- Looks promising, good efficiencies achievable
- This was also confirmed by the measurement of a first radioactive target: 7.5 µg of ^{40}K (1.1×10^{17} atoms) implanted at 30 keV



	Target	Mass (µg)	2p-1s count (10^{-6} muon^{-1})
surface targets	^{197}Au 10 nm	34.11	8.8(5)
	^{197}Au 3 nm	10.23	4.5(4)
implanted targets	^{197}Au 90 keV	10.38	4.7(3)
	^{197}Au 27 keV	9.38	4.3(3)
	^{197}Au 4.5 keV	9.45	5.2(5)

Implanting radium





- TRIDYN simulations for the implantation of the maximum allowed ^{226}Ra quantity in glassy carbon: 1.46x10^{16} atoms (5.5 µg, 200 kBq, 100 LA)
- Simulations show that we are well below self-sputtering limits
- Implantation at around 30 nm very acceptable
- Also only small loss after implantation due to recoil-sputtering

Implanting radium

- Propose to prepare two radium targets to have one as a backup for the muon measurements
- Implantation could be performed at GPS separator of ISOLDE offline using commercially obtained radium nitrate dissolved in nitric acid
- Estimates below rely on surface ionisation alone with an efficiency as observed by MEDICIS for ^{224}Ra

- “Slow” implantation for best quality ion beam and minimal losses
- “Fast” implantation at the ion load limit of around 100 nA for second target to explore capabilities for potential, future implantations

- Monitoring of implantation using the ion current and gamma-ray spectroscopy

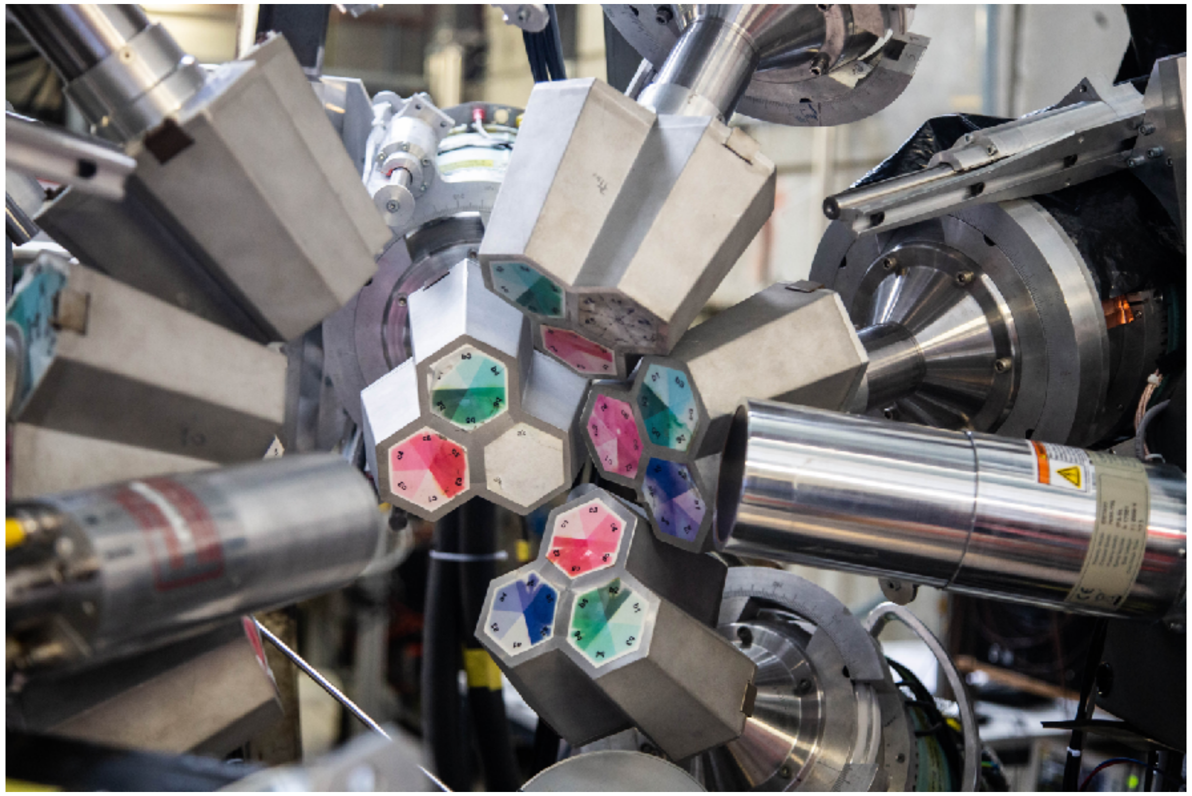
initial activity	ionisation efficiency	ion current	implantation duration
500 kBq	40%	20 nA	32.5 h
500 kBq	40%	100 nA	6.5 h

Safety

- We are aware of the safety concerns and are happy to follow any required protocols and procedures and to perform dry runs.
- We have started to discuss these issues already with corresponding CERN personnel.
- After implantation the two targets will be stored under vacuum before shipping to PSI and transferring them to the muX target chambers.

Conclusions

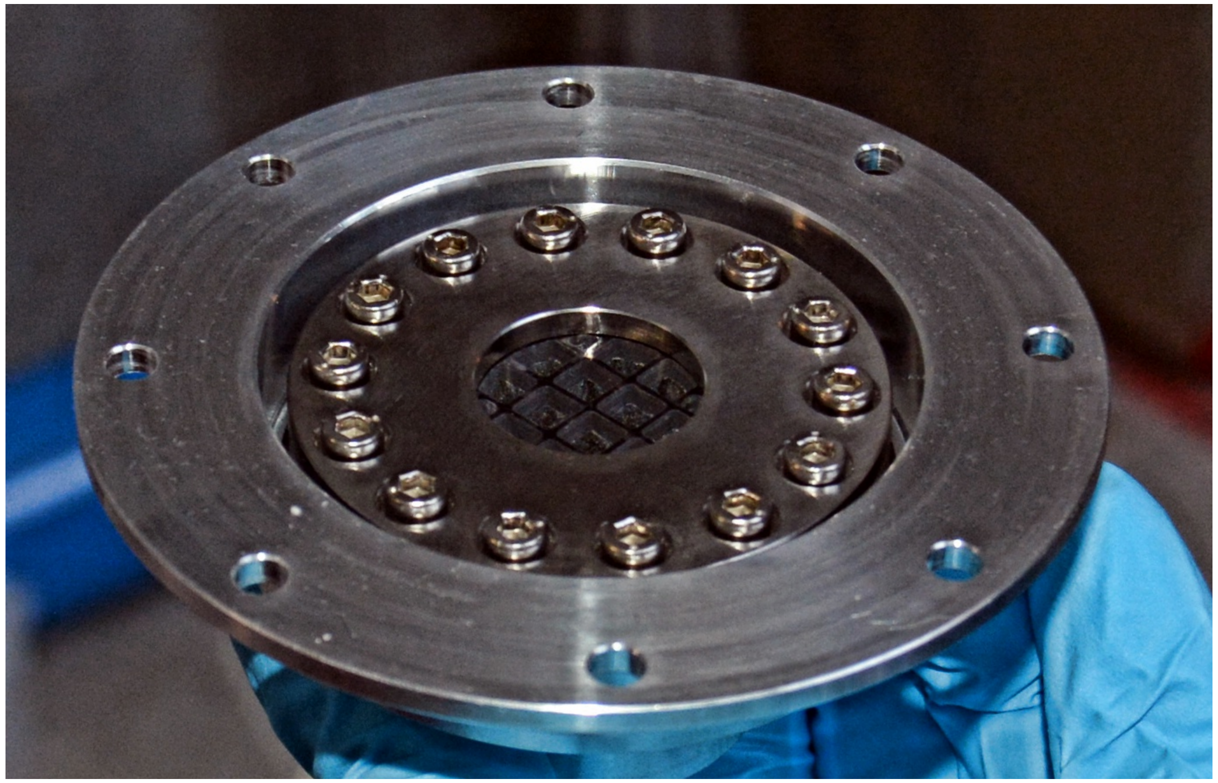
- Muonic atom spectroscopy offers the possibility to measure absolute charge radii of radioactive isotopes
- muX has developed a method to work with as little as a few microgram of target material with the explicit goal of measuring the charge radius of ^{226}Ra
- Ion implantation has been shown to be an excellent tool to prepare targets for muX
- We request 6 shifts of beam time without protons to implant two radium targets

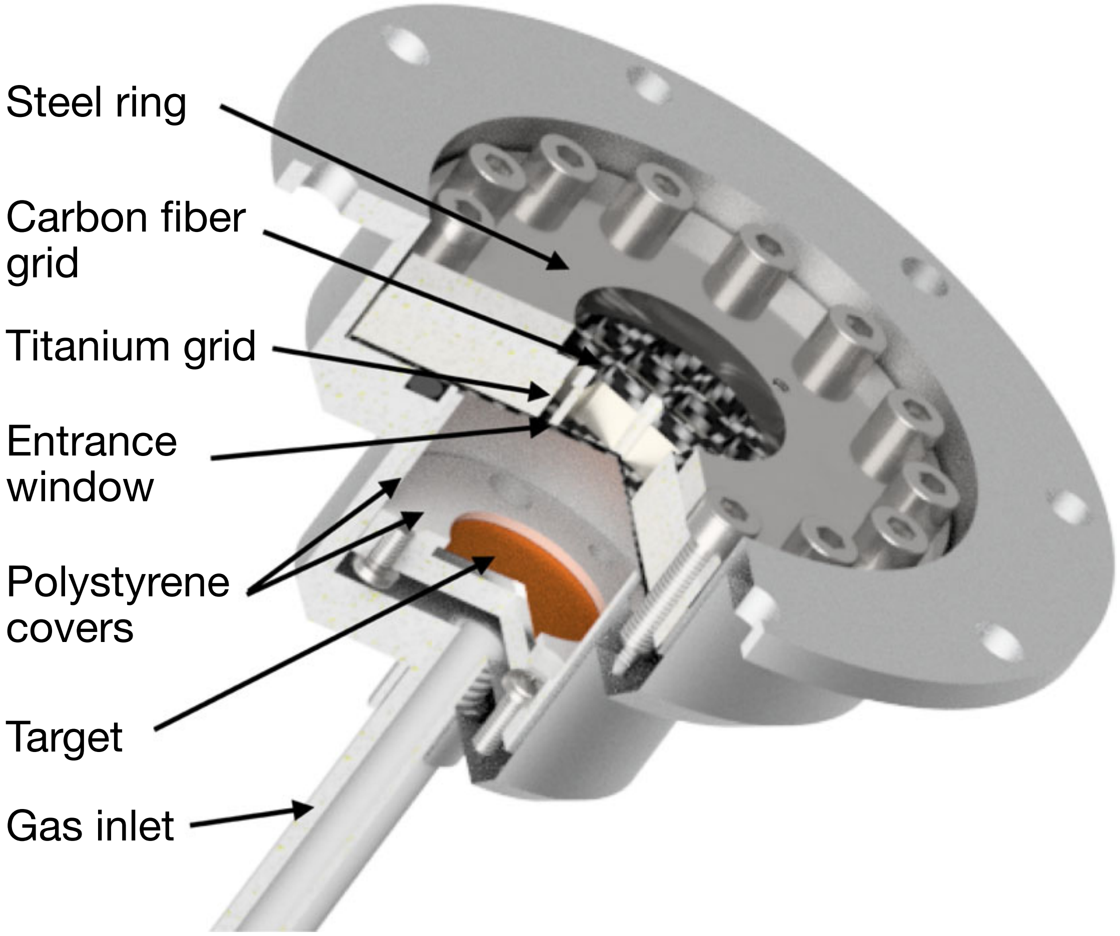


Backup

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

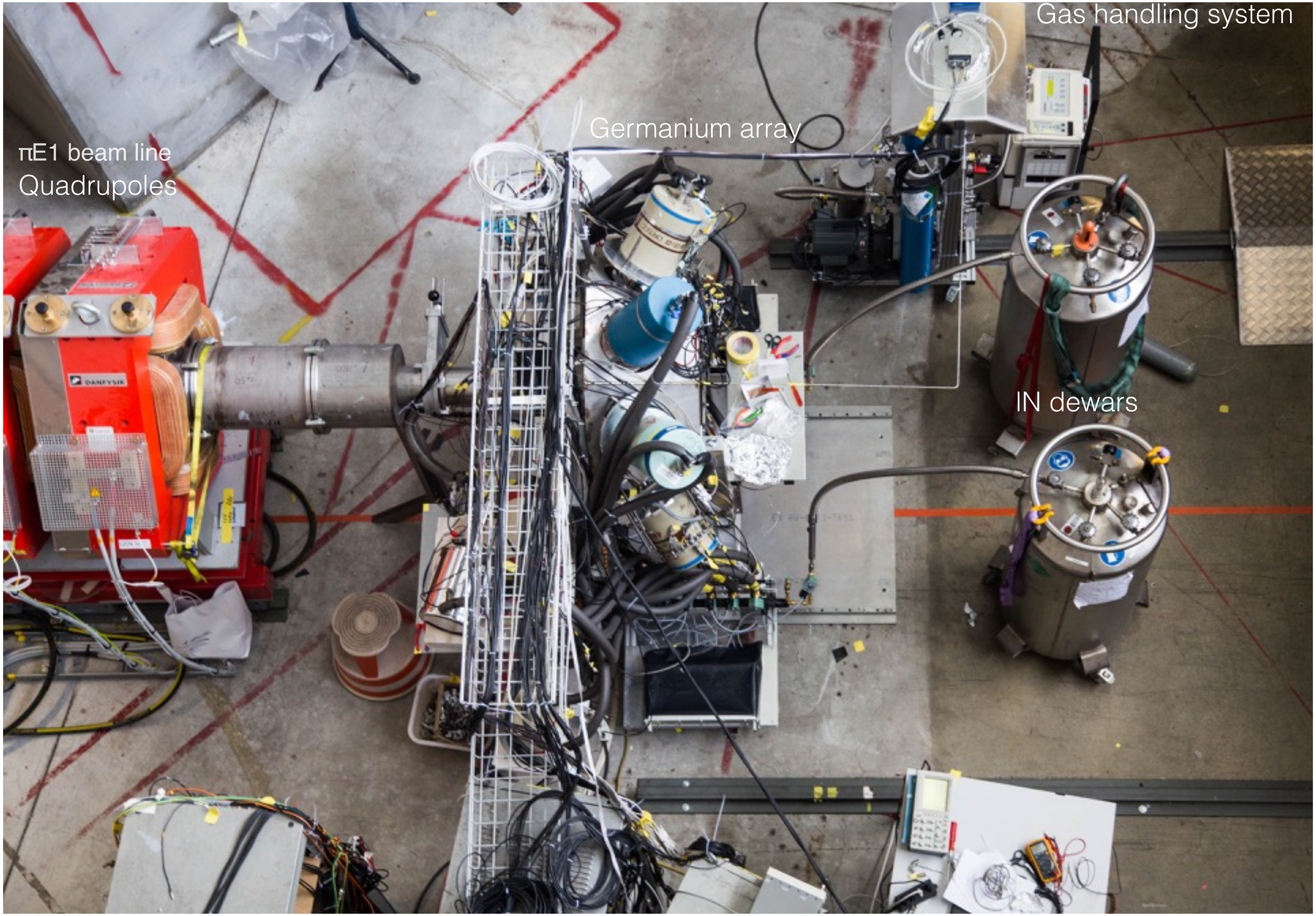




Entrance & veto detectors

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

Experimental setup



Ion load limit