UNIVERSITÀ DI PAVIA

INFN Istituto Nazionale di Fisica Nucleare

FAMU

CHNet MAXI

FAMU & Beyond

muonic atoms in fundamental and applied physics

Riccardo Rossini
University & INFN Pavia, Italy

What can we do with muonic atoms?

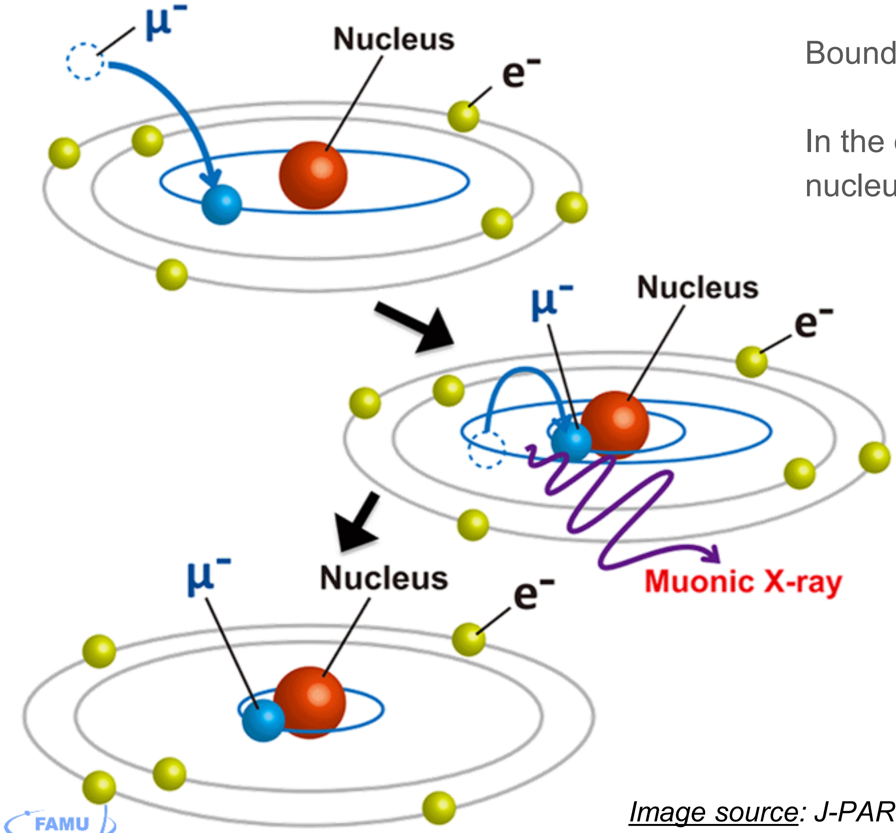


Image source: J-PARC

Bound system of nucleus and negative muons.

In the over-simplified Bohr picture, the muon is much closer to the nucleus (~ 1/187 times), which causes:

- in low-Z atoms like μH, charge shielding causes e^- loss.
- the atomic levels of muonic atoms have a proton finite-size contribution becomes dominant by a factor $(m_\mu/m_e)^3 \sim 10^7$ → good laboratory for nuclear properties.
- the muonic atom X-rays are much more energetic, up to few MeV → generally detected with nuclear radiation methods (germanium detectors, scintillators, etc…)

Istituto Nazionale di Fisica Nucleare

The FAMU experiment

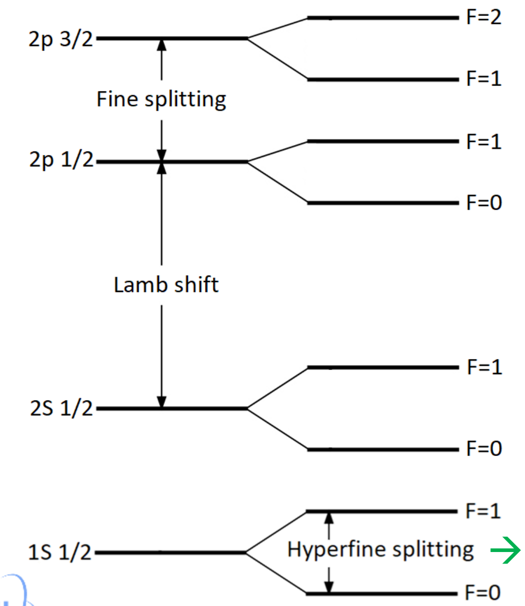
Proton Zemach radius

$$r_Z = \int r\, d^3r \int d^3r' \rho_E(\vec{r} - \vec{r}') \rho_M(\vec{r})$$

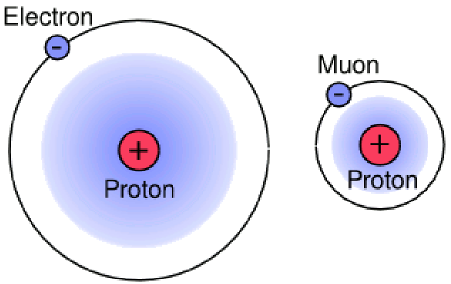
Density of magnetic dipoles
$\propto G_M(Q^2)$ form factor

Density of electric charge
$\propto G_E(Q^2)$ form factor

Hydrogen atomic levels:



→ *1S-hfs* → strongly dependent on the Zemach radius



Proton Zemach radius and *1S-hfs* in μH

Relationship between proton r_Z and muonic hydrogen *1S-hfs* is the following (Antognini et al., 2022):

Proton finite size correction (Zemach)

$$E_{1S-hfs}^{\mu H} = \left[E_F + 1.350(7) + 0.004 - 1.30653(17)\frac{r_Z}{\mathrm{fm}} + E_F \cdot \{1.01656(4) \cdot 0.0000846(6) + 1.00402 \cdot 0.0004\} \right] \mathrm{meV}$$

QED + weak correction

hadronic vacuum polarisation correction

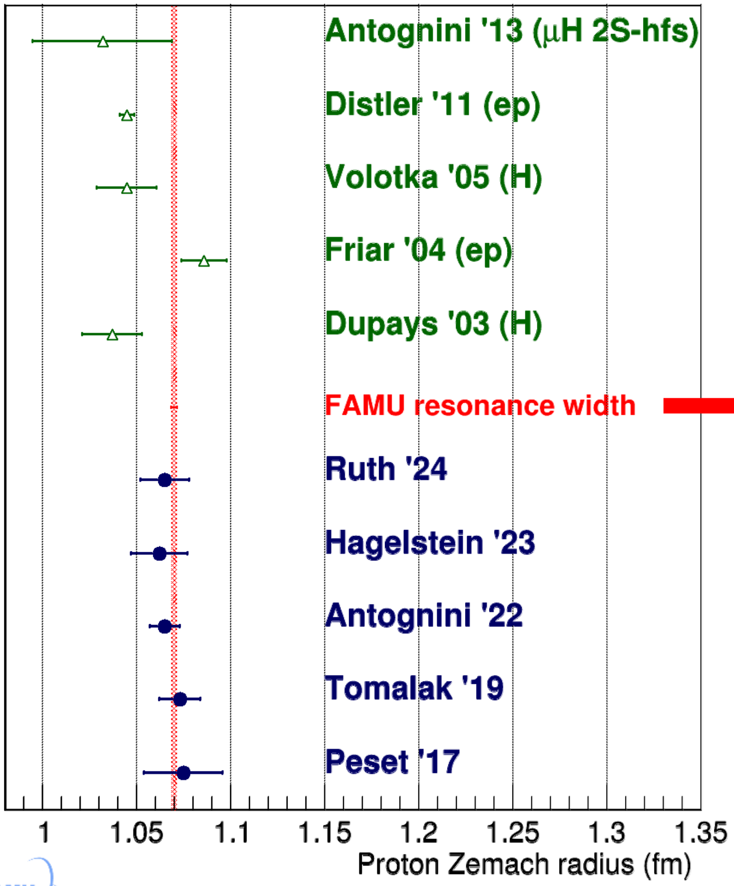
proton recoil correction

proton polarisability correction

with Fermi energy: $E_F = 182.443\ \mathrm{meV}.$

Measurement of r_Z:
- gives information about the relationship between G_E & G_M form factors
- is a probe to check the QED corrections

r_Z in μH as of today



Experimental estimations (not from μH 1S-hfs)

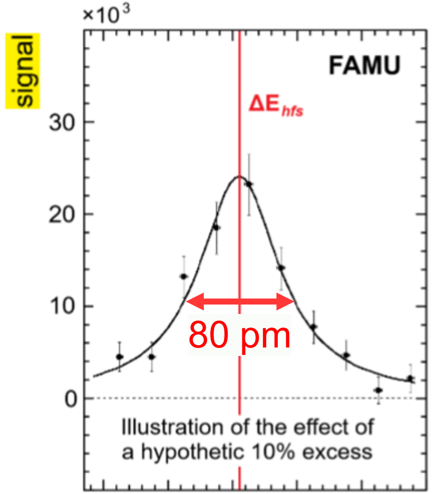
Expected width:

10^{-5} on *hfs* ↔ *0.3% on* r_Z

Smaller σ on the centroid

→ **unprecedented accuracy!**

Theoretical predictions



1S hyperfine splitting

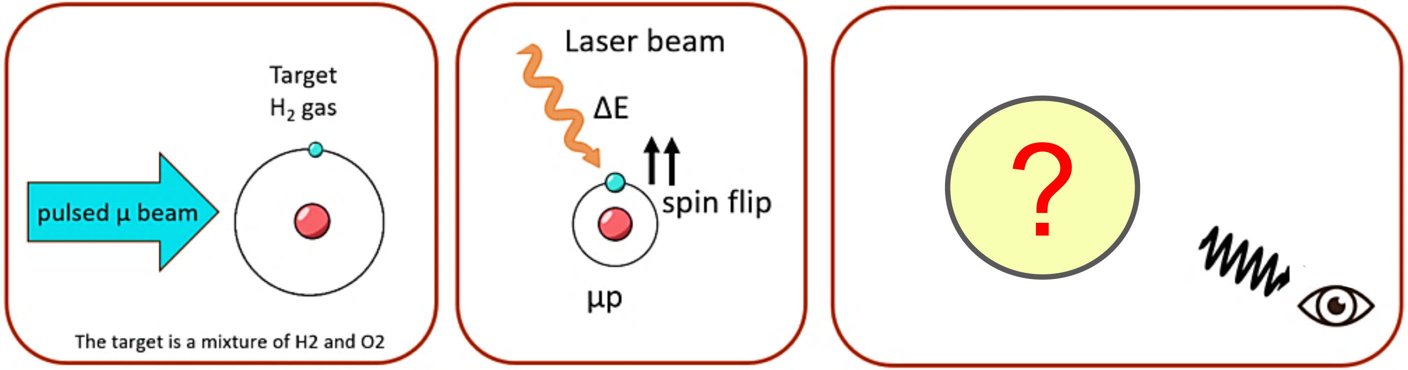
Experimental method

First proposed in 1993 by Bakalov, Vacchi, et al.
[10.1016/0375-9601(93)91021-V](https://doi.org/10.1016/0375-9601(93)91021-V)

1 – produce ground-state muonic hydrogen atoms

2 – excite the 1S-hfs transition with a wavelength-tunable laser beam

3 – find an observable sensitive to the transition and track its changes as a function of the laser wavelength.
three experiments in the world are currently attempting this measurement with different observables

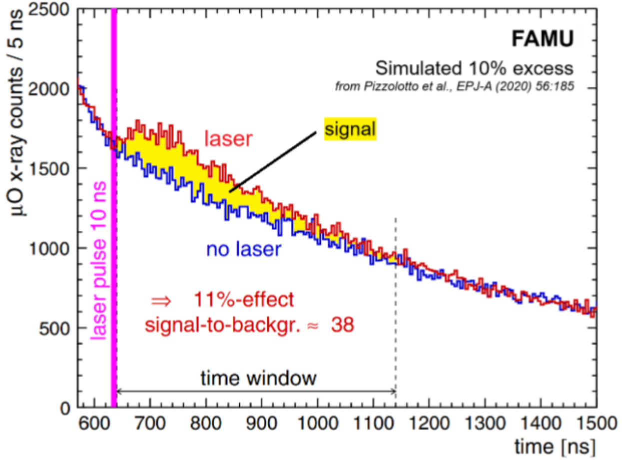


Experimental method

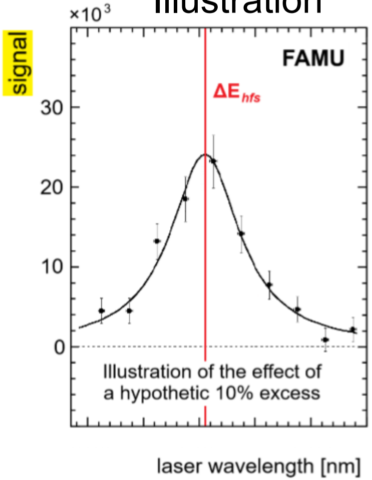
FAMU observable:

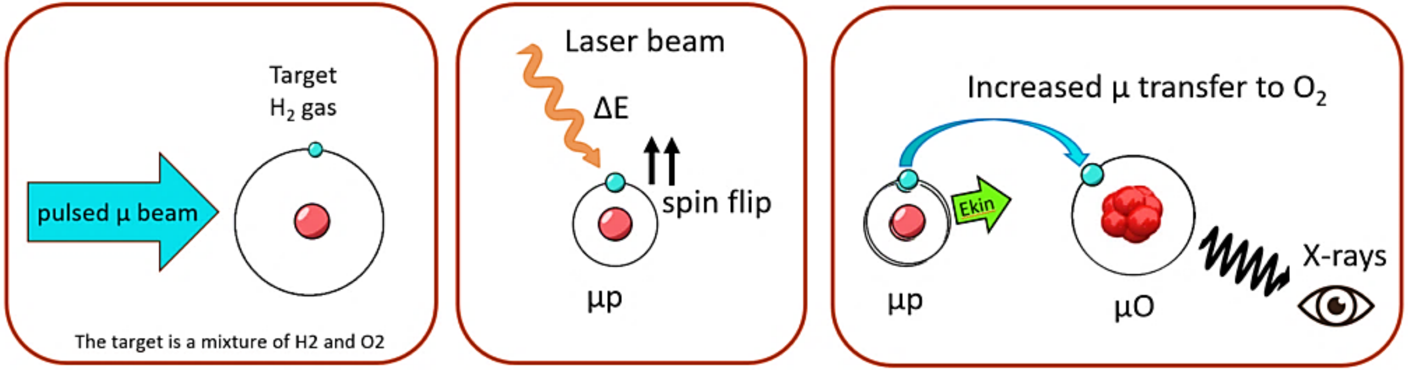
Spin flip → recoil 120 meV → enhanced probability of transfer of the muon from H to other atoms.

Simulation

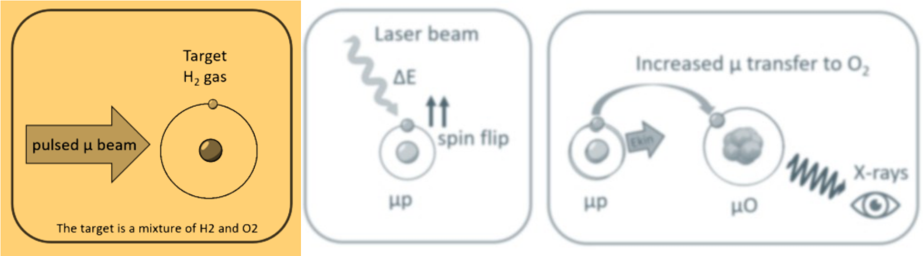


Illustration

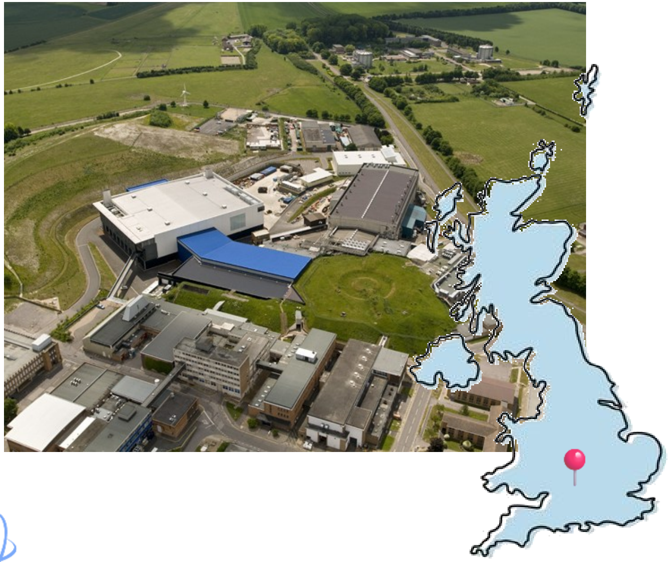


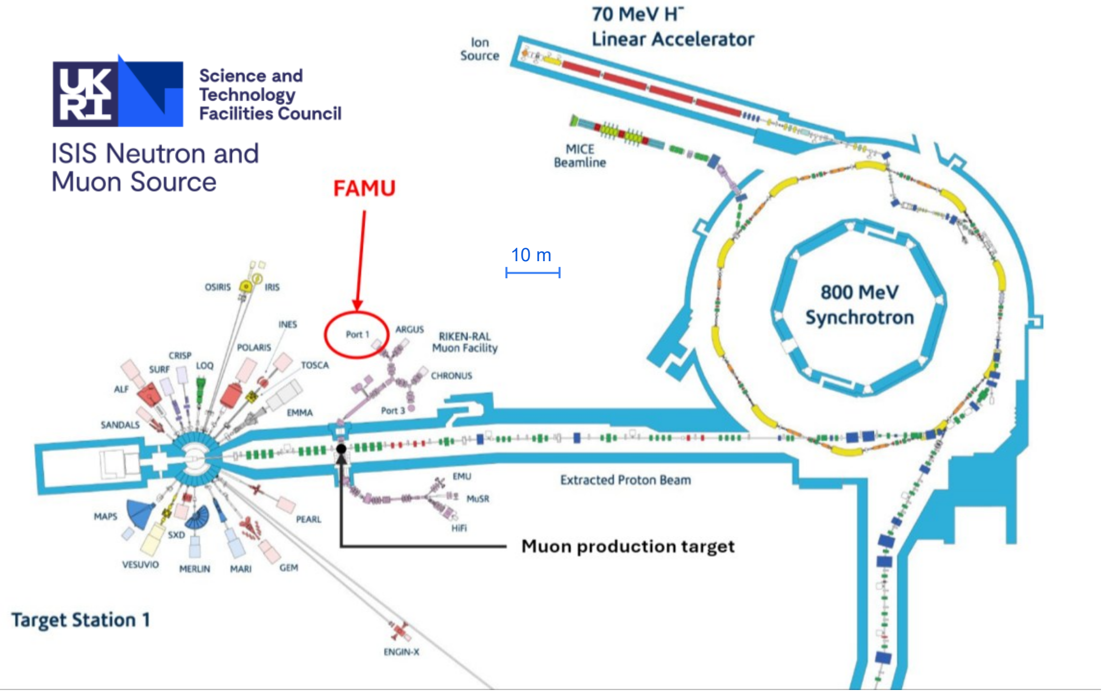


Experimental setup



ISIS Neutron and Muon Source,
Rutherford Appleton Laboratory (RAL),
Didcot, Oxfordshire, United Kingdom





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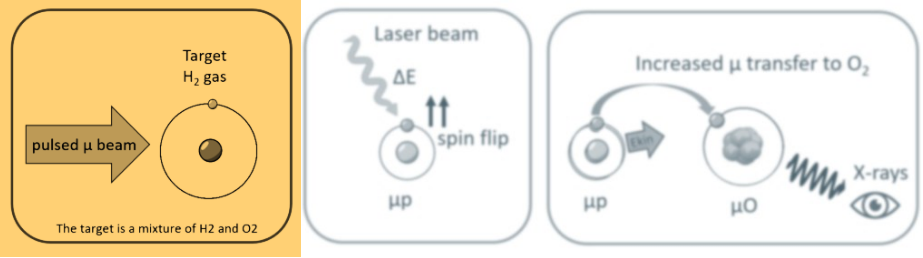
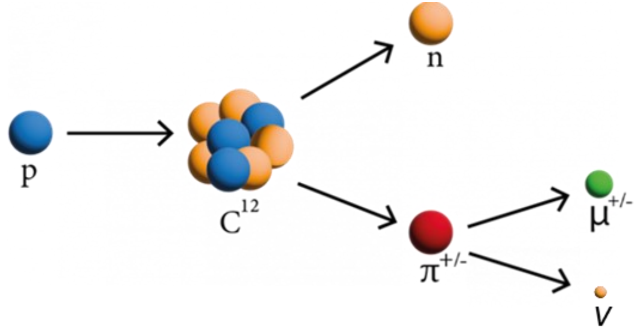
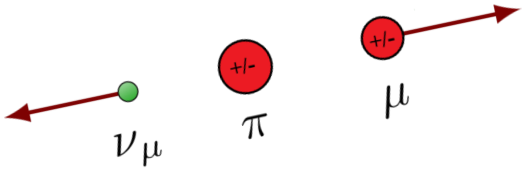
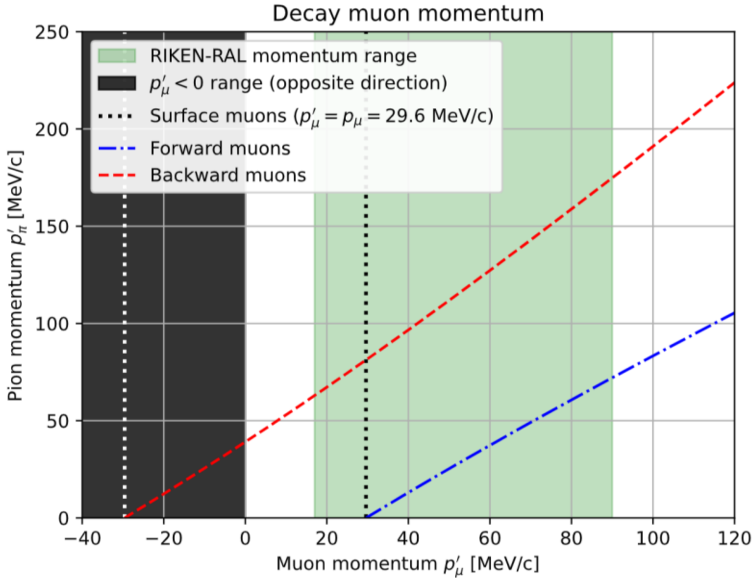




Surface muon: pion remains implanted in the C target
→ only μ^+ with momentum 29.6 MeV/c.

Decay muon: pion escapes the C target, transported in the beamline
→ $\mu^{+/-}$ with tunable momentum.





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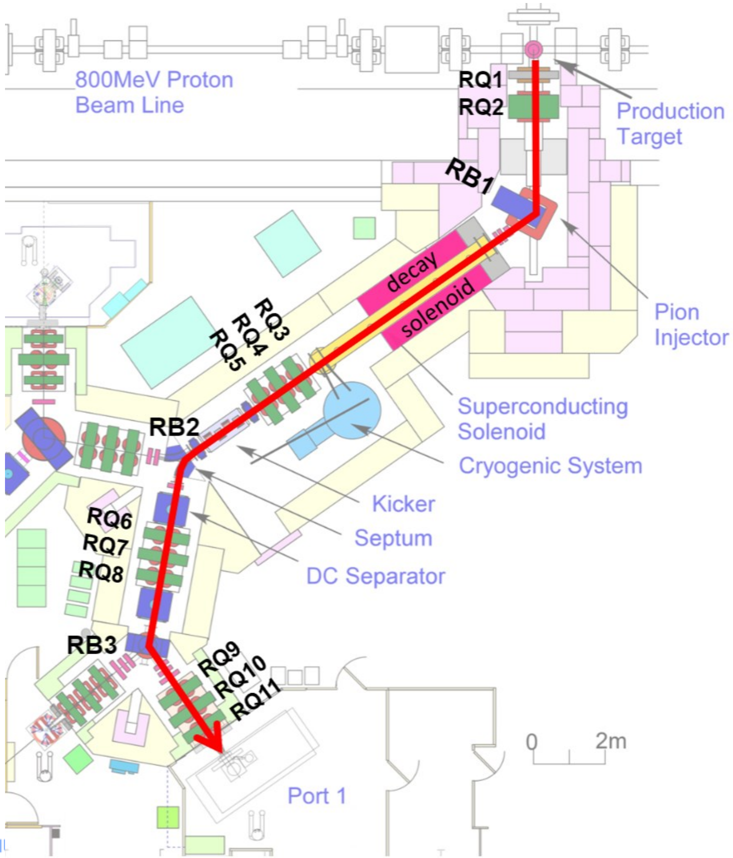
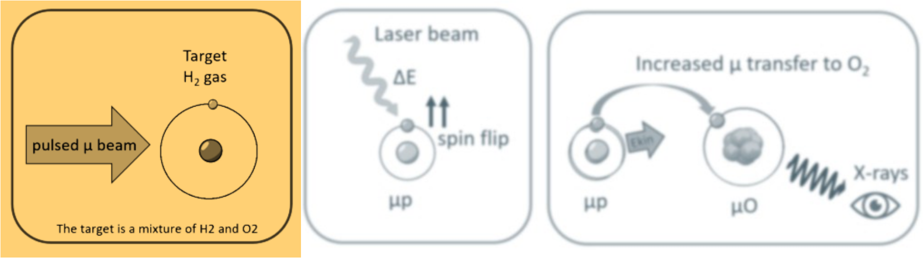
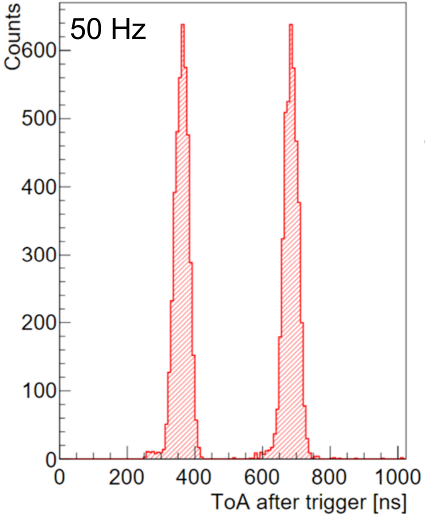
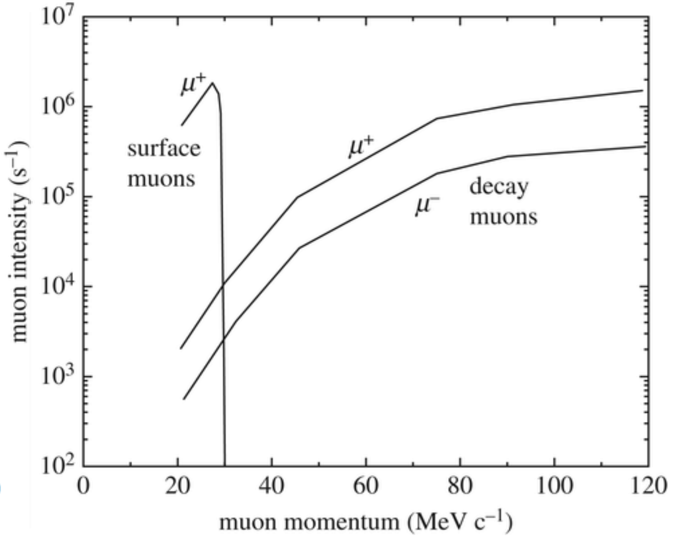




RIKEN-RAL muon facility → Port1.





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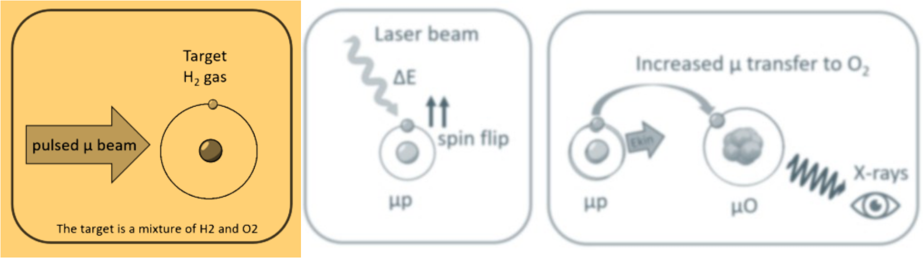
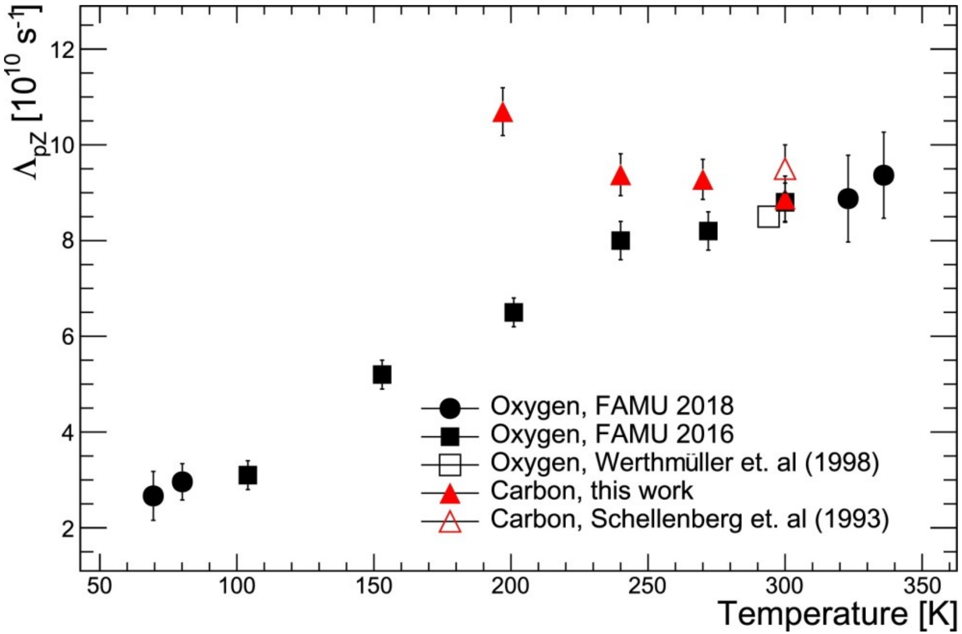


https://doi.org/10.1016/j.physleta.2025.130867



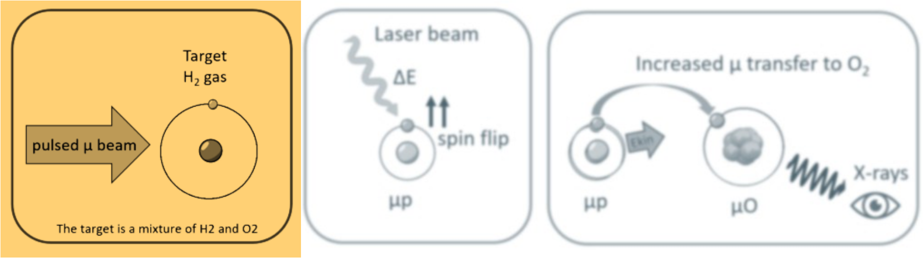
Target design based on previous FAMU data taking, simulation and optimisation (2014 – 2020).

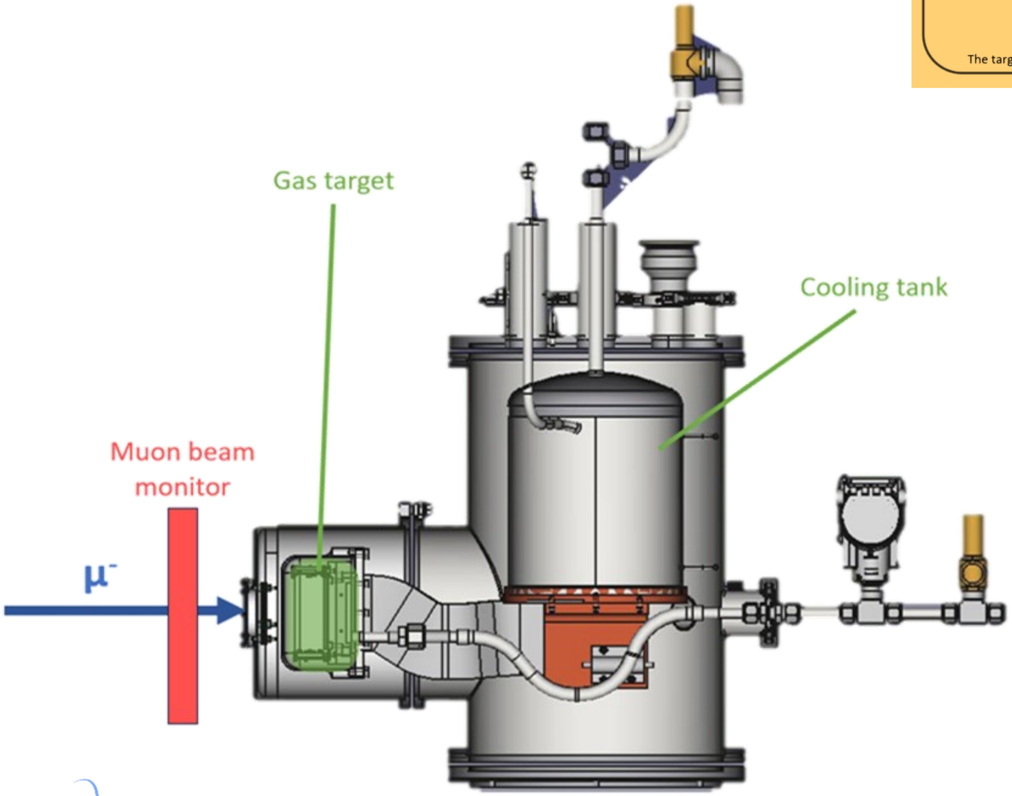
Transfer rate of the muon from muonic hydrogen to standard oxygen (Λ_{pO}) and to carbon (Λ_{pC}) studied as a function of temperature.

Nominal features:

- Pressure: 8 bar
- Temperature: 90 K
- Gas mixture: H_2 + 1.5%wt. O_2

Experimental setup





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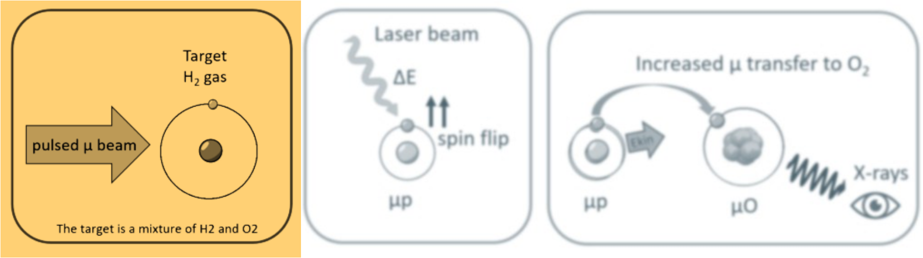
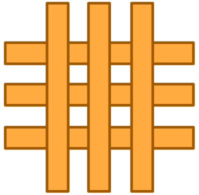
Transfer rate of the muon from muonic hydrogen to standard oxygen (Λ_{pO}) and to carbon (Λ_{pC}) studied as a function of temperature.

Nominal features:

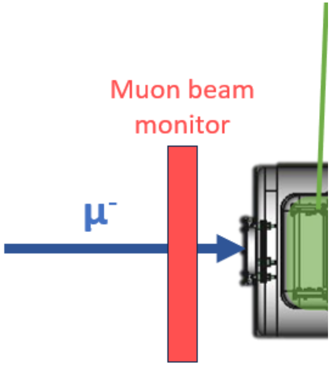
- Pressure: 8 bar
- Temperature: 90 K → *liquid nitrogen tank*
- Gas mixture: H_2 + 1.5%wt. O_2

Experimental setup

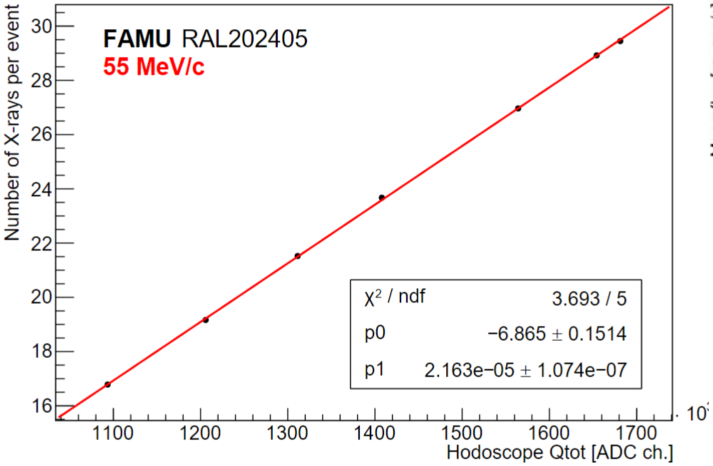




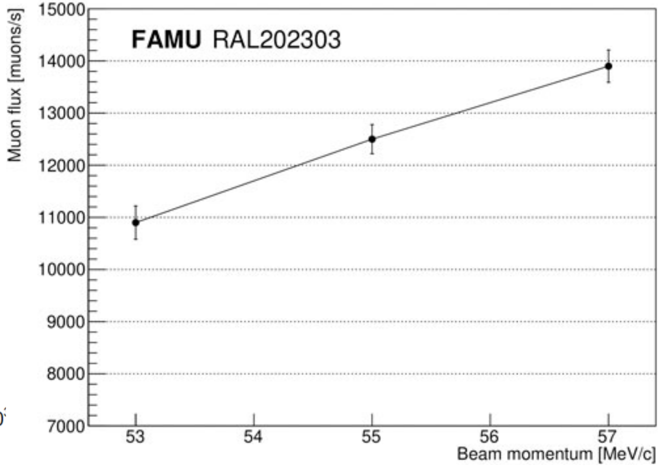
Two planes of squared scintillating fibres (32+32)
Fibre pitch: 1 mm
Fibre spacing: 1 mm



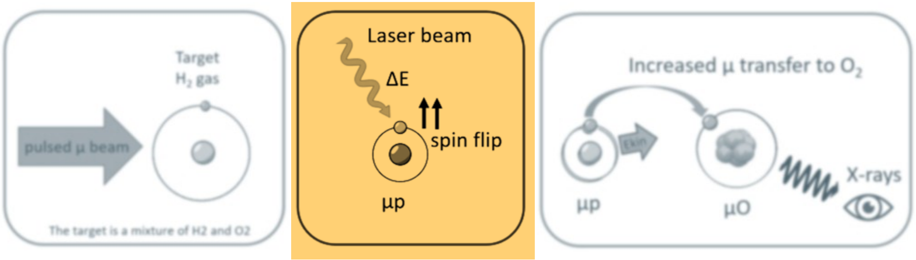
Hodoscope linearity test

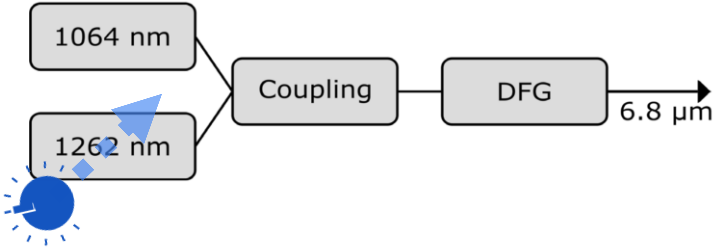


High-rate flux estimation



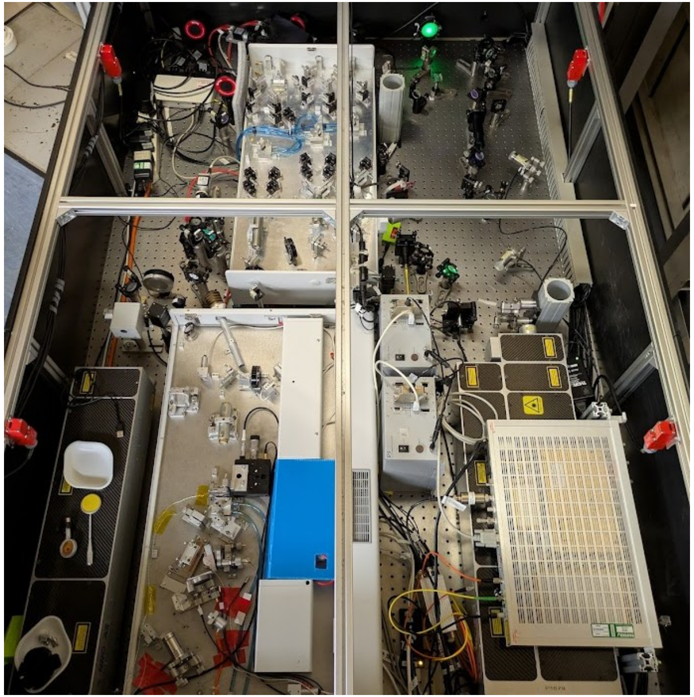
Experimental setup



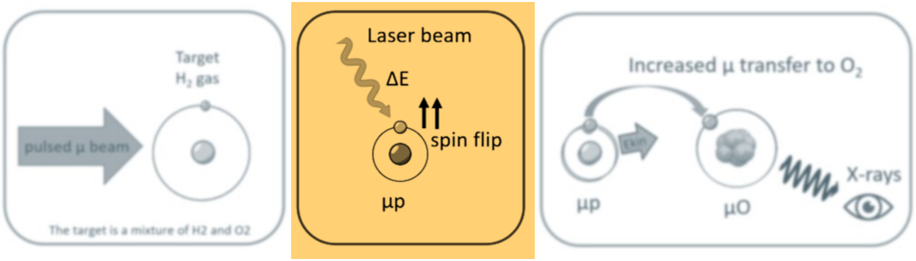


Two lasers injected in a non-linear optical crystal which carries out a Difference Frequency Generation (DFG) process.
Tunable 1262 nm laser to allow final wavelength tuning.

Parameter	FAMU requirement	Current FAMU result
Wavelength	6786–6792 nm	6400–8000 nm
Energy output	> 1 mJ	1.7 mJ
Line-width	< 0.07 nm	0.015 nm
Tunability step	< 10 nm	25 pm (used), 3 pm (min)
Pulse duration	< 10 ns	7 ns
Repetition rate	25 Hz	25 Hz



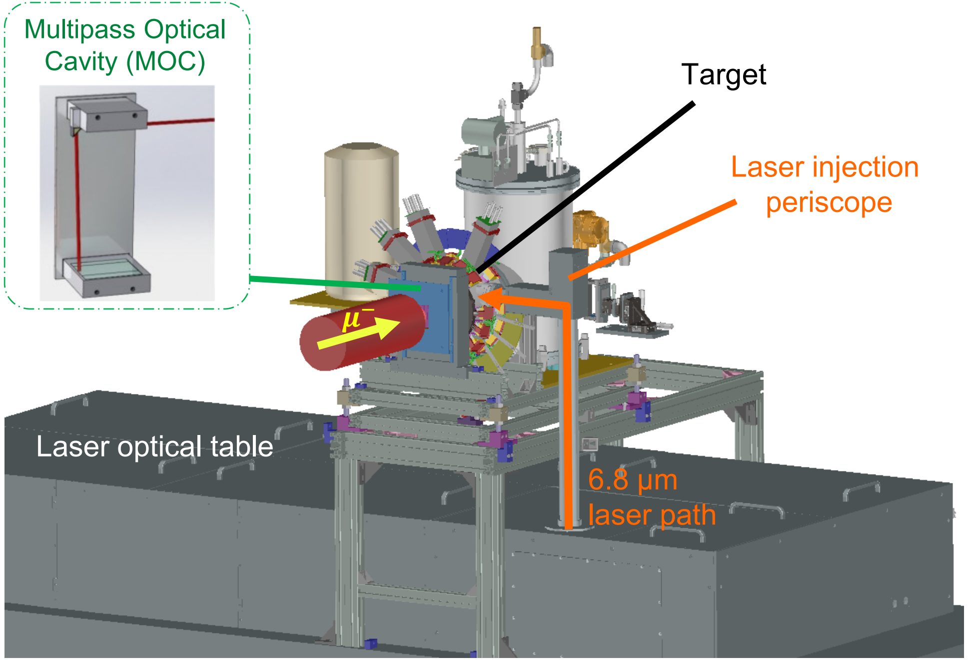
Experimental setup



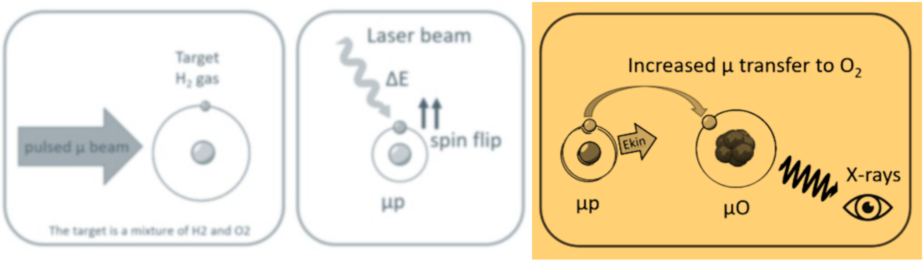
Laser beam injected in the FAMU gaseous target through a periscope.

To maximise the interaction between μH atoms and laser photons the target contains a Multipass Optical Cavity (MOC):

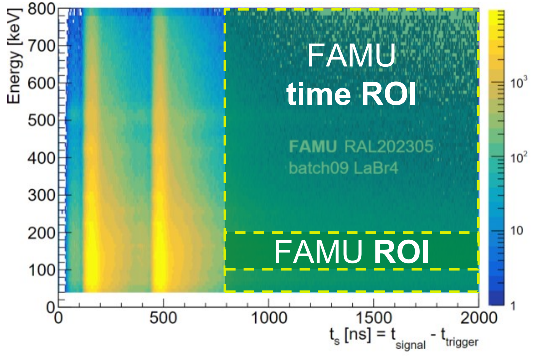
Structure material	invar
Mirror material	Si
Mirror coating	ZnS/Ge
Mirror 6.78 μm reflectivity	99.890(2)%
Distance between mirrors	10 cm
Simulated number of reflection	$\sim 10^3$
Simulated laser lifetime in the cavity	304 ns
Simulated mean laser path	91 m



Experimental setup



FAMU observable: excess of the number of delayed μO X-rays when the laser is injected in the target.



The *1S-hfs* transition is 4 orders of magnitude less probable than the *2p* Lamb shift.

↓

Good efficiency required in range 100-200 keV [FAMU ROI]

$K_\alpha^{\mu O} \simeq$ 133 keV

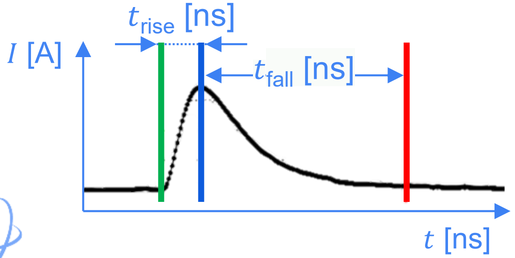
$K_\beta^{\mu O} \simeq$ 158 keV

$K_\gamma^{\mu O} \simeq$ 167 keV

↓

Good energy resolution required in range 100-200 keV [FAMU ROI]

Fast signal characteristic times



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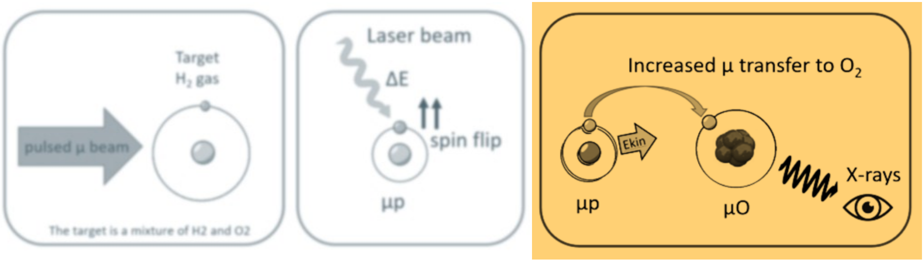
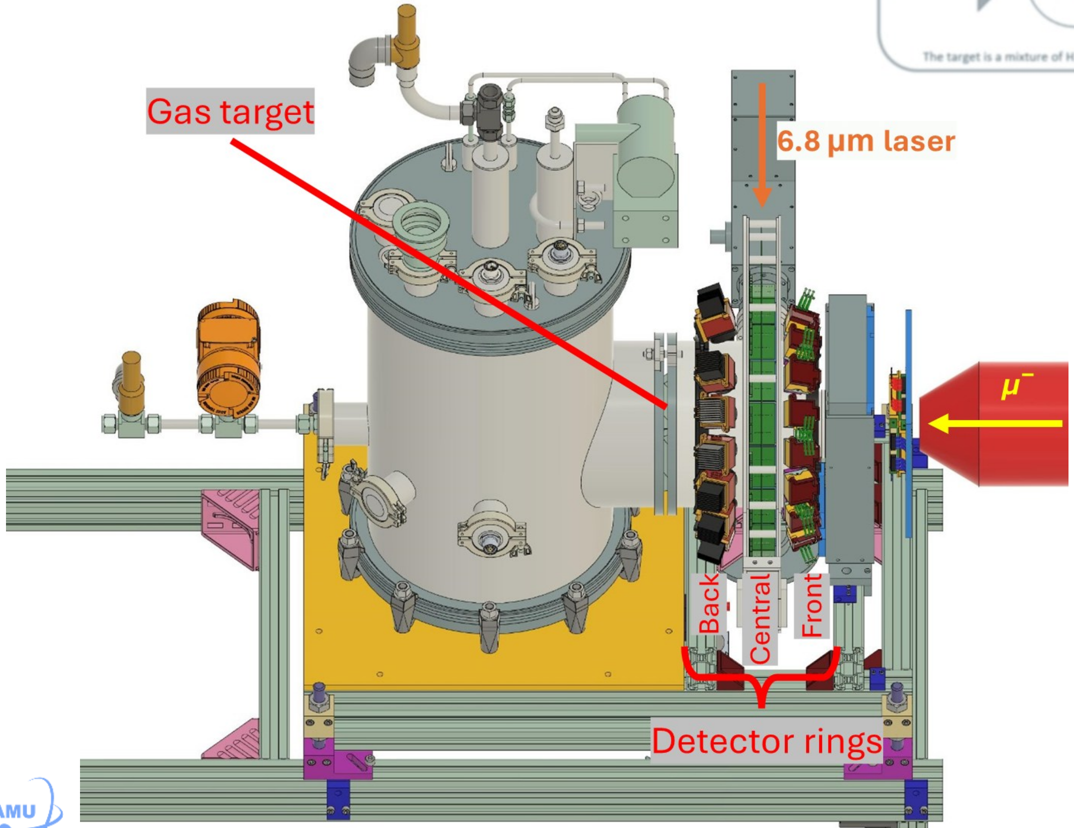




LaBr3:Ce scintillating crystals:

- fast scintillation time
- high density → high efficiency
- good energy resolution.

Detector setup for 2023 data acquisition:

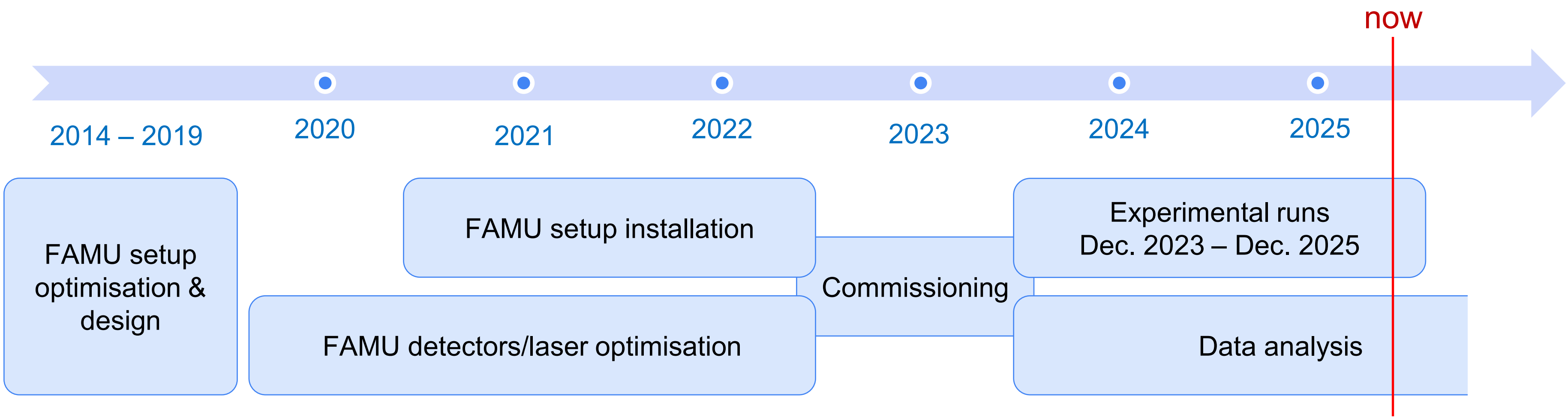
- 6x 1''-PMT detectors
- 16x 1''-SiPM detectors
- 12x ½''-SiPM detectors

Detectors mounted on 3 rings around the target.

In 2024 setup all ½''-SiPM substituted by 1''-SiPM (+32% solid angular coverage).

FAMU aim and status

Measurement of *1S-hfs* in μH allows the extraction of the proton Zemach radius with unprecedented <1% accuracy.

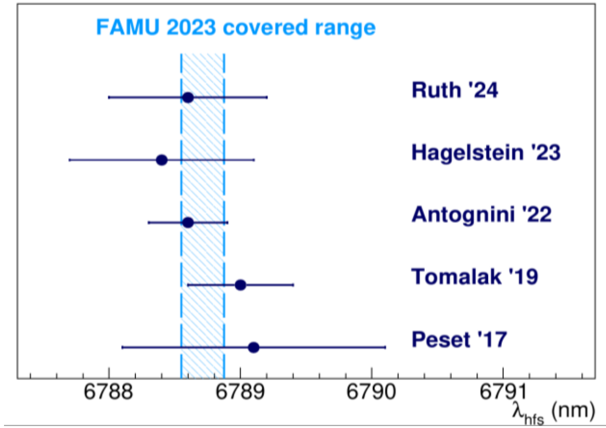


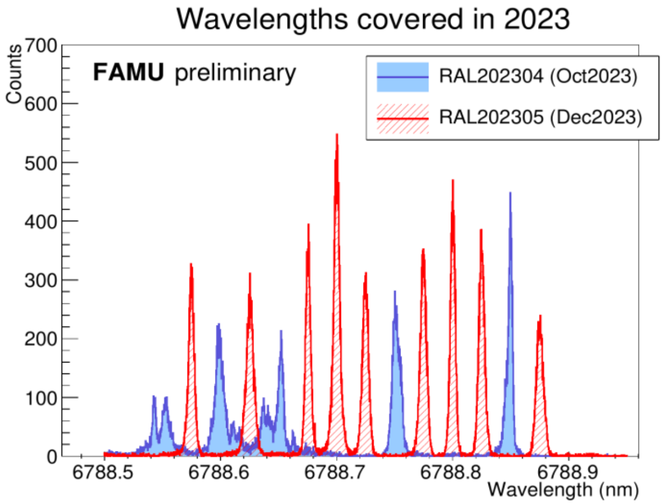
FAMU aim and status

Automatic detector calibration based on know energy of muonic X-rays from target materials.

First two runs for physics: October and December 2023 for a total of 17 days of beam time.

14 wavelengths measured in **2023** with the required statistics (at least 21-22 hours of live time) and spanning from 6788.550 μm to 6788.875 μm, with laser power around 1 mJ/pulse.





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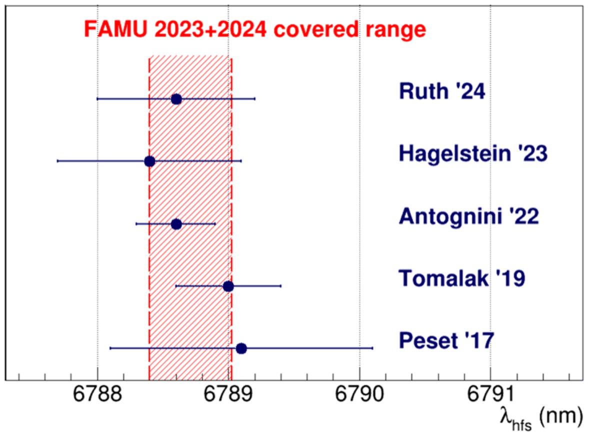
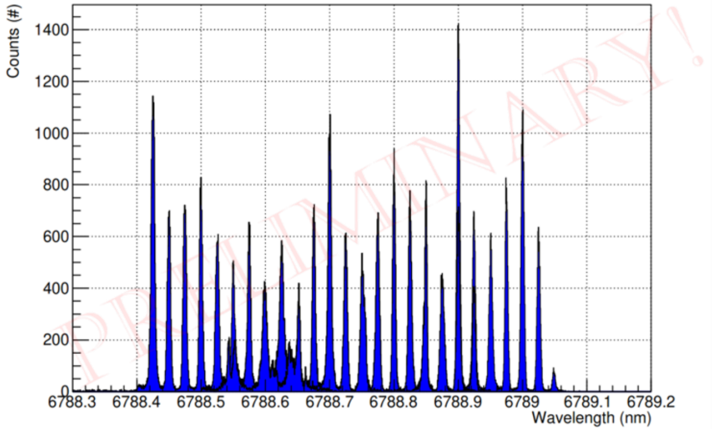
14 wavelengths measured in **2023** with the required statistics (at least 21-22 hours of live time) and spanning from 6788.550 µm to 6788.875 µm, with laser power around 1 mJ/pulse.

Two more runs for physics in July and October **2024**: extension of the range of the scanned wavelengths up to **29**, from 6788.400 µm to 6789.050 µm.

Two experimental periods are foreseen for late **2025** with enhanced laser stability and power (up to 2.8 mJ/pulse).



Wavelengths covered



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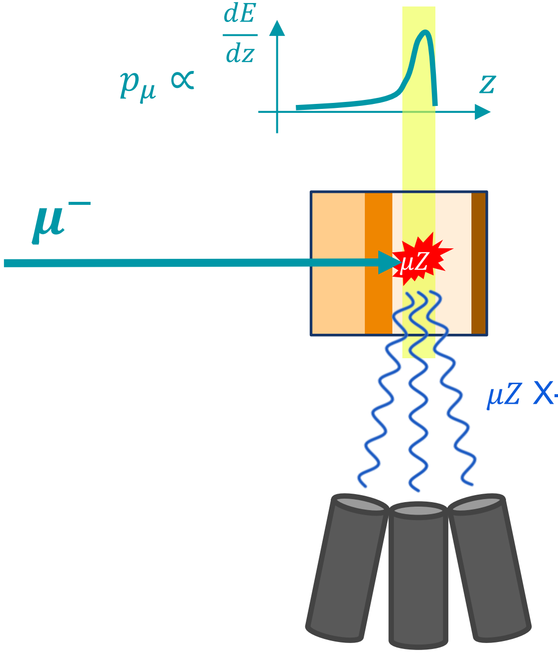
Elemental and isotopic characterisation of samples

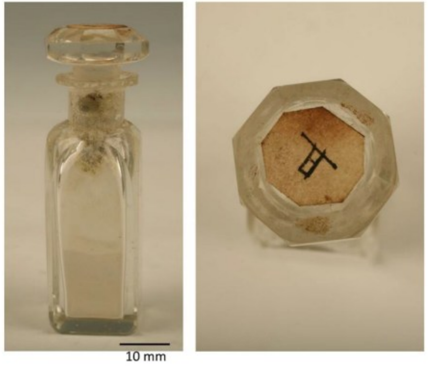
Elemental analysis



HPGe detectors

Muon Bragg peak → depth-tunable muonic atom formation (p_μ)
High energy X-rays (10 keV – 10 MeV) → limited self absorption
Can be performed non-destructively on whole samples → ideal for Cultural Heritage characterisation.

Muonic atom X-ray Emission Spectroscopy (μ-XES)
Non-destructive, depth-dependent technique for bulk quantitative elemental analysis.
At ISIS, currently carried out at RIKEN Port4.



Sealed medicines (19^{th} cent.) @J-PARC
10.1007/s11418-021-01487-0

Nuragic votive ships (1000 BC) @ISIS
10.1016/j.nima.2018.11.076

Pb isotopic analysis

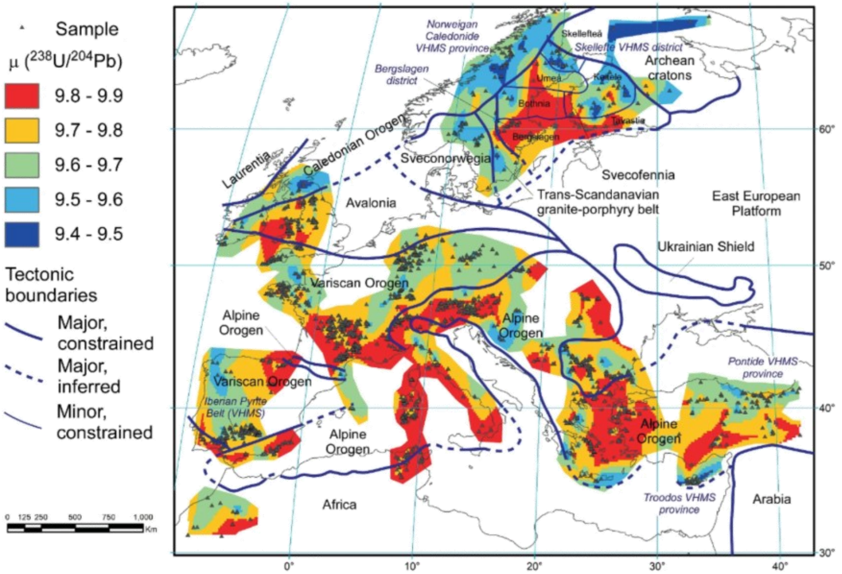
CHNet MAXI

^{204}Pb ^{206}Pb ^{207}Pb ^{208}Pb ^{210}Pb

CHNet-MAXI: ongoing INFN experiment exploring the feasibility of isotopic analysis in Pb using μ-XES.
First data acquisition with standard Pb samples: Dec. 2025.

Goal: 0.01% sensitivity.

The lead isotopic composition in historical samples is a marker of the origin of the extracted Pb.
Currently, only destructive techniques are available (ICP-MS).

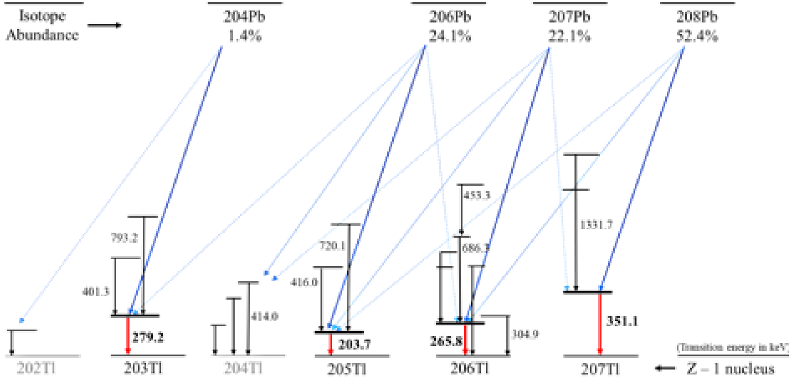


Pb isotopic analysis

Nuclear markers → gamma emission following reaction:

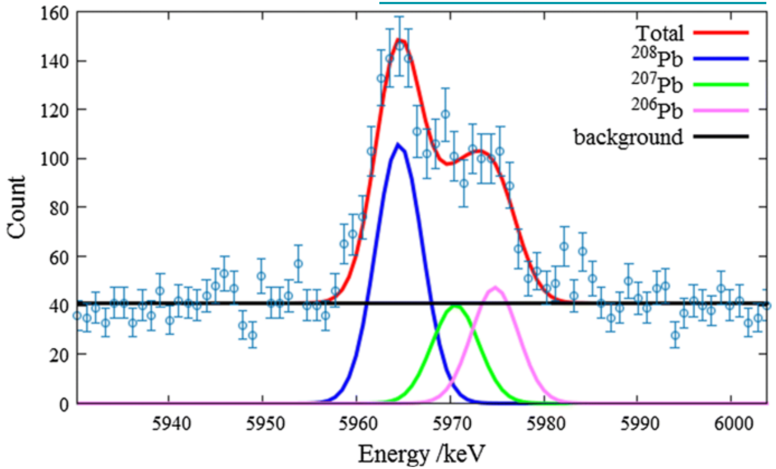
$$\mu^- \; p \rightarrow n \; \nu_\mu$$

$$\mu^- \; {}_{Z}A \; \rightarrow \; {}_{Z-1}A \; \nu_\mu$$



Atomic markers → muonic X-ray shifts

10.1007/s10967-019-06506-9



Both figures of merit require HPGe detectors (best energy resolution at high energy to identify the isotopic shifts) supported by fast scintillators (to get timing information, useful for identification of nuclear markers).

Conclusion

Conclusion

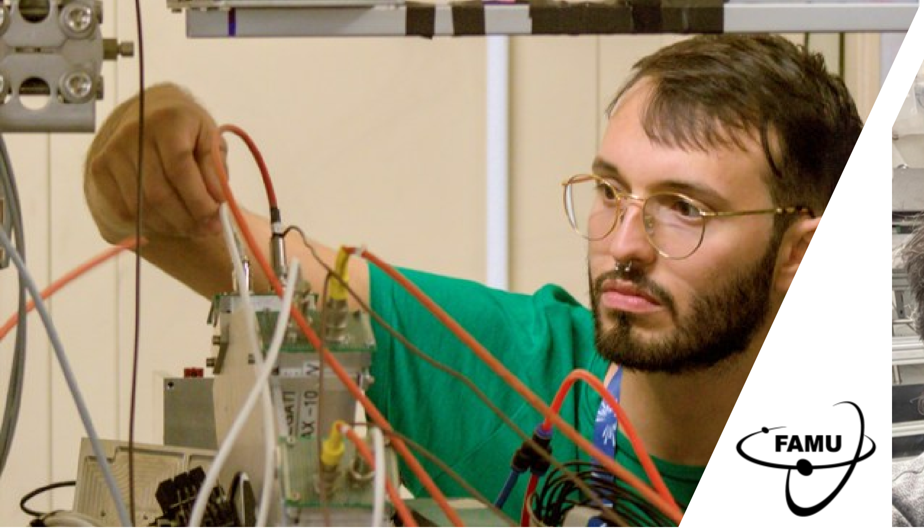
INFN (IT) involved in pure (FAMU) ad applied (CHNet-MAXI et al.) activities using low-momentum negative muons at ISIS (UK).

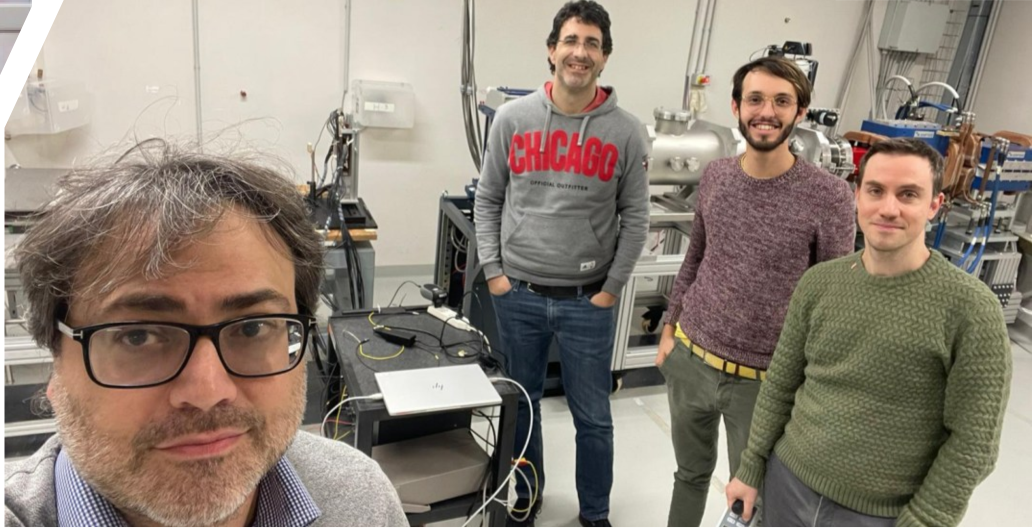
FAMU will carry out the 5th and 6th data taking periods in late 2025, aiming to cover the 95% CL of the most accurate proton Zemach radius prediction (Antognini 2022, 10.1146/annurev-nucl-101920-024709).

Elemental analysis through μ-XES is already being performed at ISIS (MuX beamline) with momentum between 20 and 100 MeV/c.

CHNet-MAXI will start its data taking in late 2025 aiming to study the possibility of using μ-XES to study the Pb isotopic composition with a 0.01% accuracy.

While current INFN activities at ISIS focus on the stopped muon applications discussed above, the complementary potential of higher-energy beams for nuclear and material characterisation is of great importance. These could enable new techniques for muon imaging, non-destructive assay of large objects, or studies of fundamental physics.





Thank you for your attention