Muonic Atom Spectroscopy of ^{238}U for the Extraction of Nuclear Properties

CHIPP Winter School of Particle Physics 2025

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on behalf of the muX collaboration

22/01/2025

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PSI

muX Collaboration

Goal

Determine the absolute nuclear charge radius of ^{226}Ra for the first time
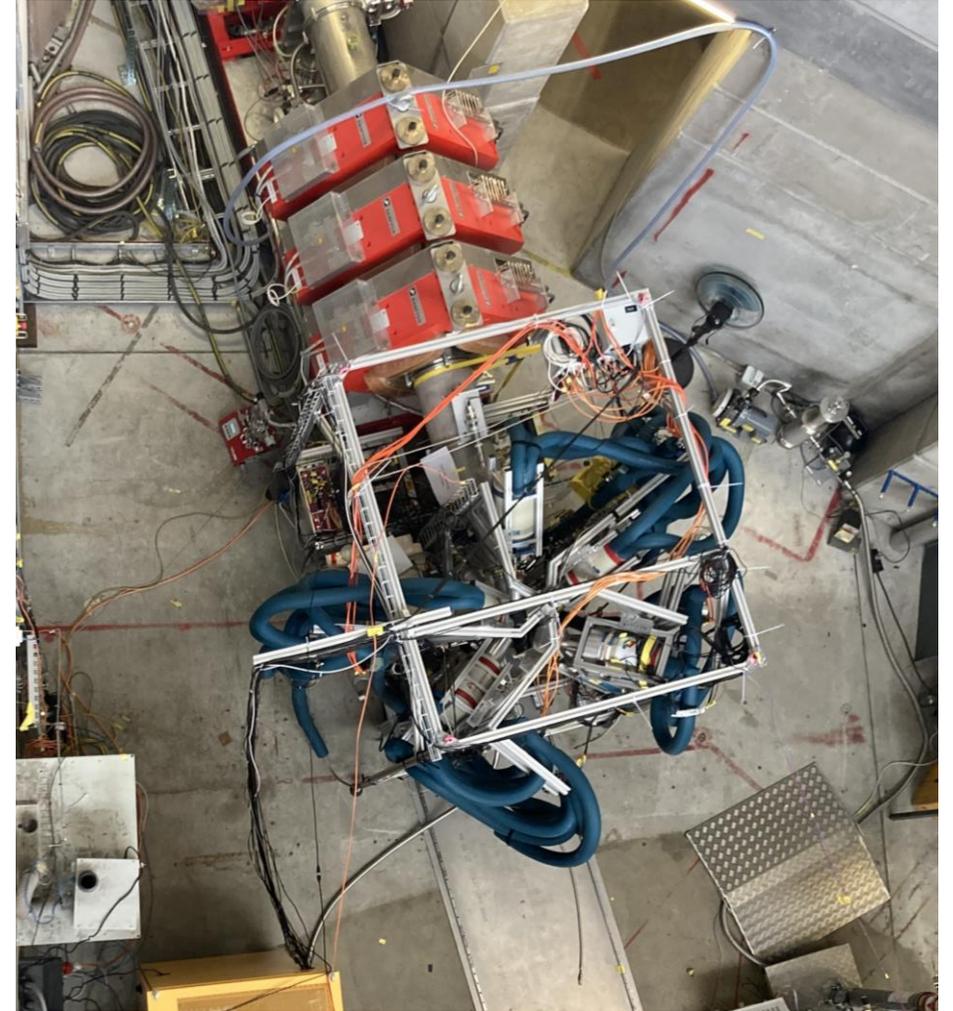
Why ^{226}Ra ?

Excellent candidate for measurements of atomic parity violation → physics beyond the standard model

BUT

Open radioactive sources available in microgram, μg, quantities

WAY

Performing muonic atom spectroscopy with a novel muonic capture technique

Muonic Atoms

Muons (μ^-) are leptons, with an electric charge of -1, spin-½ and 207 times more massive than electrons:
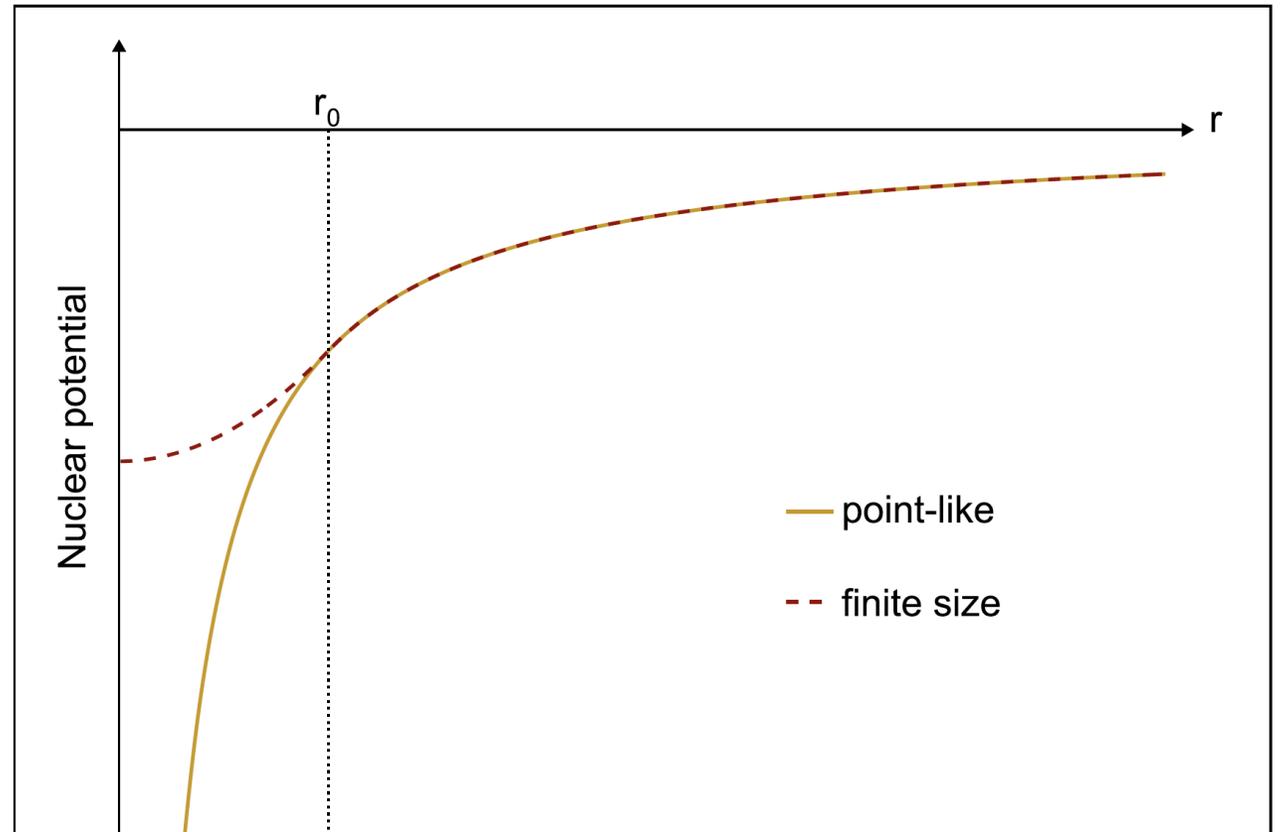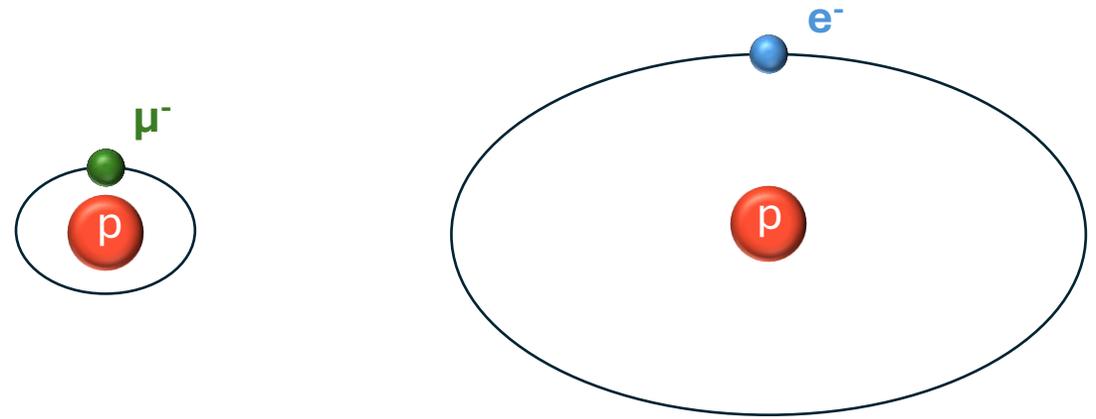
$m_\mu \approx 207 \, m_e$

Muonic atoms are formed when a muon gets captured by a nucleus

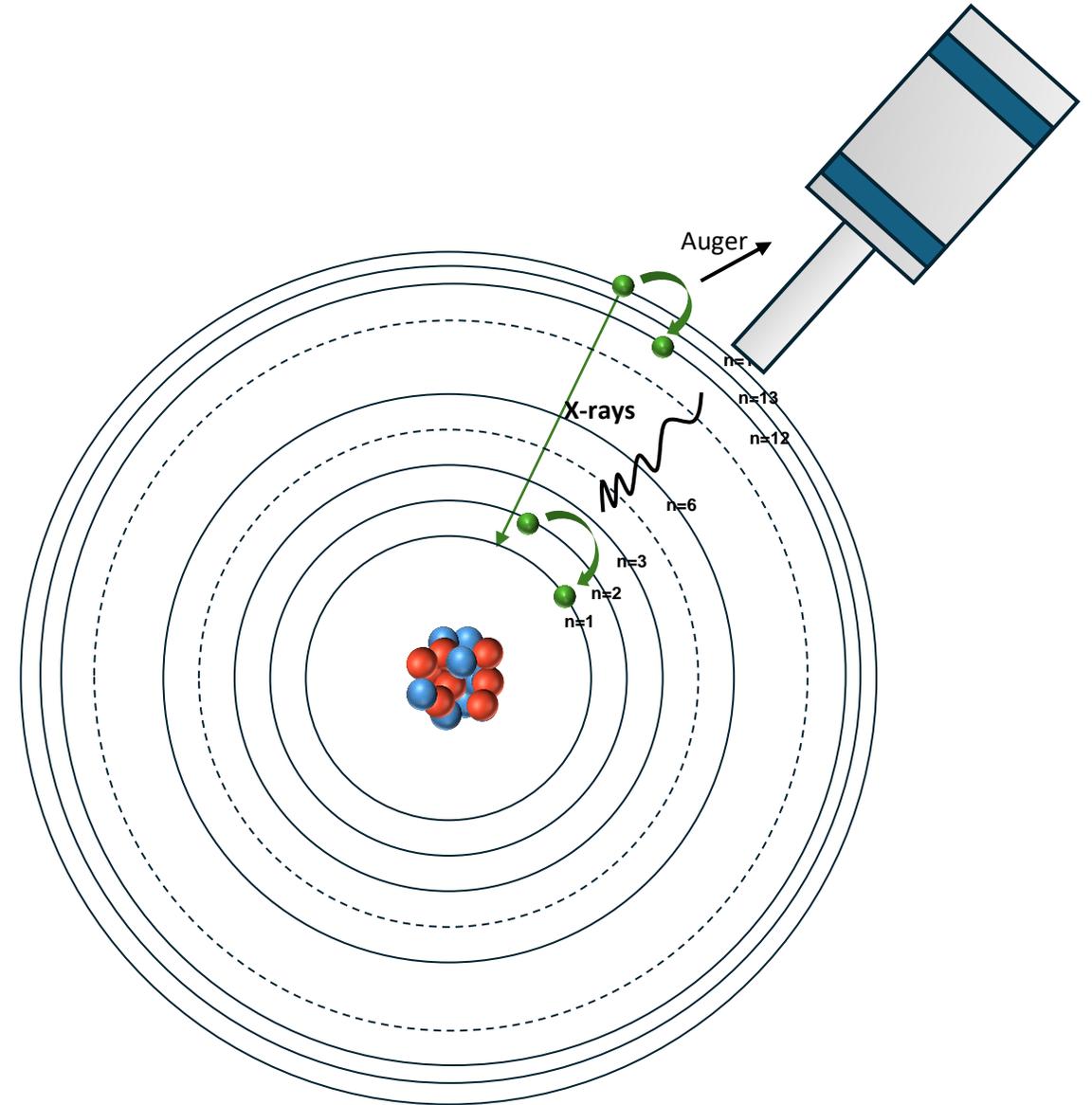Muon orbits 207 times closer to the nucleus than electrons :

Bohr radius: $r_\mu \approx \dfrac{1}{207} \, r_e$

Muonic wave function overlaps with the nuclear charge distribution → muonic energy levels show high sensitivity to the nuclear properties
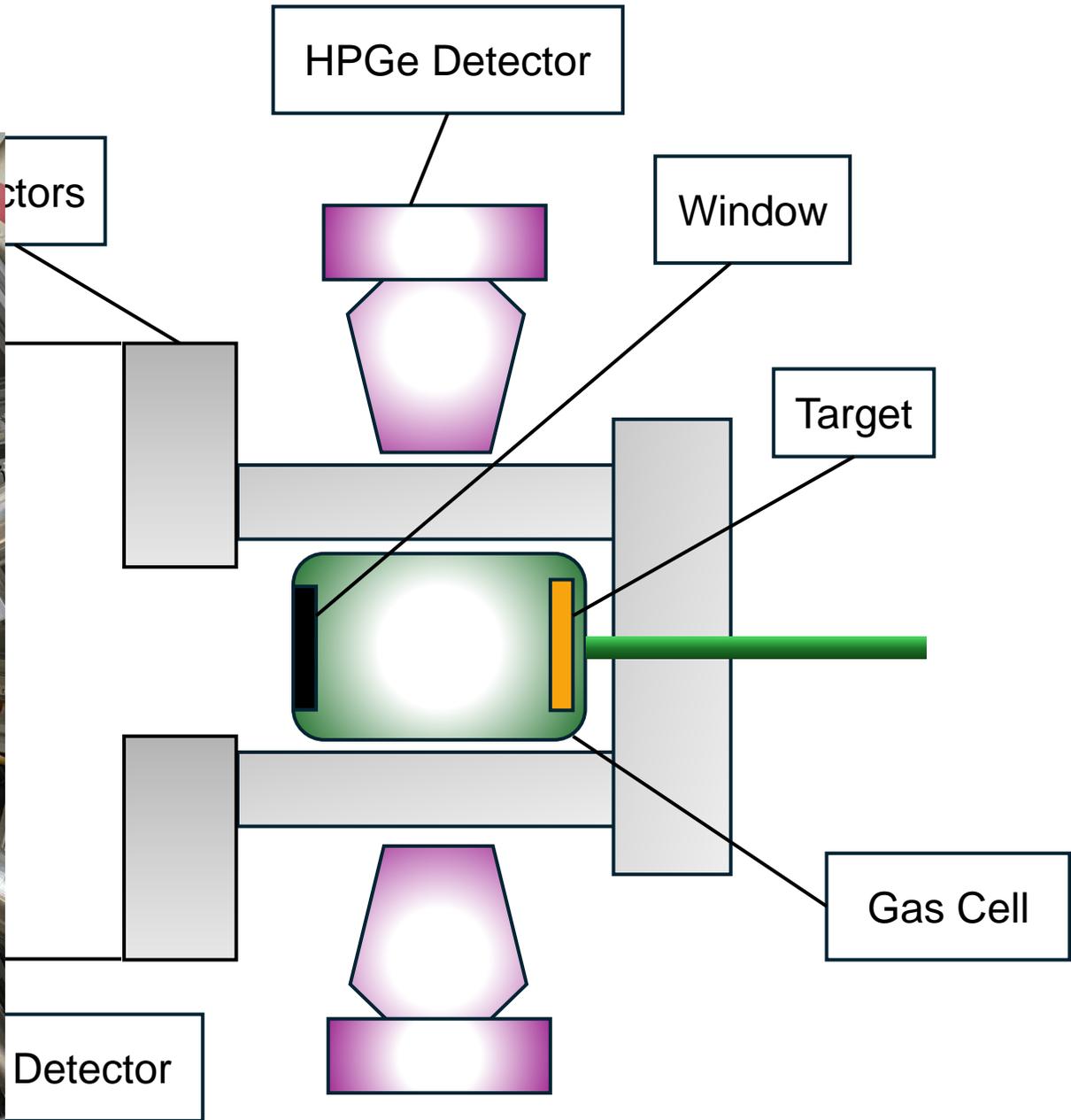
Muonic Atom Spectroscopy

1. Muon gets captured at n ~ 14

2. Cascades down to the ground, 1s, state

3. Beginning of the cascade → strong Auger effect

4. Below n ~6 → radiative transitions dominant, emission of muonic X-rays

✓ Muonic X-rays (between keV to MeV) detected by High-Purity Germanium detectors (HPGe)

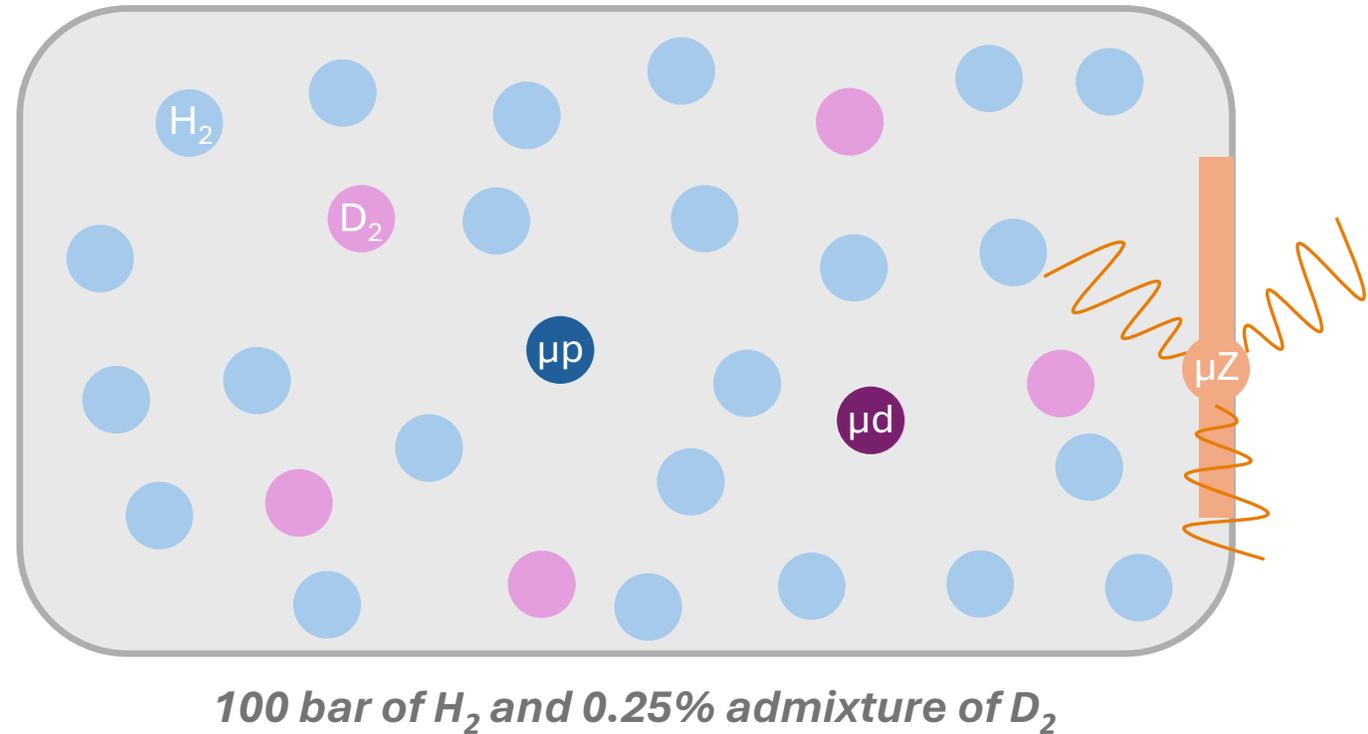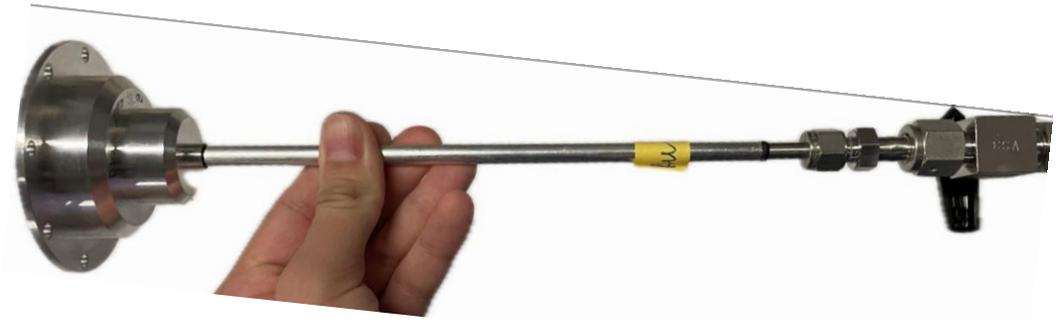5. Reaching the ground state muon gets captured by the nucleus or decays

The muX Experimental Setup

HPGe Detector

Window

Target

Gas Cell

Detector

ctors

Transfer of Muons in a Gas Cell

1. The muon (μ^-) enters the gas cell

2. Muon interacts with hydrogen (H_2) and forms muonic hydrogen (μp)

3. Muonic hydrogen (μp) interacts with deuterium (D_2) and forms muonic deuterium (μd)

4. Muonic deuterium (μd) gains kinetic energy of 45 eV (boosted)

5. Muonic deuterium scatters and gradually looses its kinetic energy

6. At 4 eV μd "blind" to H_2 (Ramsauer-Townsend effect)

7. Muon reaches and gets captured by the heavy-Z target material

100 bar of H_2 and 0.25% admixture of D_2

Muonic atom spectroscopy of ^{238}U

Performed the muonic atom spectroscopy of ^{238}U and examined the cascade behavior for direct and transfer muon capture.

DATA SETS

2017 data transfer muon capture, muons go through gas mixture and to the target

2023 data direct muon capture, muons directly shot to the target
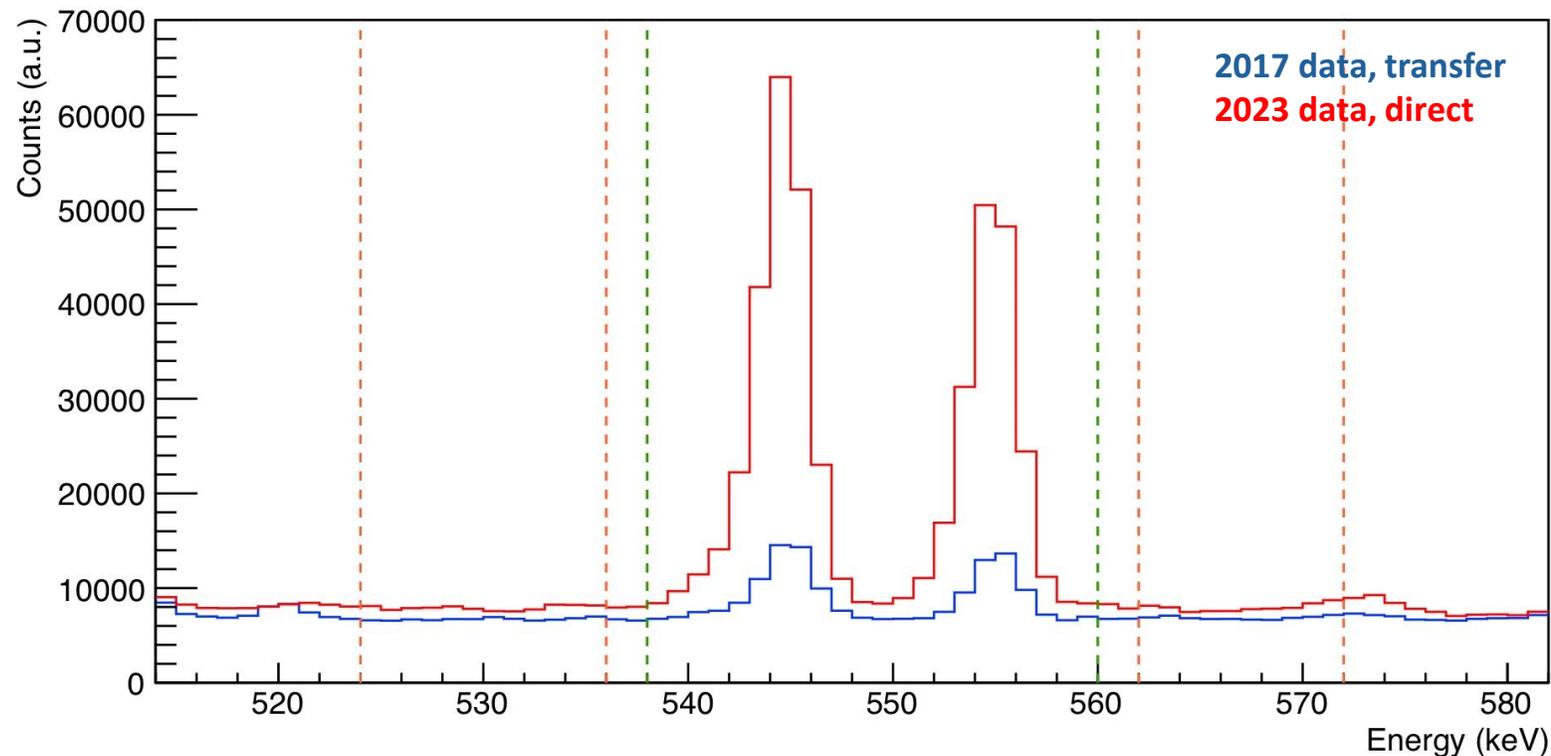
APPROACH

Performed muonic ^{238}U spectroscopy by:

1. Removing the background and calculating the intensity of the possible transition 2p →1s, 3d →2p, 4f →3d and 5g →4f

2. Scaling the 2017 data with respect to the 2023 data

3. Compare the cascade behavior between the two years and with the cascade simulations for late and prompt time windows

Transition Intensity and Background Removal

1. **Transition Intensity without Background**: Going at each transition/peak of the energy spectrum, calculate the integral underneath and remove the background based on the integrals of the neighbouring regions:

$$Intensity = \sum_{j=1}^{N} Cj - \frac{N}{2}\frac{1}{M}\sum_{i=1}^{M} Ci - \frac{N}{2}\frac{1}{L}\sum_{l=i}^{L} Cl$$

5g->4f transition

544 keV
554 keV

Data Scaling

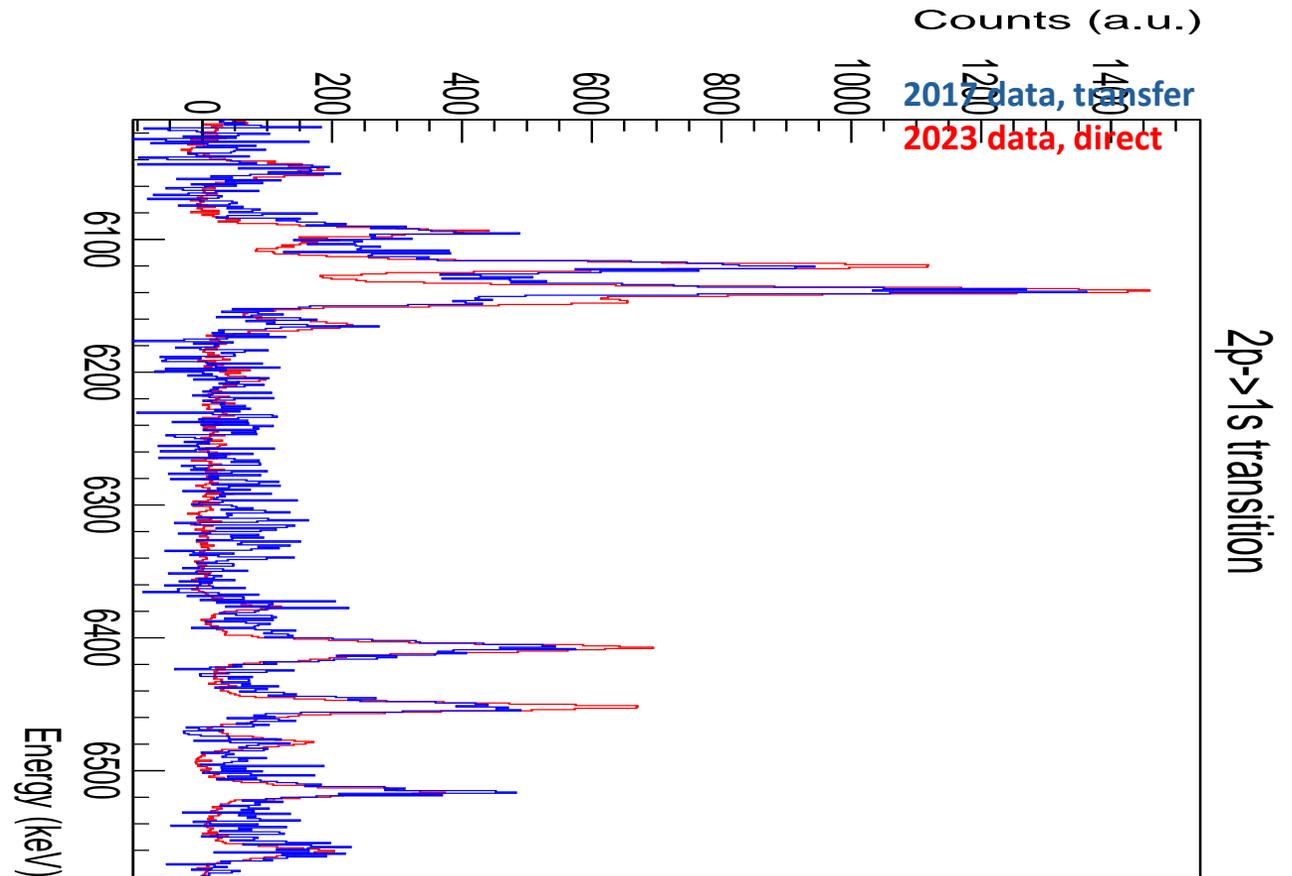In order to compare the energy spectrum of the two different data sets:

2. **Scaling data**: Scaled 2017, transfer data relative to the 2023, direct data with respect to the most prominent peaks of the ^{238}U spectrum at 2p $\rightarrow$ 1s transition:

$$Scaling\ Factor = \frac{I\ 2p \rightarrow 1s\ (2023)}{I\ 2p \rightarrow 1s\ (2017)}$$

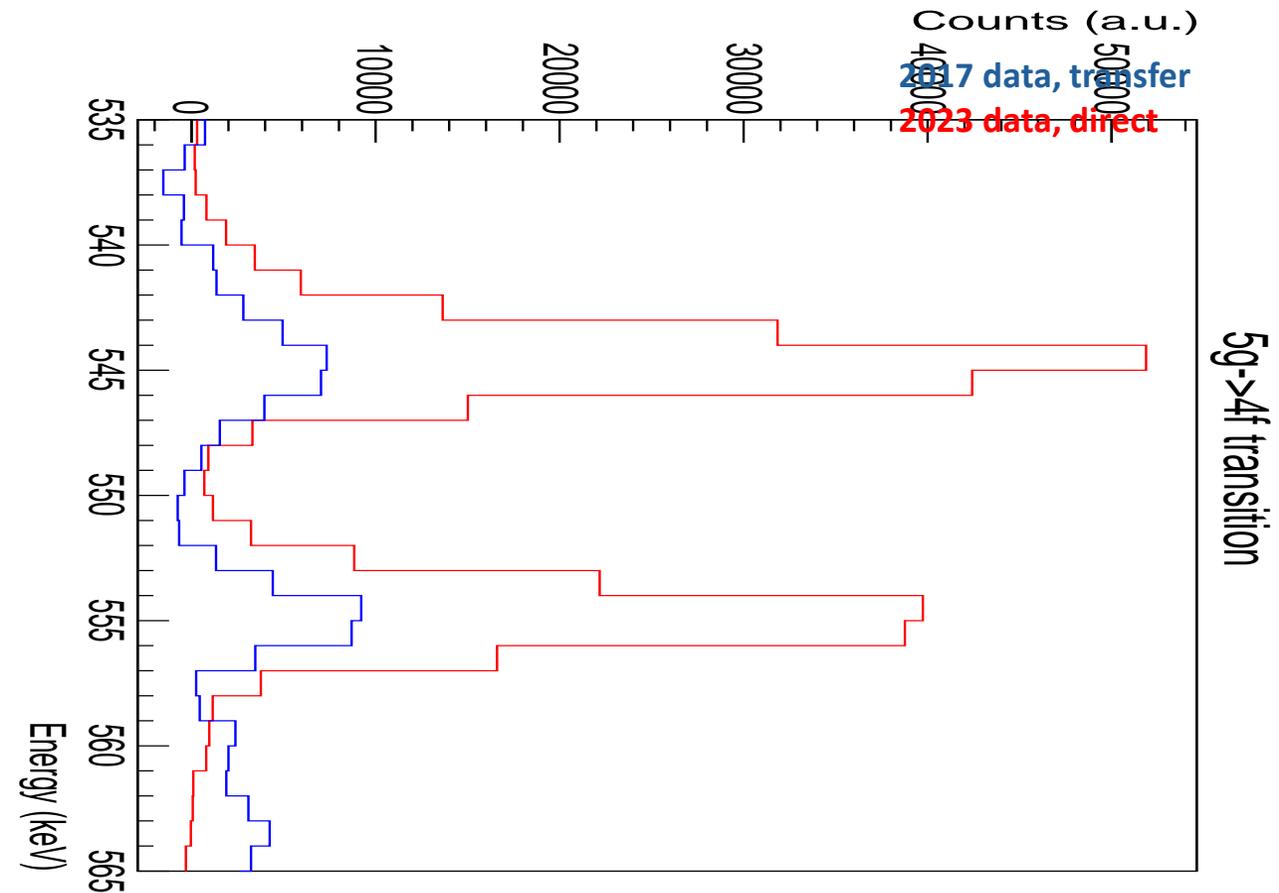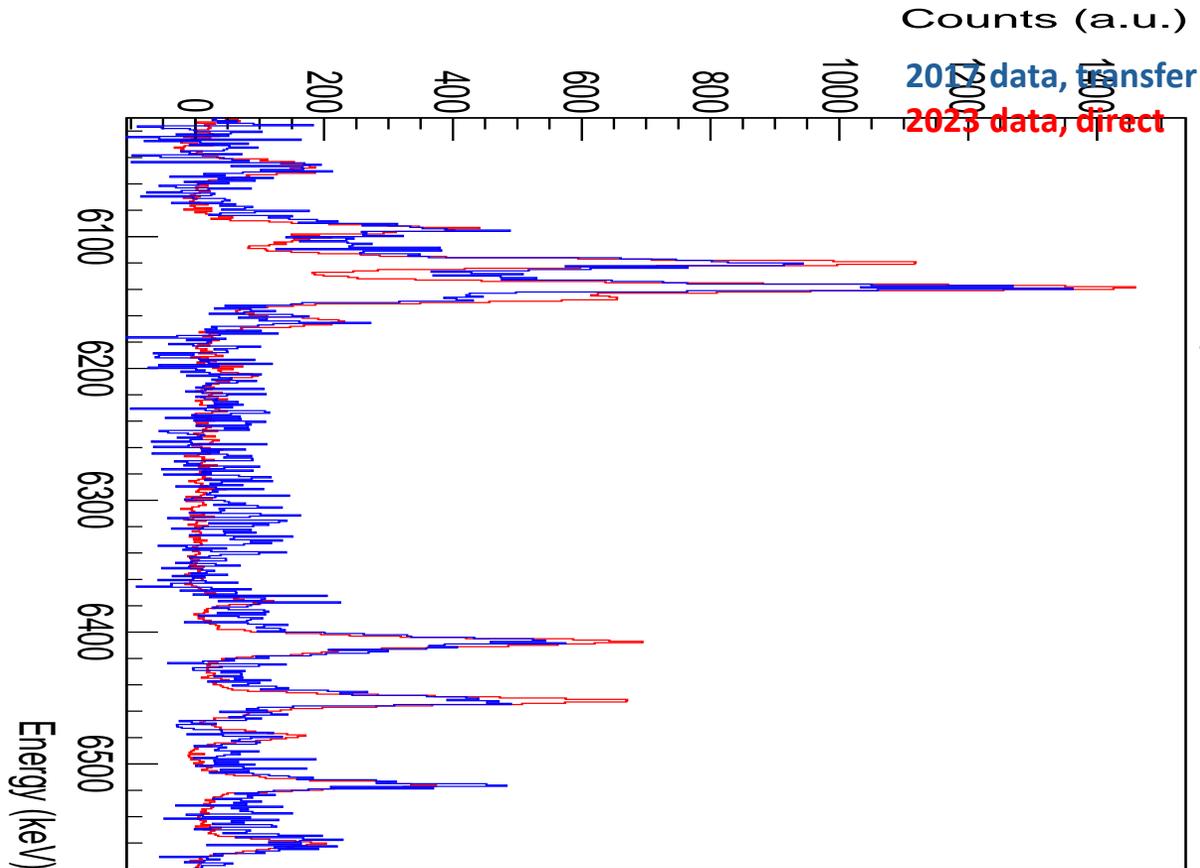2023 data, for a prompt time interval (-50 to 50 ns)

2017 data, for a late time interval (+50 to 260 ns)

✓ After scaling the two data sets overlap

Transition 5g → 4f, Direct versus Transfer Muon Capture

2023, direct data ~ 5 times more intense peaks than 2017, transfer data
✓ Matching predictions of the cascade simulations

Conclusions

- Muonic atom spectroscopy is used to study nuclear properties such as charge radius and quadrupole moment

- muX collaboration developed a method based on transfer reactions in a gas cell to perform muonic atom spectroscopy with materials that are available in microscopic quantities, like radioactive

- Muonic atom spectroscopy of a heavy-Z target material, ^{238}U, showed that circular transitions are more favored for direct than transfer muon capture

- Goal of the muX Collaboration is to determine the ^{226}Ra absolute charge radius → candidate for APV and thus physics BSM

Thank you for your attention!

BACKUP SLIDES

CHIPP Winter School of Particle Physics 2025
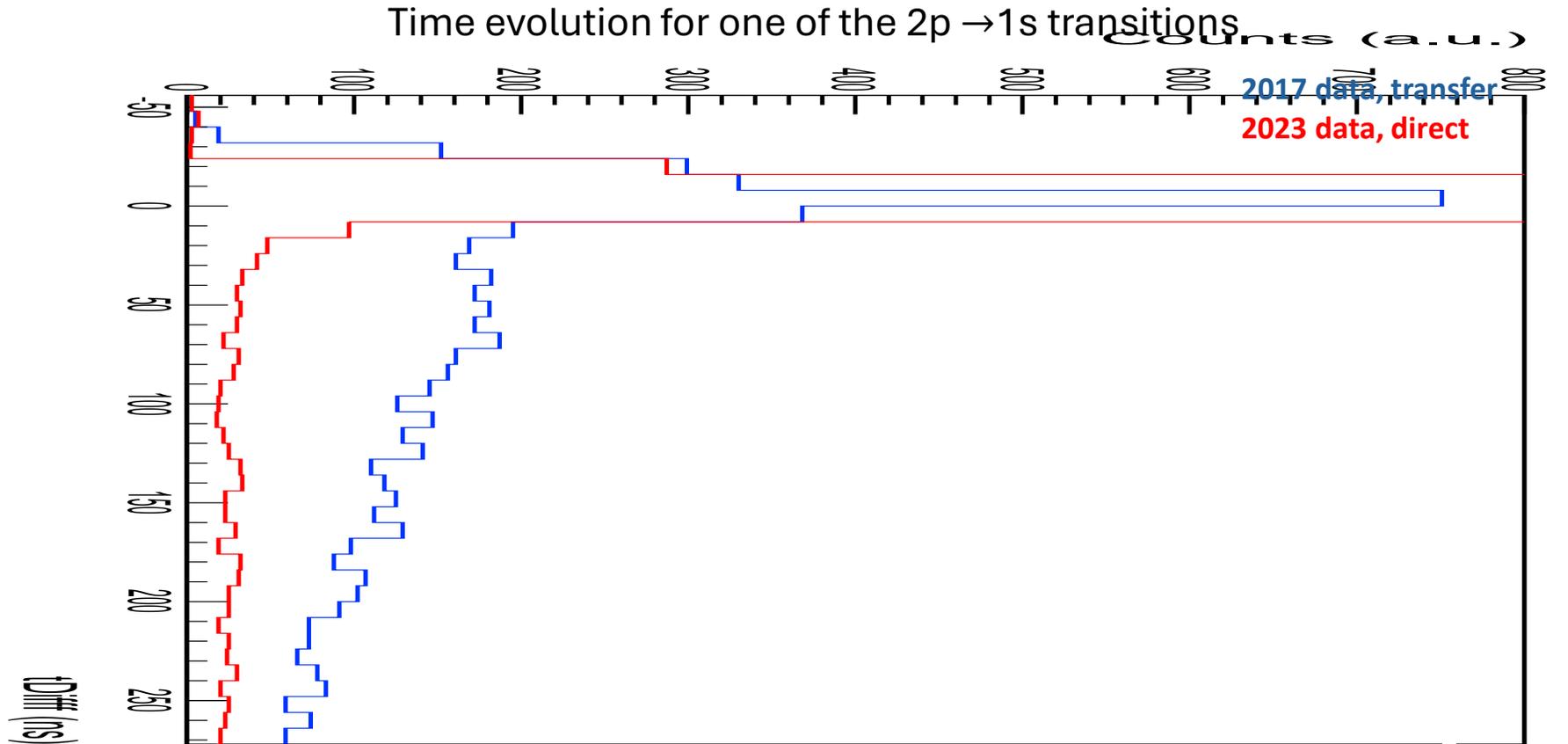
Muon Capture Timing

DATA SETS

2017 data transfer muon capture, muons go through gas mixture
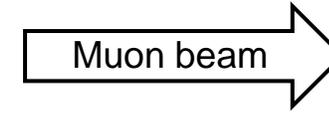
➔ Prompt and late muon capture
➔ Peak and long tail

2023 data direct muon capture, muons directly shot to the target
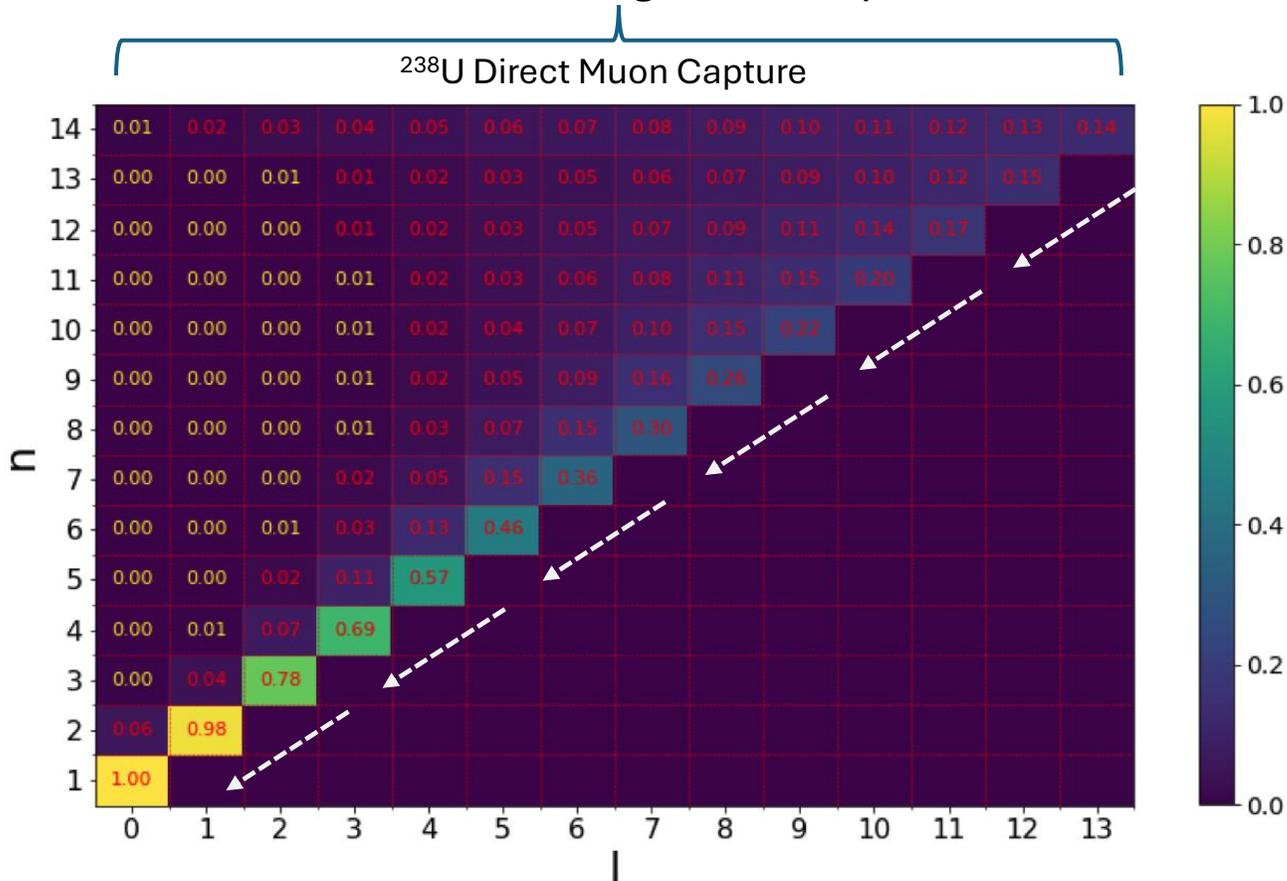
➔ Pompt muon capture
➔ Sharp peak

Time evolution for one of the 2p →1s transitions

2017 data, transfer
2023 data, direct

Direct Muon Capture

Target available in macroscopic quantities, more than 100 mg. Muons shot and directly stopped at the target.

Muon beam →

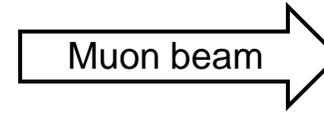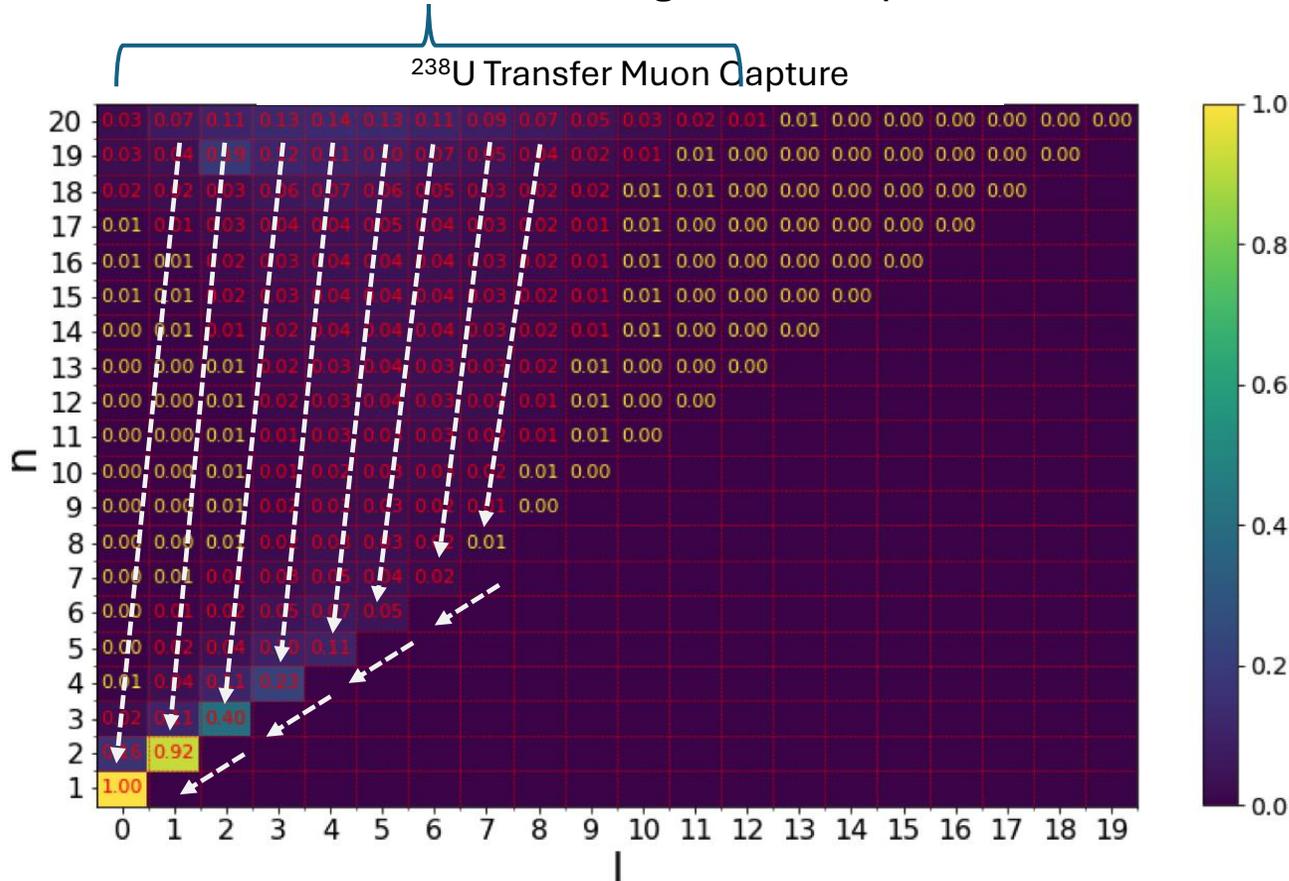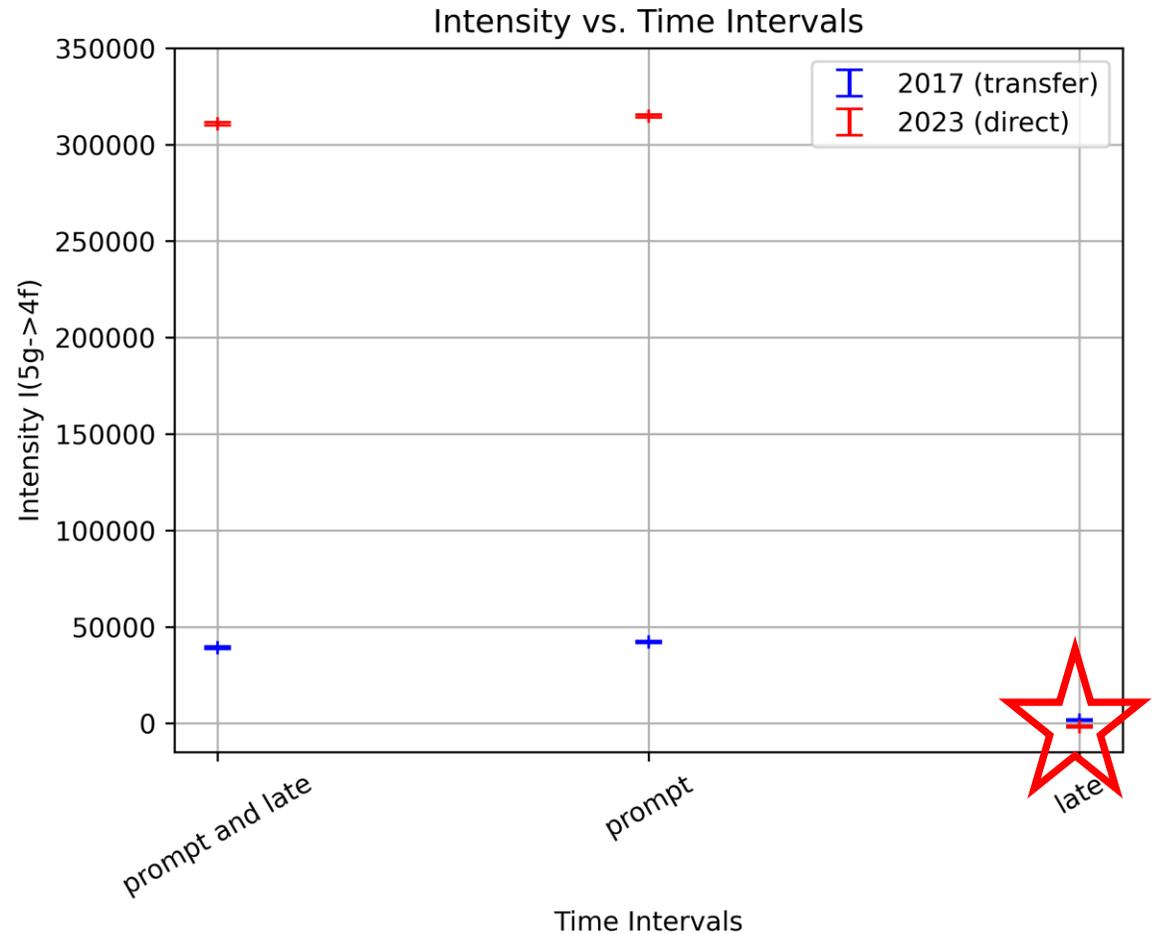<u>Cascade simulation</u> calculating the rates/probabilities for the Auger and X-ray transitions

238U Direct Muon Capture

- Muons captured at n~14

- Angular momenta of captured muons distributed based on (2l+1) statistical distribution

- (n, l=n-1) → (n-1, l=n-2) transitions favored (circular transitions)

Transfer Muon Capture

Target available in microscopic quantities, in the order of μg. Muons transverse the gas cell, undergo a three-stage transfer process and get captured by target material.
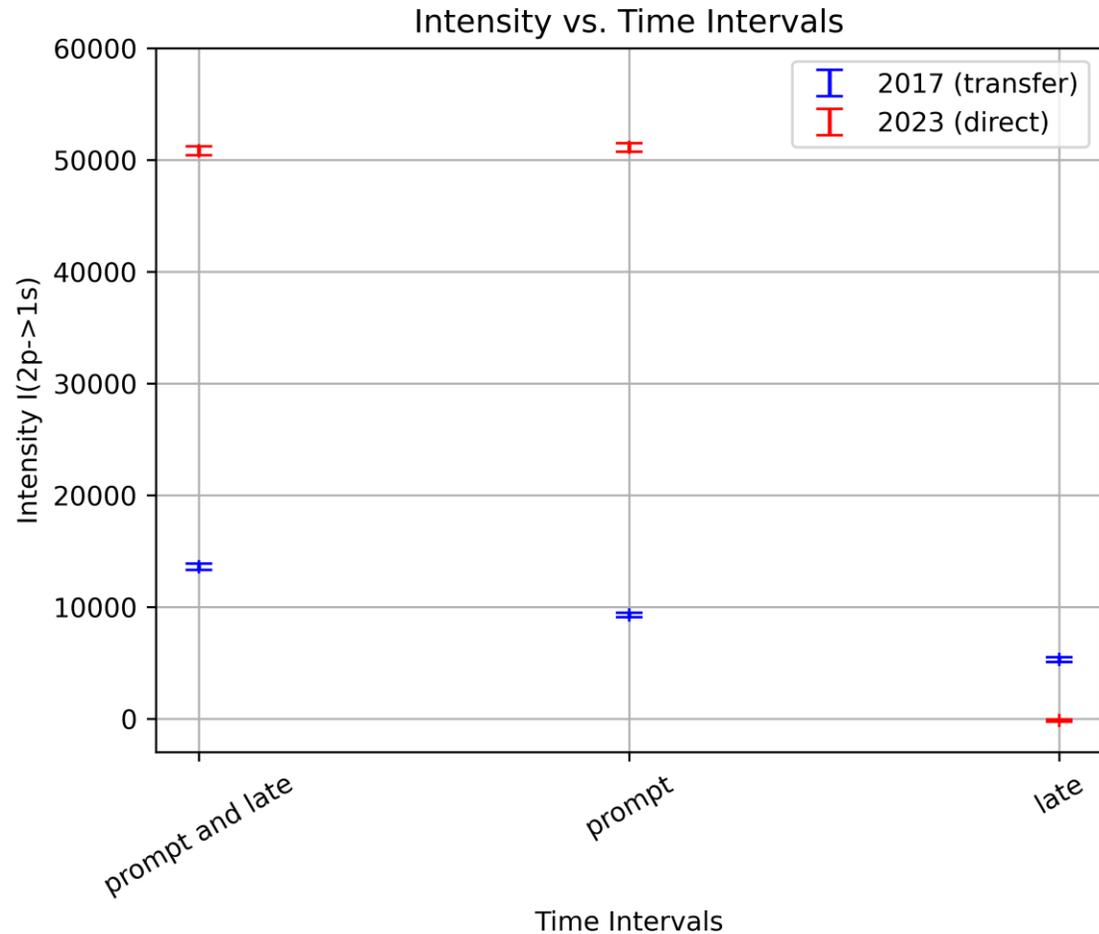
Muon beam

Cascade simulation calculating the rates/probabilities for the Auger and X-ray transitions
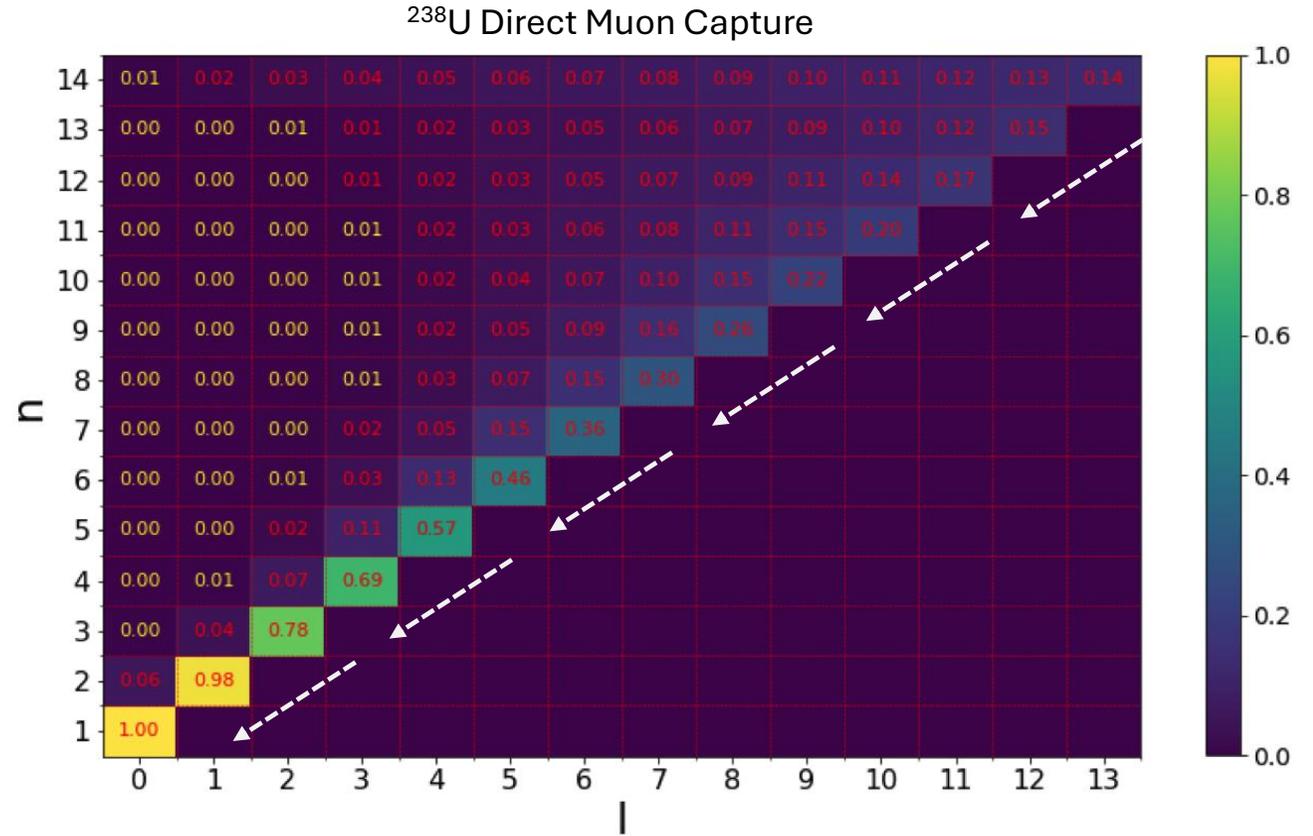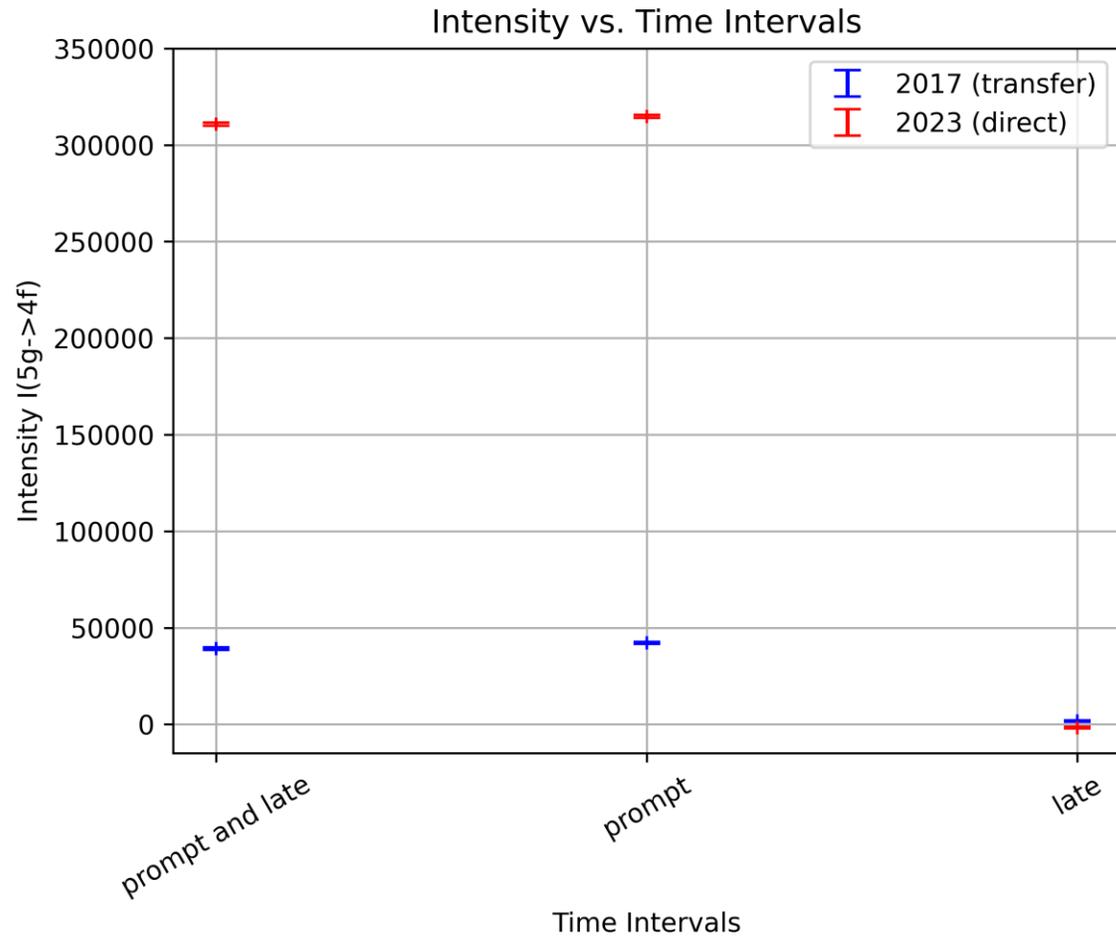

^{238}U Transfer Muon Capture

- Muons captured at n(Z), n(Z)≫14 for heavy-Z atoms

- Captured muons concentrated at low angular momenta

- Starting concentrated at low angular momenta cascade down to the 1s state

Intensity of Transitions 2p → 1s and 5g → 4f versus Time

- 2017 data, transfer muon capture at prompt and late time intervals
- 2023 data, direct muon capture at prompt time interval

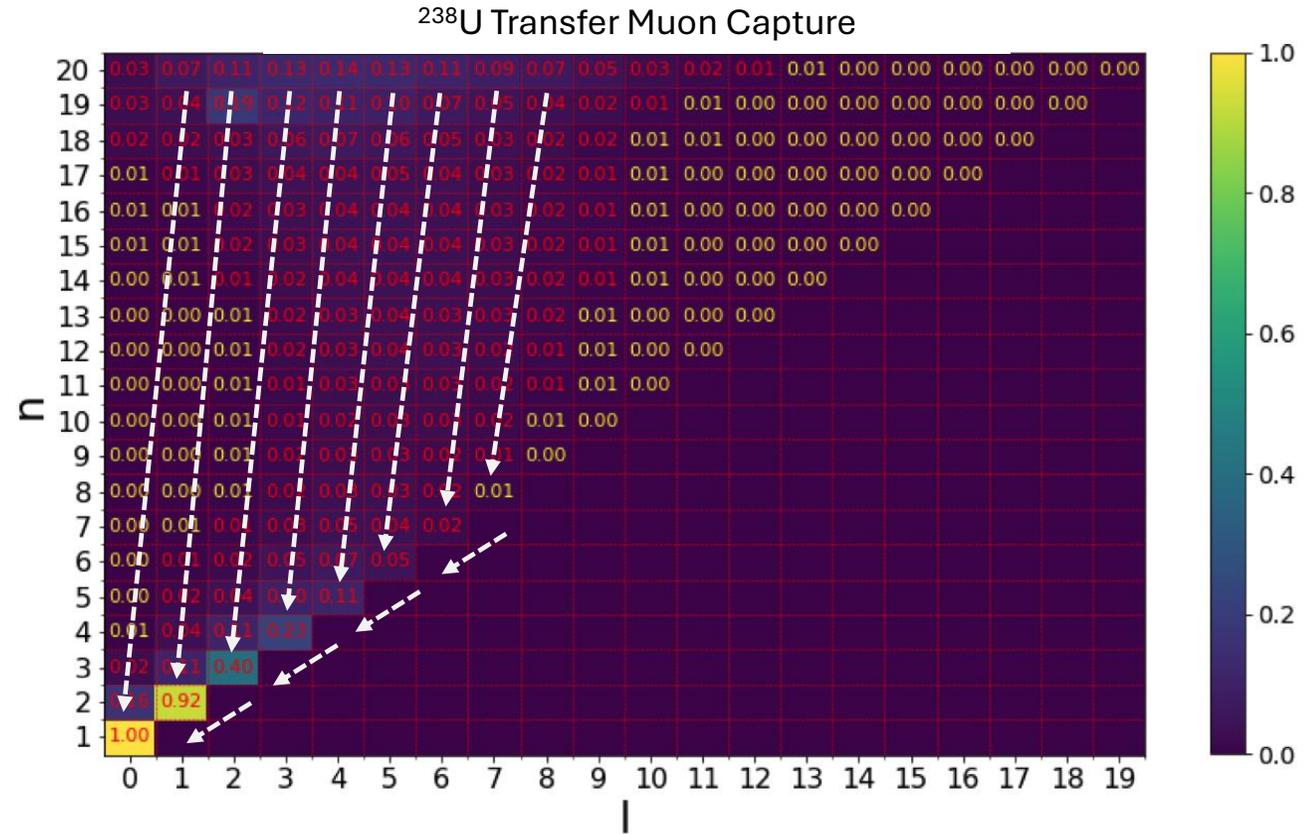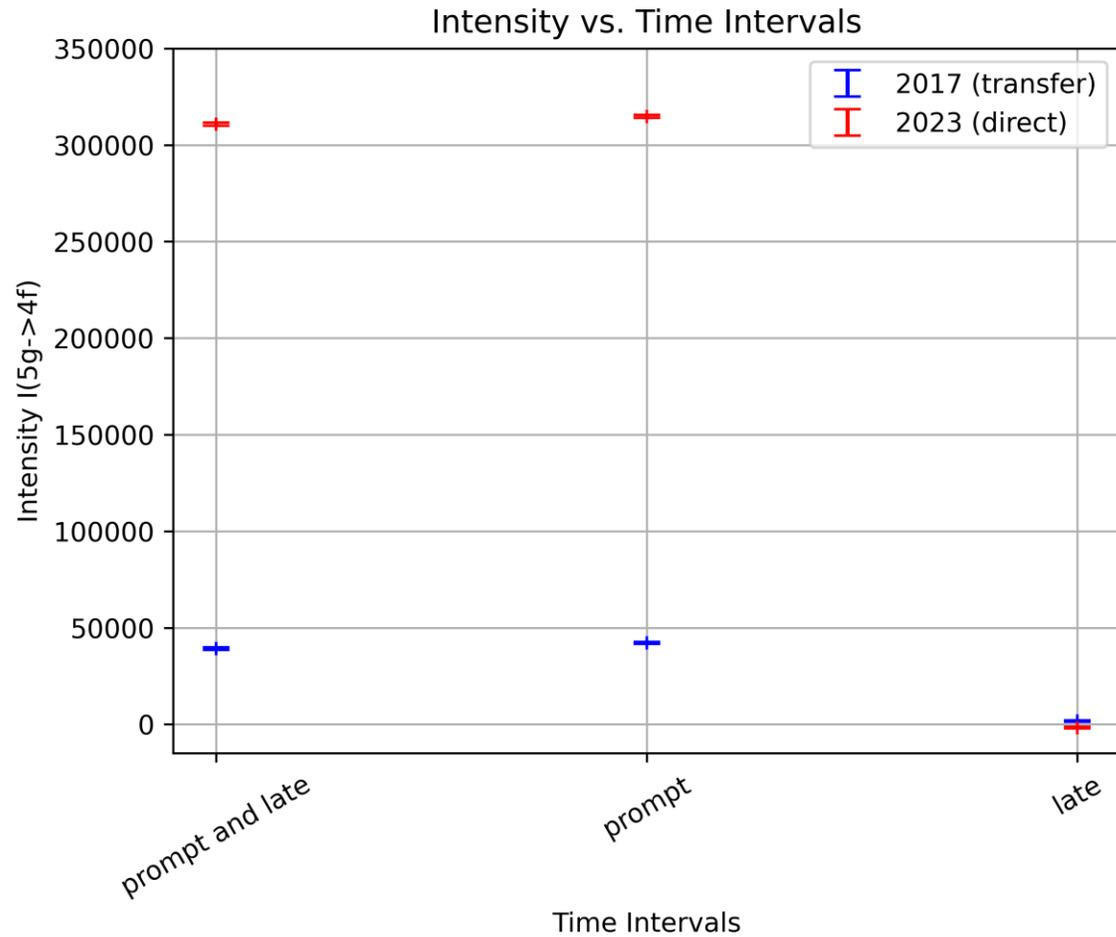# Transition 5g → 4f, Direct Muon Capture

Direct muon capture: favors (n, l=n-1) → (n-1, l=n-2) circular transitions

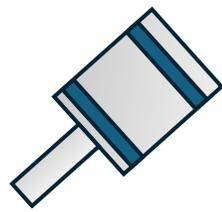➤ Circular transitions and thus 5g → 4f transition favored for prompt, direct capture

Transition 5g → 4f, Transfer Muon Capture

Transfer muon capture: starting concentrated at low angular momenta cascades down to the 1s state

➢ Circular transitions and thus 5g → 4f transition not favored for late, transfer capture

Germanium Detectors

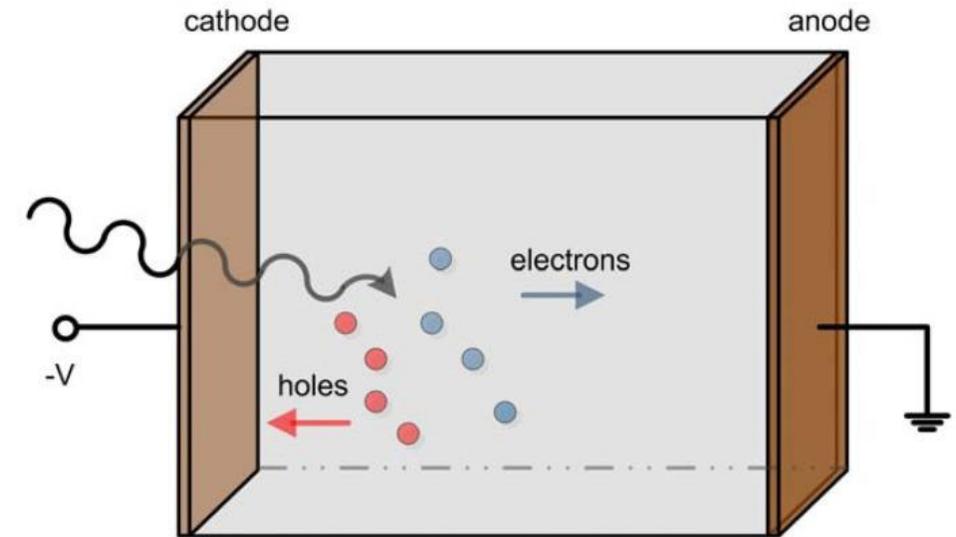
Germanium crystal under a reverse biased voltage, collecting the charge carriers produced by the ionizing radiation.

Detection Process

✓ Apply reverse bias voltage on the crytal → large depletion region → little to no current flowing through the circuit

✓ Charged particle enters the depletion region and produces electron-hole pairs

✓ Collect charge carriers with the applied voltage deference

✓ Number of charge carriers proportional to the ionization radiation energy

Depletion thickness: $d = \left(\frac{2\varepsilon V}{eN}\right)^{1/2}$, where V is the reverse bias voltage and N is the impurity concentration.
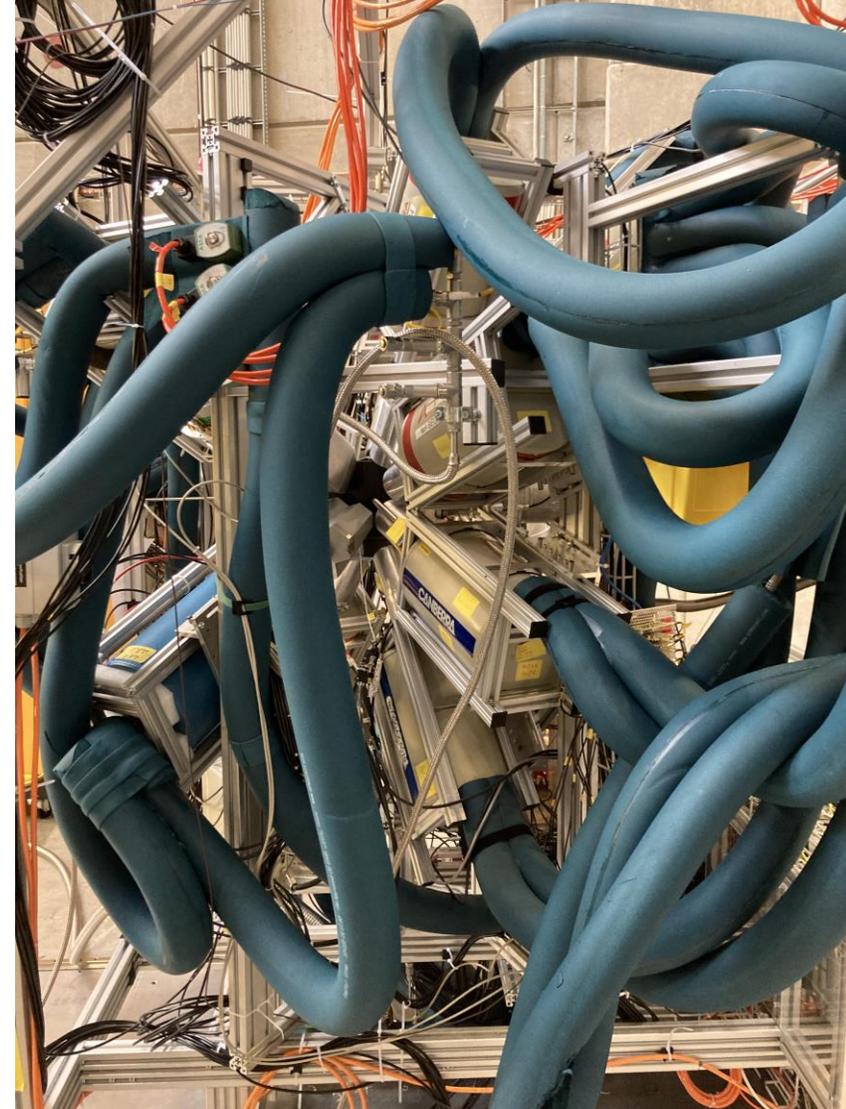
Thus for greater depletion depths, and better energy resolution the impurity concentration needs to be decreased (High purity Germanium Detectors (HPGe)).

Germanium Detectors, Cooling

As the Germanium semiconductor has a small band gap, at room temperature electrons can move from the valence to the conduction band due to thermal excitations. This creates an unwanted current, called leakage current.
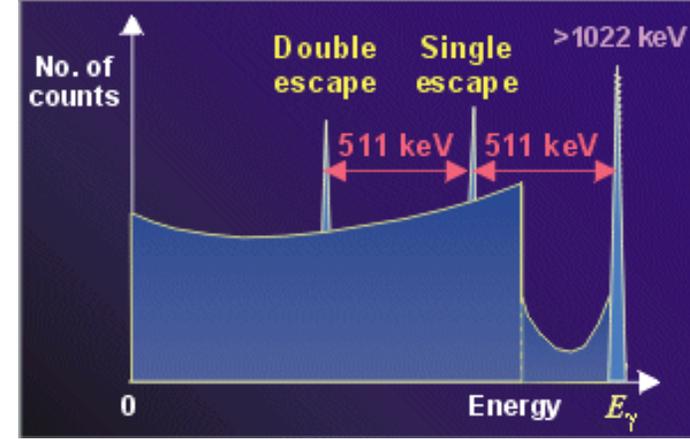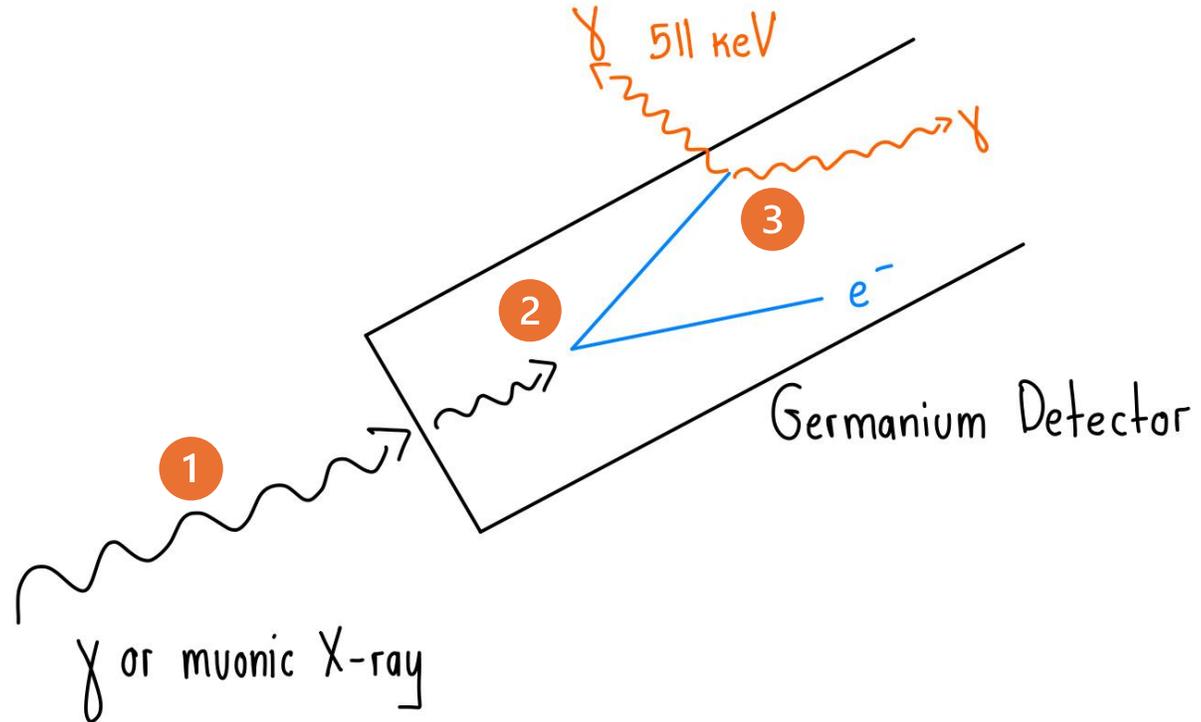
➢ So we cool down Germanium detectors to avoid any thermal noise, with liquid nitrogen (77K)

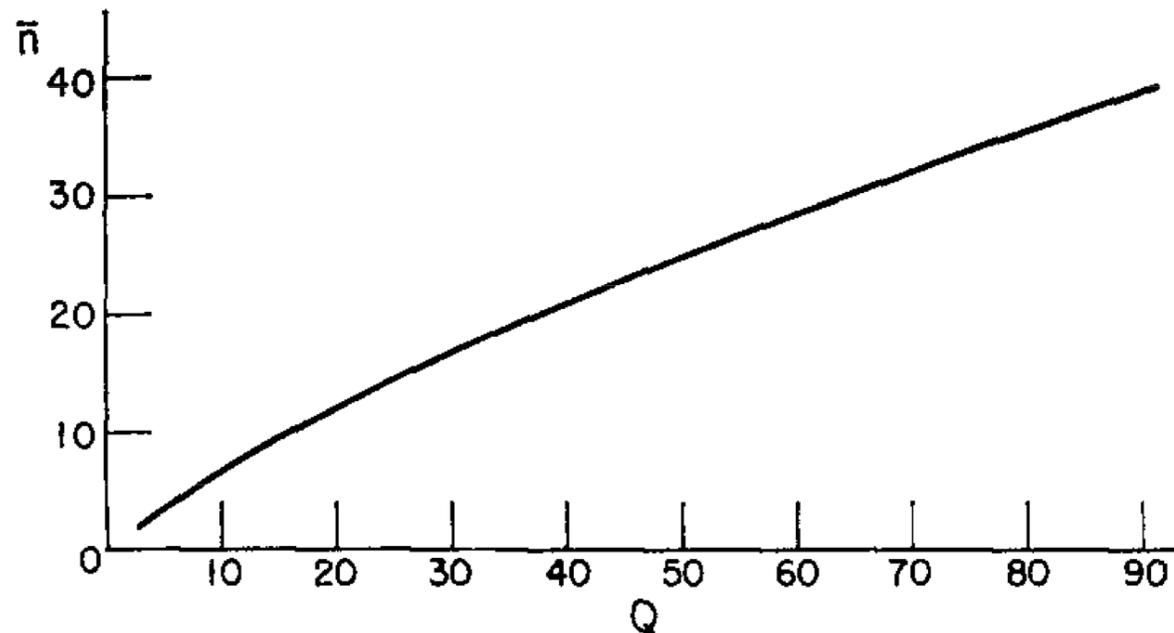# Single & Double Escape

Single & Double Escape

1. Gamma or muonic X-ray enters the Germanium Detector.

2. Interacts with the detector and produces an e^--e^+ pair.

3. The positron interacts with one of the plenty Germanium detector electrons and produces two γ-rays. When one of them escapes we have *Single Escape.* When both of them escape we have *Double Escape*.

Principle Quantum Number for Transfer Muon Capture

For a heavy-Z material (Z=Q) the states n populated by muons after transfer capture are given by:

$$n \sim \left[\frac{Q(1 + 2Q^{\frac{1}{2}})}{1 + 2Q^{\frac{1}{2}}} \right]^{1/2}$$

Flushing and Filling the gas cell

Interactions in the gas cell

- µd interacts with hydrogen (small cross section but non-zero probability)
- $(p\mu d)^+$ decays via two muon catalyzed fusion channels
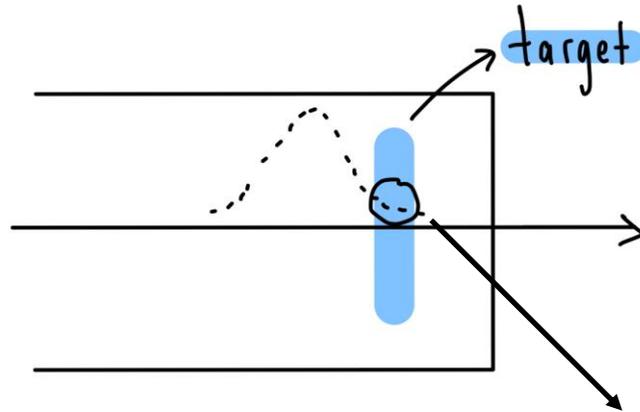
Filling circle of the gas cell

1. Pump the gas mixture from the gas cell
2. Flush with H_2 (10 cycles) up to 10 bars, ensuring no remaining gases
3. Flush with 100 bars of gas mixture
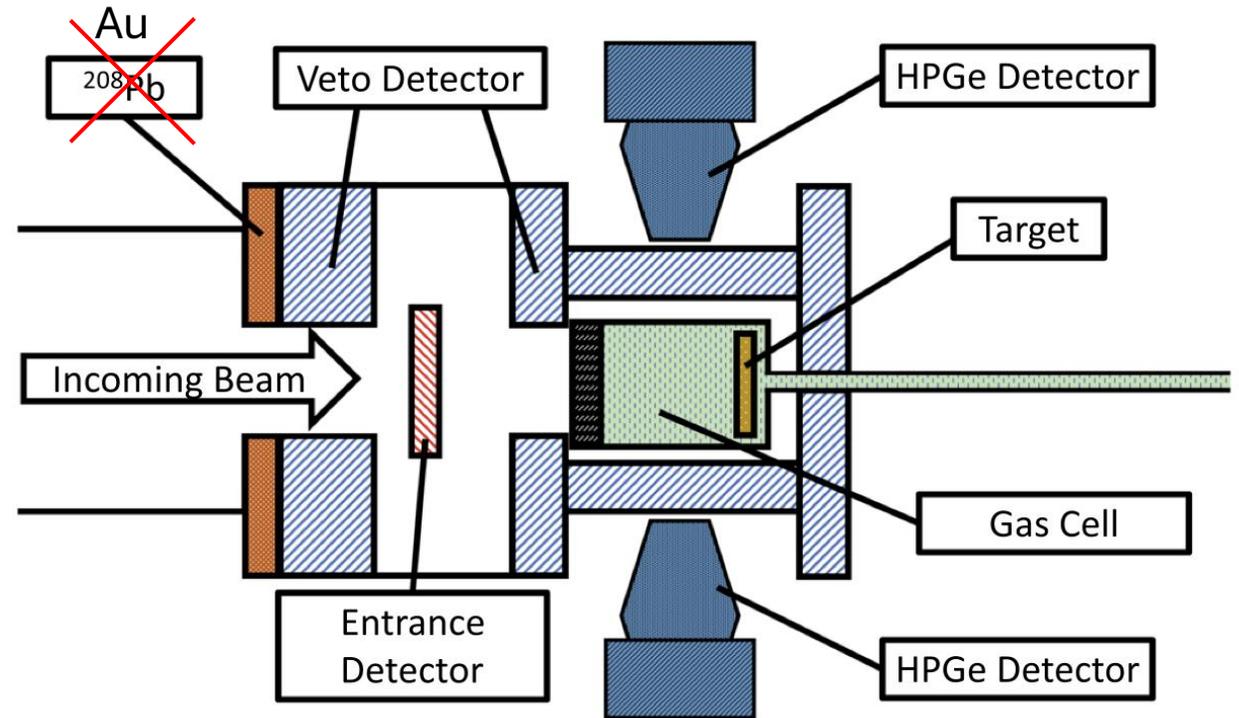4. Fill with 100 bars of the gas mixture

Thick and Thin ^{137} Au Target

Placed a **thick gold** and a **thin gold** sample in the target position to study direct and indirect capture.
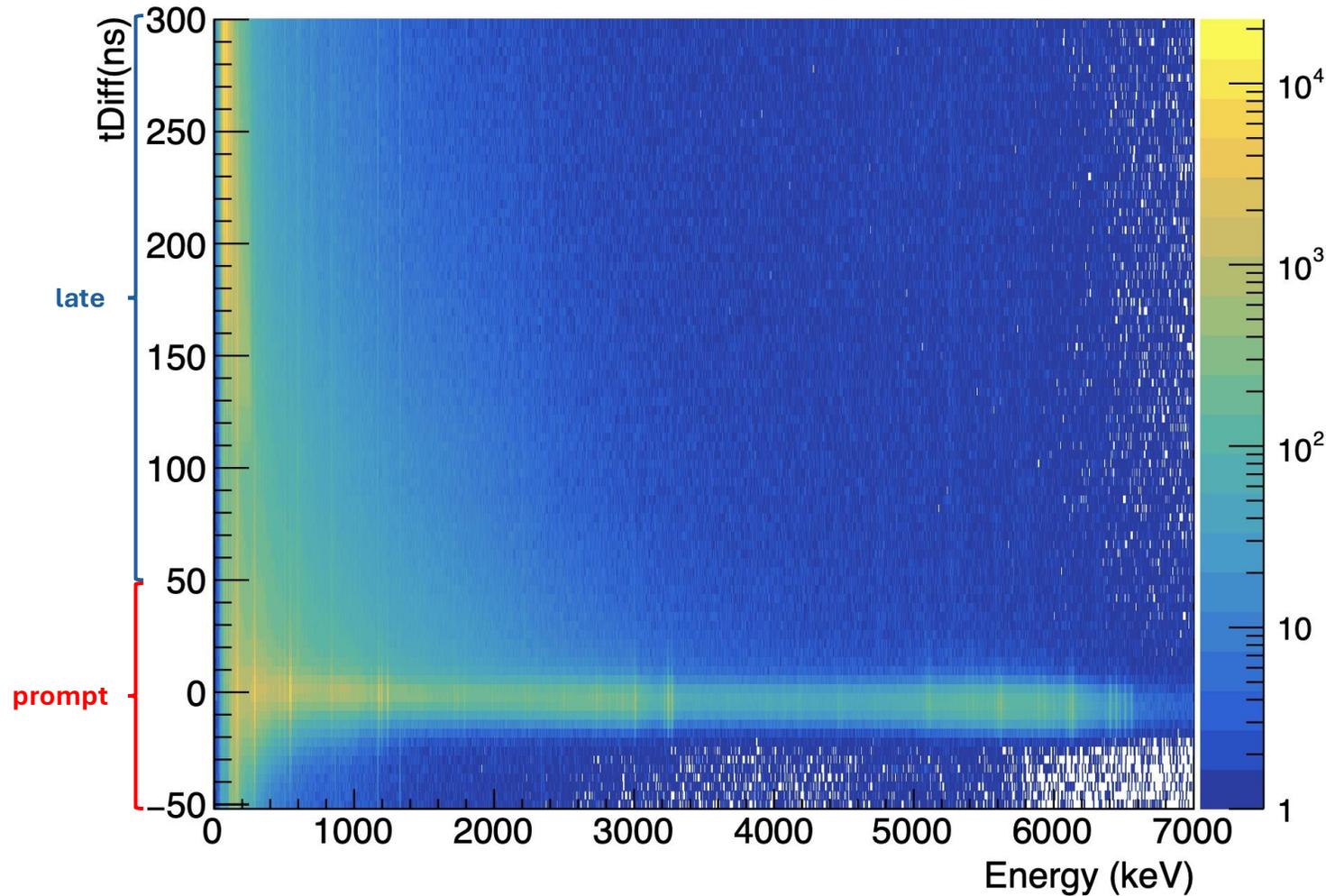
The thicker the target the more the directly detected muons (bigger part of the muon tail detected),

Directly detected muons the rest of them get captured by the gas mixture.
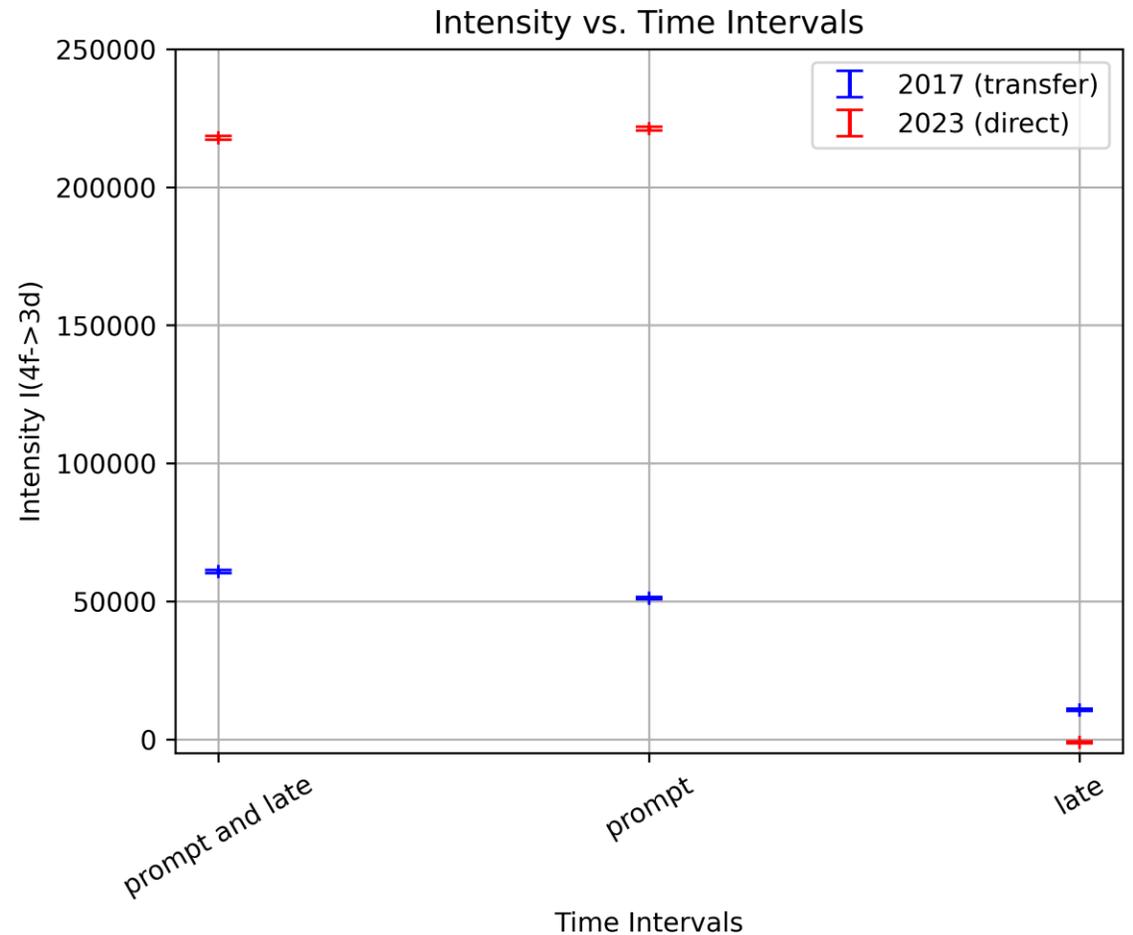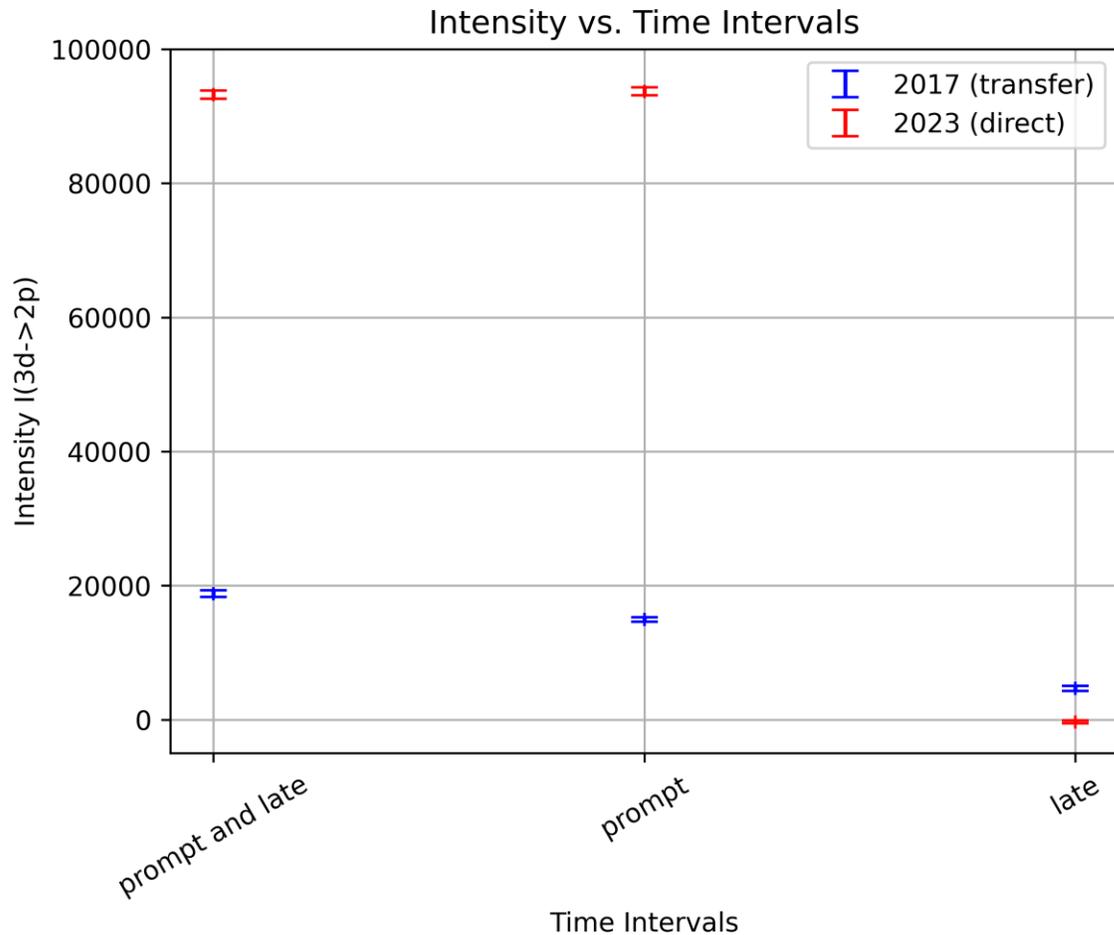
HPGe detectors, Direct Muon Capture

High Purity Germanium Detectors (HPGe) show bad time resolution at low energies
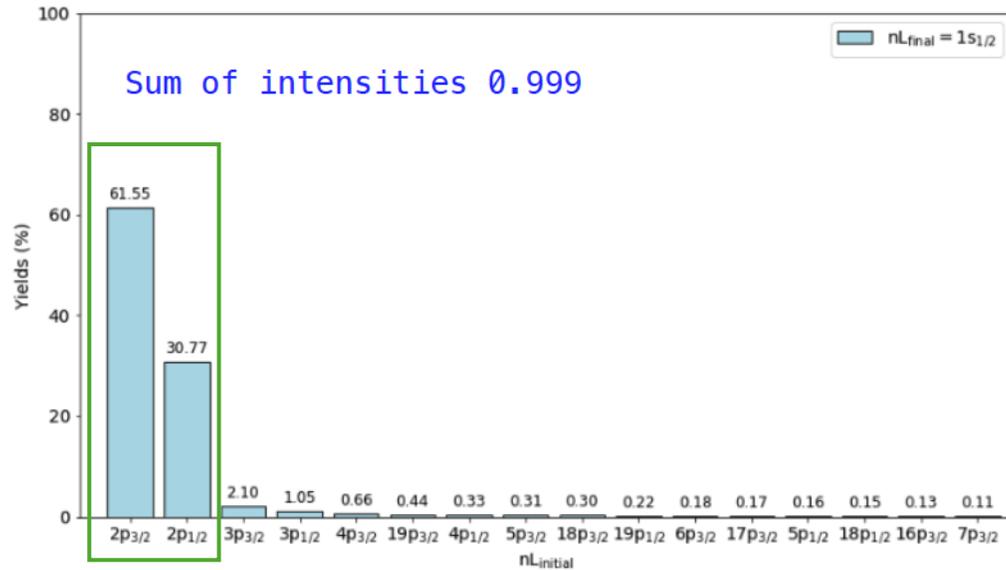HPGE detectors resolution: 500-1000 eV at Energy < 100 keV

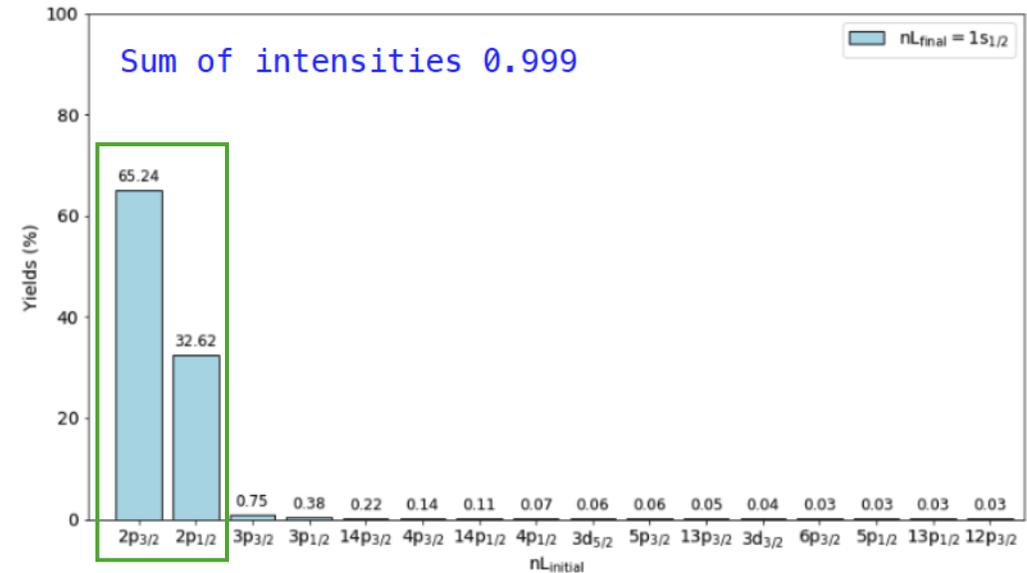# Intensity of 3d→ 2p and 4f → 3d transitions versus Time

- 2017 data, transfer muon capture at a prompt and late time interval
- 2023 data, direct muon capture at a prompt time interval

Results of Cascade Simulation for ^{238}U: 2p → 1s Transition
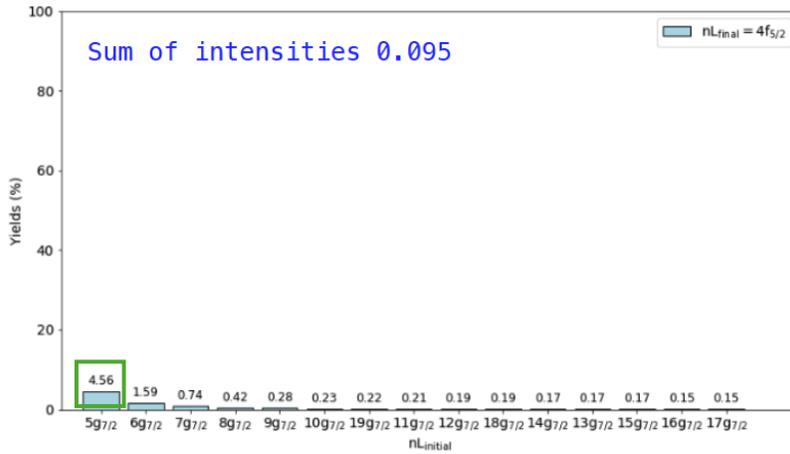
After transfer

After direct capture

Capture	Transition	Yield (%)
Transfer	$2p_{3/2} \to 1s_{1/2}$	61.55
	$2p_{1/2} \to 1s_{1/2}$	30.77
Direct	$2p_{3/2} \to 1s_{1/2}$	65.24
	$2p_{1/2} \to 1s_{1/2}$	32.62

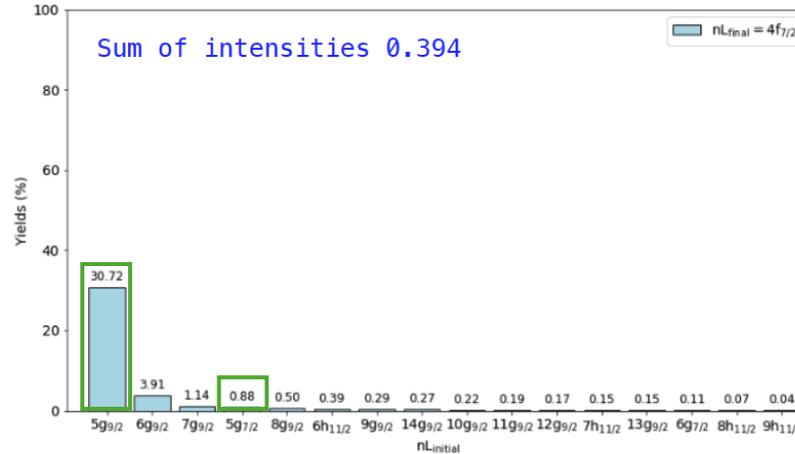| Capture	Transition	Yield (%)
Transfer	2p->1s	92.3
Direct	2p->1s	97.9

Results of Cascade Simulation for ^{238}U: 5g → 4f Transition

After transfer

After direct capture

Capture	Transition	Yield (%)
Transfer	$5g_{7/2}$->$4f_{5/2}$	4.56
	$5g_{9/2}$->$4f_{7/2}$	5.91
Direct	$5g_{7/2}$->$4f_{5/2}$	23.70
	$5g_{9/2}$->$4f_{7/2}$	30.72
	$5g_{7/2}$->$4f_{7/2}$	0.88

Capture	Transition	Yield (%)
Transfer	5g->4f	10.5
Direct	5g->4f	55.3

5g → 4f transition, Transfer vs Direct Muon capture

Capture	Transition	Yield (%)
Transfer	2p->1s	92.3
Direct	2p->1s	97.9

Capture	Transition	Yield (%)
Transfer	5g->4f	10.5
Direct	5g->4f	55.3

Normalized with respect to 2p->1s

Capture	Transition	Ratio
Transfer	(5g->4f) /(2p->1s)	0.11
Direct	(5g->4f) /(2p->1s)	0.56

x ~5

2p → 1s Transition: Removing Oxygen Background

We are breaking the 2p->1s transition into two **integrals** and we sum them up. This way we get rid of the **oxygen region**.

➤ **Oxygen region** there is some ^{16}O leaking in the gas mixture. Muons get captured by the oxygen nucleus and produce $^{15}N^* + n + \nu$, excited nucleus de-excites to its ground state and produces some γ-rays (peaks between the two integrals).