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Muonic X-ray measurements at PSI with medium and high-Z nuclei

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Muonic atoms are an outstanding tool to study short range muon-nuclear interactions and to probe various nuclear moments. The *muX* experiments deploys a high-purity germanium detector array at the Paul Scherrer Institute in Switzerland to measure the *muonic* X-rays which are emitted during the formation of a muonic atom. In addition, novel gas-targets are deployed enabling a precise measurement of the characteristic X-rays with a target of only a few micrograms. The experiments aims to measure transitions of interest for atomic parity violation, and to determine the charge radius of radioactive isotopes such as ^{248}Cm and ^{226}Ra.

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1. The *muX* experiment

A muonic atom is formed when a negative muon comes to rest in a material, where it quickly gets captured by a nearby atom in a high n atomic orbital. When this exotic atom de-excites the energy is initially transferred to Auger electrons. The last few steps down are dominated by radiative (mostly) E1 transitions, i.e. muonic X-rays, with an energy of a few keV for the lightest nuclei up to several MeV for heavy nuclei. The atomic capture and cascade process occurs on a (sub)nanosecond timescale, therefore, to most radiation detectors, the emitted radiation appears as prompt relative to a muon stopping in a target.

The muon atomic and nuclear wave function significantly overlap due to the relatively large mass of the muon. Therefore, this system is an effective tool to study short range muon-nucleon/nucleus interactions and to measure various nuclear moments. Muonic atoms have been used to determine the absolute nuclear charge radii of most stable nuclei by measuring the $2p-1s$ transition energy [1], most recently by the CREMA collaboration [2–4] for the lightest nuclei. The *muX* experiment aims to extend this to rare and long-lived radioactive isotopes, starting with ^{248}Cm and ^{226}Ra [5]. Radium is a prime candidate for Atomic Parity Violation (APV) experiments, using laser spectroscopy on trapped ions [6–8]. For such a measurement, an accurate charge radius will serve as an important input to relate the experimentally accessible parity-non conserving E1 amplitude of the transition of interest to the weak charge of the nucleus. In addition, the *muX* collaboration is performing a feasibility study for a possible APV experiment with muonic X-rays [9], and the apparatus is being used by a series of projects in material science [10] and nuclear physics [11, 12]. A first physics result of the project was a measurement of the quadrupole moments of ^{185}Re and ^{187}Re derived from the hyperfine structure of the $5g-4f$ muonic X-ray transition [13].

1.1 Experimental apparatus

The *muX* experiment (figure 1) is running at the πE1 secondary muon beamline at the Paul Scherrer Institute (PSI), which provides a DC beam of a few 10^4 μ^-/s with typical momenta in the range of 20-40 MeV/c. Thin in-vacuum scintillating detectors record the arrival times of the individual muons before they get stopped in a dedicated target (Sec. 1.2). The target is surrounded by Michel-electron detectors and an array of 10 to 15 high-purity germanium detectors, resulting in a 2 to 3 % full-energy peak efficiency at 1 MeV. A sketch of the detector setup in shown in figure 2. All detector signals above threshold pass through a digital-signal processing stage, physics events are reconstructed offline in software.

1.2 Transfer target

The muon beam arriving at the apparatus has a too large momentum to be stopped in the amount of target material available when working with radioactive elements, e.g. 5 μg in the case of ^{226}Ra. The collaboration has developed a novel method, where muons are stopped in a 100 bar H_2 target, with a small admixture of D_2. Through a series of transfer reactions the muon is transported to the target material mounted at the back of the cell as shown in figure 3, hereby exploiting the Ramsauer-Townsend effect which causes H_2 gas to become almost fully transparent for μd atoms with a few eV of kinetic energy [14–16]. It was shown that a total stopping and transfer efficiency per muon of about 1 percent can be achieved for a 5 μg gold target. (figure 4).

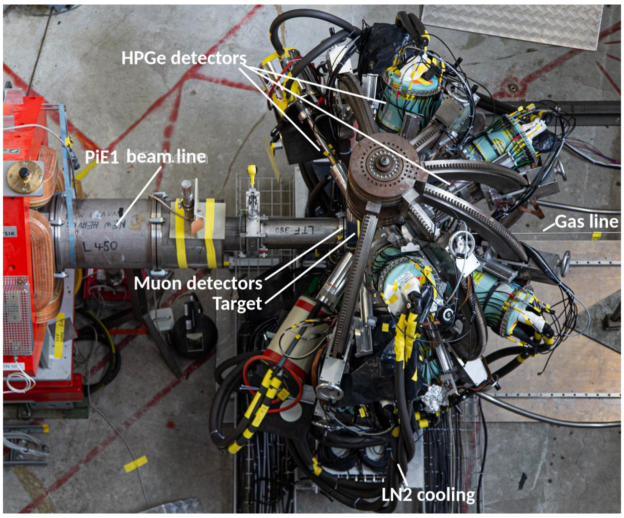

Figure 1: The *muX* experiment deployed at the πE1 beam line. For the 2019 experimental run, the MiniBall array with eight cluster detectors complemented by a 70 % coaxial detector and a low-energy planar detector were deployed. The target is mounted directly on the end of the beam line, surrounded by muon and electron detectors.

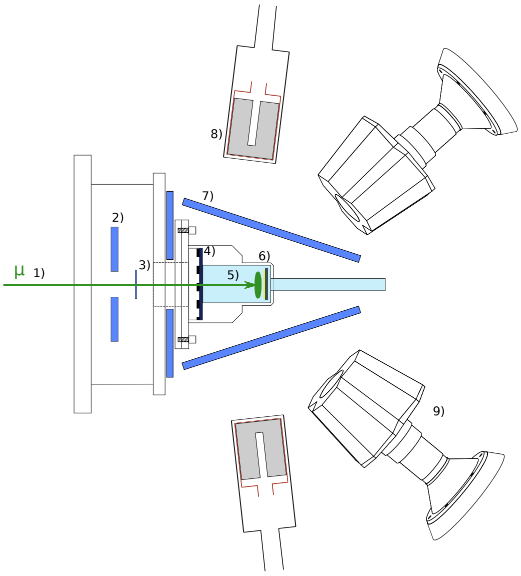

Figure 2: The muX setup, with 1) the μ^- beam passes through 2) a veto and 3) a 200 μm thick μ-detector detector. The cell with 4) a 600 μm CF window supported by a Ti grid holds 5) 100 bar of hydrogen gas. The 6) target is mounted in the back. 7) Electron detectors. 8) Standard and 9) MiniBall cluster HPGe detectors.

2. Radioactive target measurements

In 2019, the full MiniBall high-purity germanium array [17] was deployed at PSI (see figure 1) for a series of muonic X-ray measurements. After a transfer efficiency optimization with a gold target, a first campaign with radiative targets was conducted. For this method, it is essential to produce uniform targets where the atoms are deposited on or near the surface. Several ^{248}Cm and ^{226}Ra targets were produced combining a custom electro-deposition technique with a novel drop-on-demand method where micro-drops of activity in solution are deposited on glassy carbon disks, the low-Z backing material of the target [18]. This first batch of targets turned out to be sub-optimal, nevertheless, a clear muonic X-ray spectrum was obtained from a 15 μg curium target. Figure 5 shows the $2p - 1s$ muonic X-ray spectrum of ^{248}Cm after background subtraction. The ground state of this nucleus has spin 0, the atomic levels of muonic Cm however also mix with the lowest excited nuclear states, which leads to a complicated dynamic hyperfine structure in the spectra [19] which can only be fully understood by state of the art QED calculations [20]. When extracting the nuclear charge radius from the data, theoretical uncertainties on in the transition energy caused by e.g. the two-photon exchange nuclear polarization [21–23] will dominate the experimental uncertainties.

3. Atomic parity violation with muonic X-rays

Muonic atoms are a long-standing candidate to measure APV through the M1-E1 mixing in the $2s - 1s$ radiative transition [24, 25]. For Z≃30 nuclei, this parity non-conserving transition has a

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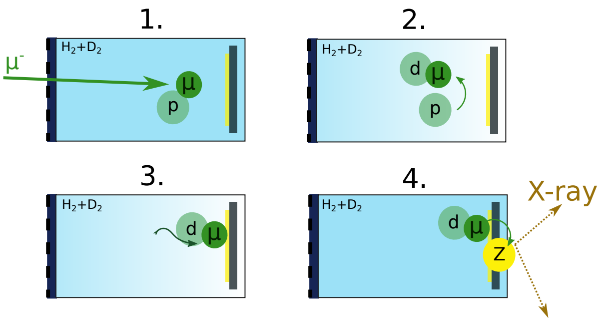

Figure 3: 1) Muons stopping in our target form a μp atom. 2) In O(100) ns, the muon transfers to deuterium, gaining 45 eV in kinetic energy. 3) At an energy of a few eV the μd-H_2 scattering cross section becomes negligibly small, and the μd atom travels freely until it hits our target, where 4) the muon transfers to a high-Z atom.

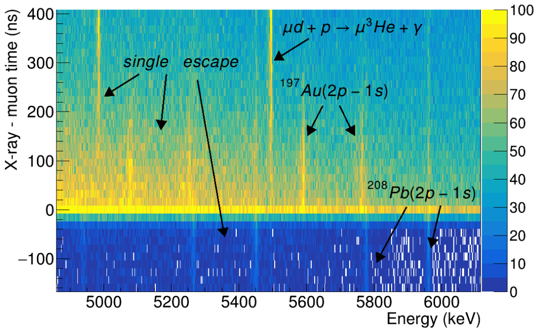

Figure 4: Gold muonic X-ray energy versus time spectrum for a 5 μg target. X-rays from direct muon stops appear at time 0 ns, the Gold X-rays appear over 100 ns, the typical timescale of the transfer processes. The back ground mainly consists of decay electrons, and neutrons emitted after nuclear muon capture.

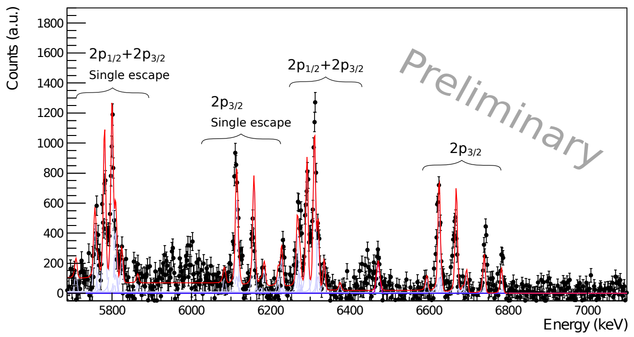

Figure 5: The hyperfine structure of the $2p-1s$ transitions in the background-subtracted muonic X-ray spectrum ^{248}Cm. The fitting model is based on a data-driven line-shape combined with detailed QED calculations with the nuclear charge-radius and a global energy offset as free parameters.

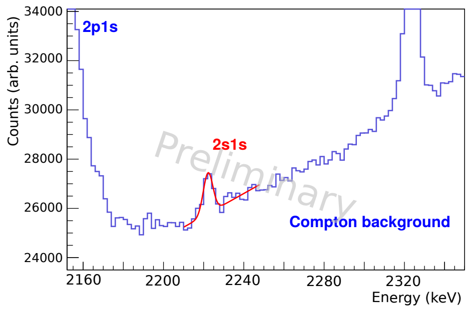

Figure 6: The $2s-1s$ full energy peak of muonic Kr at 2.22 MeV on the Compton background of $(n>2)p-1s$ transitions. The background from radiation from muon decay and nuclear capture processes is subtracted.

relative large branching ratio of $O(10^{-4})$ in the cascade. A precision APV measurement is however challenging because of a considerable background from scattered $(n>2)p-1s$ X-rays, Michel electrons, and neutrons and γ-radiation emitted after muon capture. The muX collaboration aims to isolate the $2s-1s$ transition and significantly improve the signal-to-background to determine the reach of a possible APV experiment.

A clear single-photon $2s-1s$ peak was observed for the first time utilizing a gaseous Kr-H_2 target. After the formation of μH, the muon transfers to a nearby Kr atom at a low orbital quantum number l [26]. Starting the cascade at a low initial l enhances the $2s$ population by a factor ~3. The $2s-1s$ transition in the muonic X-ray spectrum of Kr obtained during a 1 week measurement is shown in figure 6, where a signal-to-background ratio of about 1/10 was achieved. It is currently under investigation how to improve the signal quality by using photon-photon correlations in the cascade.

With the observed yield, a μAPV experiment with a sensitivity of 10^{-3}-10^{-4} to a parity-odd observable can be envisioned at a high-intensity muon beamline [27], meaning a $O(1)$ Standard Model test [28, 29]. A larger parity-violating amplitude of 10^{-2}-10^{-3} is expected for low-Z nuclei [24], in principle allowing for a more sensitive experiment. However, due to competing Auger transitions and small energy differences between the different X-ray transitions, isolating the $2s - 1s$ transition becomes a challenge and requires novel target and detector developments [27, 30].

4. Future measurement program

The *muX* collaboration is improving the target production e.g. by shallow implantation of the ^{226}Ra activity in glassy carbon target at a depth of a few tens of nanometers, still in the range of the diffusing μd atoms. In addition, the program will be extended to other radioactive elements, aiming to measure the third of three isotopes of odd Z-elements needed to calibrate the vast amount of isotope shift data available from laser spectroscopy on radioactive elements [31]. The first series of experimental campaigns in 2017-2019 have also prompted renewed efforts at PSI among which a project which will measure partial ordinary muon capture rates on nuclei of interest for neutrinoless double $\beta - decay$ searches [11, 32], and a new facility for elemental analysis [10] is being installed at the πE1 beam area in close collaboration with *muX*.

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