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Towards nuclear structure with radioactive muonic atoms

The nuclear charge radius of radioactive isotopes from measurements of muonic X-rays

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Summary. — The muX project at the Paul Scherrer Institut aims to perform high-resolution muonic atom X-ray spectroscopy for the extraction of nuclear charge radii of radioactive isotopes that can be handled only in microgram quantities. Measurements of the absolute charge radii of high-Z radioactive elements are complementary to the measurements of relative differences in mean-square radii along the isotopic chain available from laser spectroscopy. One of the major limitations of atomic structure calculations is related with the uncertainty of the nuclear charge radius. This is the case for the extraction of the Weinberg angle from atomic parity violation in ^{226}Ra. A new approach to solve previous limitations of muonic atom X-ray spectroscopy experiments is the application of multiple muon transfer reactions in a high-pressure hydrogen gas cell with a small admixture of deuterium. The validity of this method has been demonstrated with a measurement with only 5 μg of gold.

1. – Introduction

Muonic atoms as laboratories for fundamental physics provide crucial test of bound-state QED, weak and strong interactions. Muonic atom X-ray spectroscopy, i.e., the detection of the muonic X-rays emitted, in the de-excitation process following the muonic atom formation, subsequently to the atomic capture of a negative muon, has been a widely used technique to determine nuclear charge radii [1]. This method complements the knowledge from electron scattering experiments and laser spectroscopy [2]. For elements heavier than Z=83 only few nuclear charge radii have been measured. These measurements provide anchor points for relative differences in mean-square radii along the isotopic chain available from laser spectroscopy.

The precision of atomic structure calculation can be limited by the uncertainty of the knowledge of the nuclear charge radius. This appears for the extraction of the Weinberg angle θ_W from atomic parity violation measurements on ^{226}Ra. A sufficient precise calculation requires the knowledge of the nuclear charge radius of radium at the level of 0.2% [3]. Till now, experiments with muonic atoms have been limited by low muon rates, poor beam quality and large muon stop thickness. The muX project at the Paul Scherrer Institut (PSI) is performing high-resolution muonic atom X-ray spectroscopy for the extraction of nuclear charge radii of radioactive isotopes that are available or can be handled only in microgram quantities. The primary goal is to measure ^{226}Ra and ^{248}Cm.

2. – Setup

The maximum amount of radioactive isotopes like ^{226}Ra or ^{248}Cm, which can be handled in the experimental hall at PSI without additional precautions, is in the order of μg. A negative muon beam with a momentum $p = \mathcal{O}(10\,\mathrm{MeV/c})$ prevents to stop an appropriate number of muons in such a tiny amount of target material. A newly developed approach solves this issue by multiple transfer processes in hydrogen gas mixtures and profits from the vast knowledge on the behaviour of negative muons in gas targets of different hydrogen isotopes obtained during the research on muon catalyzed fusion ([4] and references therein). The method developed within this project was inspired by [5] and [6].

A high-density hydrogen gas target with pressure $P = 100\,\mathrm{bar}$ at room temperature and a small admixture of 0.25 % volume deuterium enables to stop muons with a momentum of $p \simeq 28\,\mathrm{MeV/c}$ within a FWHM of 7 mm in beam direction. The gas is enclosed in a cylindric aluminium gas cell with a 30 mm diameter. The entrance is sealed by an O-ring and a 0.6 mm thin carbon fibre window. Two additional support grids made of titanium and carbon fibre, respectively, strengthen the window.

Incoming muons are stopped inside the gas cell and are mostly captured by a hydrogen atom resulting in muonic hydrogen (μp) that quickly thermalizes at the gas temperature. When μp scatters with deuterium, the muon might transfer to the deuteron due to the larger binding energy. This transfer process results in the creation of muonic deuterium (μd) with a kinetic energy of 45 eV [7]. Thanks to the so-called Ramsauer-Townsend effect [8], the scattering cross section of μd in H_2 has a minimum at a kinetic energy of 4 eV [7, 9, 10]. For this reason, μd moves almost freely inside the H_2 gas and is able to reach the target which is fixed on a plate at the back wall of the gas cell. Incoming muons are registered by a 20×20 mm^2 large and 100 μm thin plastic scintillator in front of the entrance window. A large Ge detector array is deployed around the target.

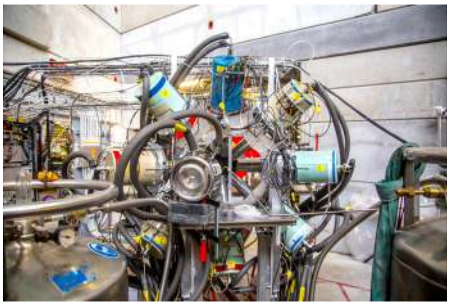


Fig. 1. – Setup for the test of muon transfer reactions in a high-density-deuterium gas mixture at the πE1 area at PSI. The gas target is placed at the center of the detector array.

The energy calibration of the Ge detectors is performed by the measurement of muonic ^{208}Pb X-rays. ^{208}Pb was placed at the outer regions of the beam in front of the entrance detector. X-rays of μPb were continously measured together with the atom of interest. The corresponding lead muonic X-rays are precisely determined by [11] and can be easily separated from the target X-rays by timing analysis. In addition, γ-rays from a ^{60}Co source are measured as well.

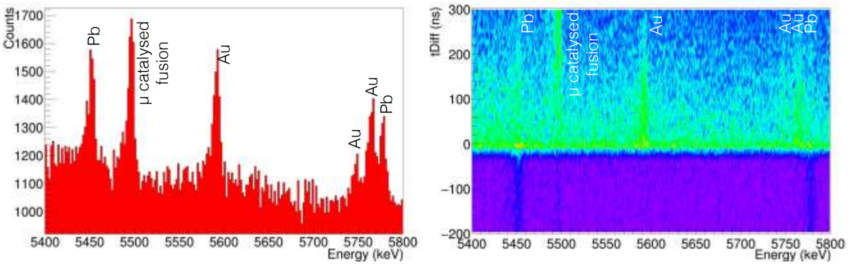
3. – Test of multiple muon transfers in a hydrogen deuterium gas mixture

During 2017, the transfer method was tested with different gold targets, whose muonic atom X-ray spectra is reasonably well known [12]. The setup was tested in the πE1 line at PSI. It consisted of seven single-crystal detectors with 60 % efficiency from the IN2P3/STFC French/UK Ge loan Pool [13], one single crystal coaxial Ge detector with 75 % efficiency from KU Leuven and a Ge detector with 70 % efficiency from PSI. In addition a Miniball cluster consisting of three individual crystals of arround 60 % each [14] and a planar detector optimized for low-energy gammas is mounted. Eight Ge detectors are mounted around the target cell in a welded steel frame. The remaining Ge detectors are placed on tables attached to this construction. Angle and distance to the gas cell are adjustable. The distances from the beam axis are varying between 10 cm and 15 cm. The total efficiency of the full detector array is about 2 % at $E = 1332$ keV.

The detection scheme was tested with a Au target of 3 nm thickness and 1 cm^2 transverse area, which is evaporated on a copper support. The total mass of the target corresponds to 5 μg. The beam momentum was $p = 27.75$ MeV/c, the gas mixture had the pressure $P = 100$ bar with 99.75 % H_2 and 0.25 % D_2 volume fraction at room temperature. The muonic atom X-ray spectrum shown in Figure 2 of the 5 μg target was taken in 18.5 h. Roughly 1 % of the incoming muons were captured by the thin gold layer. As can be seen from Figure 2(b) the transfer occurs within about $100 - 200$ ns.

4. – Conclusion and Outlook

It has been shown that enough muons can be stopped in a reasonable time in targets a of few micrograms using multiple muon transfers in a high-density hydrogen deuterium gas mixture. The next step includes the development and production of appropriate radioactive targets using methods including molecular plating [15] or drop-on-demand printing [16] and the measurement of the muonic atom X-rays of ^{226}Ra and ^{248}Cm.



(a) (b)

Fig. 2. – (a) Muonic atom X-ray spectrum of the 5 μg target taken in 18.5 h. The lines at 5.59 MeV, 5.75 MeV and 5.77 MeV are the 2p-1s lines of muonic gold. The line at 5.5 MeV is created by the muon catalyzed fusion of proton and deuteron. Lines of muonic ^{208}Pb are observed at 5.45 MeV and 5.78 MeV. (b) The 2D spectrum displays the same spectrum with the additional information on the time (tDiff) after the detection of a muon in the entrance detector.

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