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A search for atomic parity violation in muonic atoms using a high-intensity pulsed muon beam at J-PARC

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Abstract. An exotic atom consisting of a negative muon and a nucleus is a muonic atom. Atomic parity violation in muonic atoms provides a unique opportunity to determine the Weinberg angle and search for physics beyond the standard model at the low energy scale. We have proposed a new experiment to perform X-ray spectroscopy of muonic atoms using a high-intensity pulsed muon beam at J-PARC. A scintillator-based calorimeter and a low-density gaseous target were developed for the experiment. As a feasibility study, we measured the yield of muon atoms and searched for muonic atom's metastability using low-density methane gas. An overview of the experiment and the test experiment results are presented.

1 Introduction

In the standard model of particle physics, the Weinberg angle is an energy-dependent parameter that describes the mixing of the electromagnetic and weak interactions [1, 2]. The modified minimal subtraction scheme predicts the scale dependence of the Weinberg angle precisely [3, 4]. Measurements of the Weinberg angle at various energy scales are essentially important as a precision test of the standard model and search for new physics. The Weinberg angle can be determined via the neutral current interactions, mediated by the Z boson. At the low energy scale, where the typical momentum transfer is on the order of MeV [5], measurements of atomic parity violation (APV) give a precise value of the Weinberg angle. Atomic parity violation refers to a parity non-conservation (PNC) effect in atomic systems induced by the interference between the electromagnetic and weak interactions. In the leading order, the Weinberg angle θ_{W} and the weak charge Q_{W} obey the following equation,

$$Q_{\mathrm{W}} = -(N - Z + 4Z\sin^2\theta_{\mathrm{W}}), \tag{1}$$

where N and Z are the neutron and atomic numbers, respectively.

In APV experiments, the parity-violating asymmetry A_{LR} is obtained as the magnitude of the left-right asymmetry with respect to a particular direction. A naive estimation of the asymmetry's magnitude is

$$A_{\mathrm{LR}} \sim \alpha^2 \frac{m_e^2}{m_Z^2} \sim 10^{-15}, \tag{2}$$

which is so small that observation is impractical. However, the enhancement mechanism called the Z^3 law makes the magnitude observable to the order of 10^{-6}. Heavy atoms are

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advantageous for observing the asymmetry, and experiments have been performed on cesium [6, 7], ytterbium [8], thallium [9, 10], lead [11], and bismuth [12]. The most precise result to date was obtained by the experiment using cesium atom [6]. New experiments using francium [13] and radium [14] are in progress.

According to Eq. (2), the magnitude of APV is proportional to the squared mass of the lepton used as a probe. An APV measurement using muons can be a powerful method to determine the weak charge and the Weinberg angle.

When a nuclear Coulomb potential captures a negative muon, electrons around the nuclei are kicked out, and the muon forms an exotic bound state called a muonic atom. The muon in orbit is highly sensitive to the interactions between the nucleus since the muon is 200 times heavier than the electron. An APV experiment using muonic atoms provides a unique opportunity to search for physics beyond the standard model. In particular, the models predicting lepton-universality breaking are important candidates to be tested [15].

Although APV measurements using muons have been proposed theoretically since the 1970s [16, 17], there were various technical difficulties at that time. In the 1990s, several experiments were carried out at Paul Scherrer Institute (PSI) using a cyclotron trap [18, 19]. The experiments have provided valuable insights into the de-excitation dynamics of muonic atoms. However, no parity-odd transition was observed. Recently, a new APV experiment using a mixture of krypton in hydrogen has been proposed at PSI, and feasibility studies are underway [20].

At J-PARC MLF MUSE [1], a high-intensity low-energy negative muon beam is available. This is beneficial to obtain muonic atoms in a low-density gaseous target without a cyclotron trap. Towards the first observation of APV in muonic atoms, a new experiment using the high-intensity pulsed muon beam and a segmented calorimeter with fast signal processing is proposed.

2 Atomic parity violation in muonic atoms

Muonic atoms form in excited states and then sequentially de-excite through the cascade processes such as radiative and Auger transitions and Coulomb de-excitation. Typically, the principal quantum number n in an initial state is $\sqrt{m_\mu/m_e} \sim 14$ where m_μ and m_e are the muon and electron masses, respectively. Most of the muons in atoms de-excite to the muonic ground-state immediately after formation. However, for a case of a low-density gaseous target with a small atomic number, several percent of the muons stay in metastable states with $n = 2$.

The process of interest is the 2S-1S transition with one-photon emission. The selection rule suppresses this process. However, PNC mixing between 2S and 2P states enhances the probability of the one-photon transition. The transition is parity-odd, and X-ray's emission angle is anisotropic like an electron from parity-violating muon decay.

Figure 1 summarizes the APV-relevant atomic properties as a function of the atomic number Z. The asymmetry increases with Z, but the signal-to-noise ratio S/N behaves oppositely. The S/N ratio can be defined as the ratio of the rate of one-photon transition to the rate of the others. It is tiny, at a level of sub-percent at most, so a technique for background rejection is essential. For small Z, the difference in lifetime between 2S and 2P separates the signal from backgrounds, and for large Z, the energy difference can be used for background rejection. For the experiment, carbon (Z=6) is selected as the target, considering the asymmetry, S/N, and metastability's lifetime.

[1] MLF and MUSE stand for Materials and Life Science Experimental Facility and Muon Science Establishment, respectively.

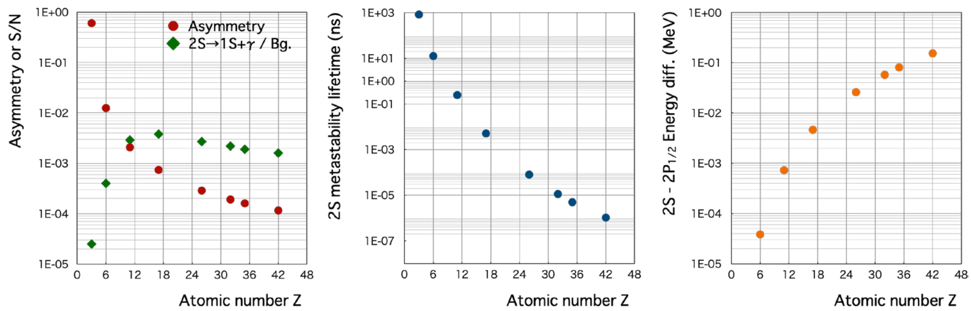

Figure 1. Atomic number dependence of some physical quantities relevant to APV measurements: (left) the APV asymmetry and the signal-to-noise ratio, (center) the lifetime of 2S metastability, (right) the energy difference between 2P and 2S states. The values are from tables I, II, and III in the reference [16].

3 Experimental method

This section outlines the experimental design, estimates the statistical sensitivity by simulation, and describes the detector development.

3.1 Overview

Figure 2 illustrates the experimental apparatus to observe the angular asymmetry of X-rays from the parity-violating transition. A polarized negative muon beam irradiates a low-density gas target. The muons form atomic bound states after slowing down by ionization. The segmented calorimeter consisting of Ce:LYSO[2] crystals and silicon photomultipliers (SiPMs) detect the X-rays from muonic atoms. A fiber hodoscope for electron tracking measures the muon stopping distribution in the target and optimizes the beam energy.

3.2 Simulation

The statistical precision of the experiment was evaluated by Monte-Carlo simulations considering the muon stopping distribution, rates of transitions, and energy distribution of emitted photons. Figure 3 shows simulation results assuming the energy resolution of 10% (FWHM) and the beam intensity of 5×10^5 Hz. Even if there is no enhancement by new physics, we expect to observe statistically significant asymmetry in two weeks of measurement.

3.3 Detector

The calorimeter unit consists of 16 SiPMs (Hamamatsu Photonics, MPPC S14160-6050HS) in a 4-by-4 arrangement. The bias voltage for SiPMs is applied in parallel, and the signal line is connected in series to be read out as a single channel. The signal is recorded by a waveform digitizer (CAEN, DT5730S) via an amplifier (Kaizuworks, KN2107). A 2.54 cm square, 3 mm thick LYSO:Ce scintillator is placed on top of the SiPM array and covered with aluminized mylar thin film. The detector design was determined based on the results of a test experiment conducted at the RIKEN-RAL muon facility in 2019 [21].

[2]Ce doped $Lu_{1.9}Y_{0.1}SiO_5$

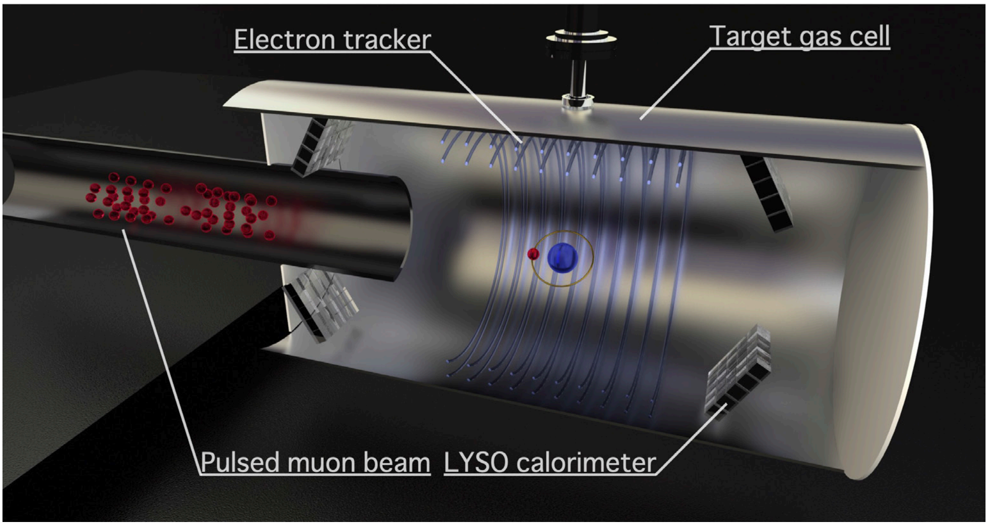

Figure 2. Experimental schematic. A low-pressure gas target is confined in an aluminum cell. A calorimeter using an inorganic scintillator and an electron tracker using scintillating fibers are placed in the cell to detect X-rays and electrons. The track reconstruction of decay electrons determines the spatial distribution of muonic atoms, and the effect of APV is quantified from the forward/backward asymmetry of muonic X-rays with respect to the muon spin direction.

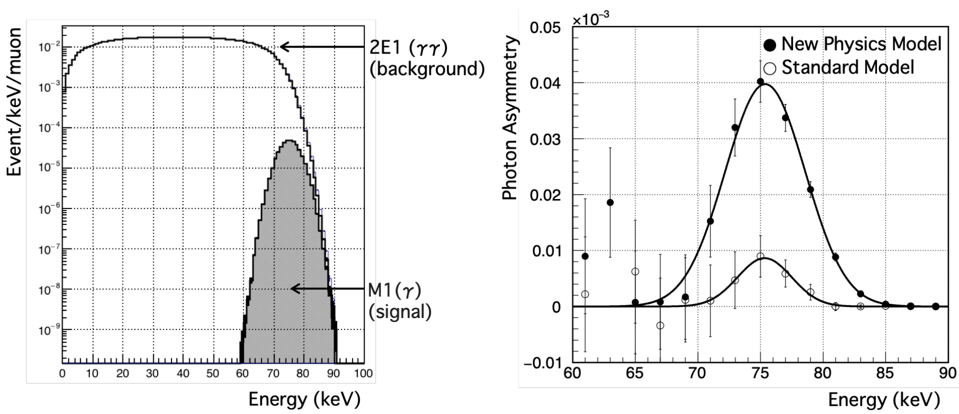

Figure 3. Results of a simulation study: (left) the energy spectra of photons from one- and two-photon transitions assuming the energy resolution of 10% FWHM, (right) the forward/backward asymmetry of photons. The enhancement of the asymmetry by the new physics was assumed to be the maximum value in the reference [15].

4 Results of a feasibility study

A feasibility study using a high-intensity pulsed muon beam was performed at the J-PARC MLF MUSE D-Line in April 2020. The purpose of this experiment is to optimize the muon beam momentum and to search for the 2S metastability of muonic carbon atoms with a low-

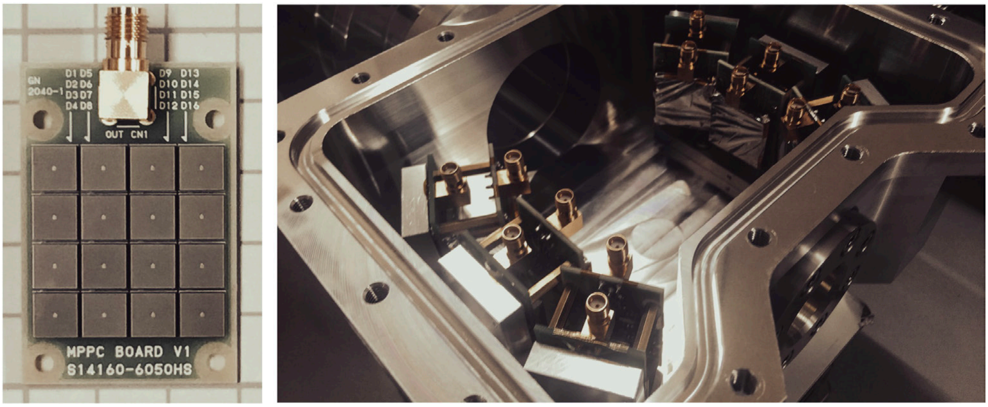

Figure 4. Photographs of the apparatus: (left) the SiPM array for calorimeter, (right) the gas cell with the calorimeters. The SiPM array consists of 16 SiPMs with a total active area of 2.54 cm × 2.54 cm. The LYSO:Ce scintillator is placed on the array (not shown in the left figure).

density methane gas target. The target cell was placed inside the μSR spectrometer [22]. The spectrometer consists of electron detectors and coils for the longitudinal and transverse fields.

We succeeded in detecting X-rays with 75 keV energy from muonic carbon atoms using a methane gas target at 0.3 atm. Detailed analysis to search for 2S metastability is in progress. In this section, we will discuss the analysis of decay electrons to evaluate the muonic atom yields and a search for muonic carbon atoms in the 2S metastable state.

Typical time spectra of decay electrons are shown on the left side of Fig. 5. The spectra were analyzed with four components taking into account the lifetime of muonic atoms to evaluate the yield of each component. Carbon and hydrogen correspond to the target gas, aluminum to the target cell, and lead to the beam collimator.

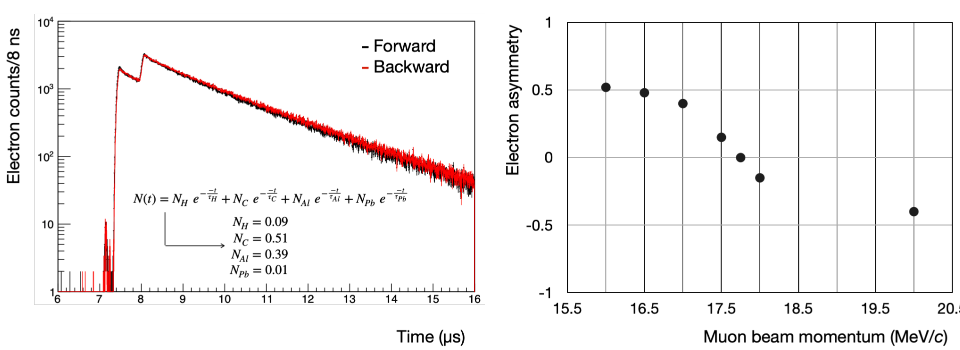

Figure 5. Experimental results: (left) decay electron time spectra obtained by the μSR spectrometer with the beam momentum of 17.75 MeV/c at the target pressure of 0.3 atm, (right) forward/backward asymmetry of decay electrons. Zero-asymmetry means that the beam stops in the center of the gas target.

The beam's momentum is optimized so that the center of the muon stopping distribution coincides with the target cell center. When this is realized, the count of electrons originating from muonic carbon atoms is equal forward and backward. The decay electron's forward/backward asymmetry is shown on the right side of Fig. 5. At a target pressure of 0.3 atm, the asymmetry was almost zero at the momentum of 17.75 MeV/c.

After momentum optimization, the 2S metastability of muonic carbon atoms was searched for. The observation of APV requires fully-ionized muonic carbon. If they are produced, muon spin rotation can be observed in a transverse magnetic field. Figure 6 shows analysis results. No significant rotation was observed in the experiment. On the other hand, spin relaxation was observed in the longitudinal field. This result suggests the existence of residual electrons, but further investigation is necessary because it may be due to other causes such as changes in muon stopping distribution or contributions from muons that have stopped beside the gas target.

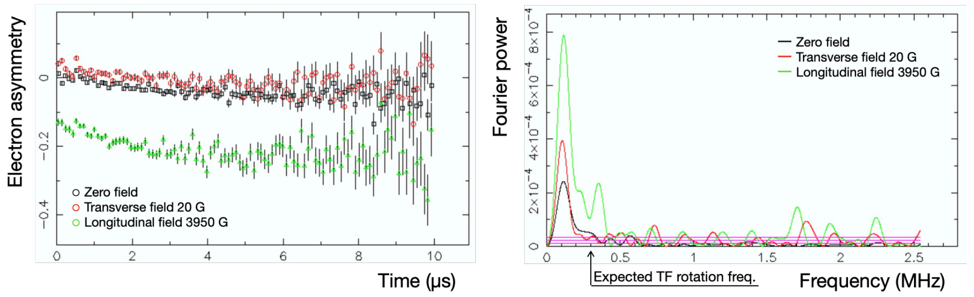

Figure 6. Results of decay electron analysis: (left) the forward/backward asymmetry as a function of time, (right) the Fourier power spectra obtained from the time spectra.

For the case of the 0.3 atm target, there is some ambiguity as to whether the muonic atom can be regarded as an isolated system, and the possibility of electron refilling from surrounding atoms cannot be ruled out. In this experiment, we also confirmed the production of muonic carbon atoms at 0.1 atm. However, the muon stopping efficiency was low, and it was difficult to obtain sufficient statistics in the limited beam time. In order to make experiments at lower gas pressures feasible, we are working on increasing the solid angle of the detector and improving the signal-to-noise ratio.

It is important to clarify what is happening during the formation and de-excitation of muonic atoms. In the case of noble gases, fully-ionized muonic atoms can be obtained at even relatively high pressures [23]. On the other hand, in the case of molecular gases, the acceleration of muonic atoms due to the Coulomb explosion causes further electron refilling. Since the re-acceleration energy depends on the structure of the gas molecules [24], targets other than methane may be the best solution. Ethane and butane were investigated in the experiment at PSI, and no 2S metastability was observed [25]. It is worthwhile to explore more possibilities systematically with numerical calculations of a cascade model considering the Coulomb explosion.

5 Summary

Atomic parity violation in muonic systems opens a unique portal to study new physics, but experiments have been challenging. A new project was proposed using a high-intensity pulsed muon beam and a fast scintillator-based calorimeter. The first experiment was performed at J-PARC MLF as a feasibility test, and the beam momentum was optimized. The proposal for a continuing experiment has been approved, and it will be conducted in February 2022.

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