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Precision measurements of charged pion decays with the PIONEER experiment

Toshiyuki Iwamoto[a,*]

[a] *ICEPP, The University of Tokyo,*
7-3-1 Hongo Bunkyo-ku, Tokyo, Japan

E-mail: iwamoto@icepp.s.u-tokyo.ac.jp

PIONEER is a next-generation precision experiment proposed at PSI to perform high precision measurements of rare pion decays. By improving the precision on the experimental result of the charged pion branching ratio to electrons vs. muons and the pion beta decay by an order of magnitude, PIONEER will provide a pristine test of Lepton Flavour Universality and the Cabibbo angle anomaly. In addition, various exotic rare decays involving sterile neutrinos and axions will be searched for with unprecedented sensitivity. This paper covers the theoretical motivations for PIONEER, as well as the ongoing simulations efforts to precisely determine the detector performance and inform decisions on the experiment design. It will show results from recent beam test campaigns on the pion beamline itself and various sensor candidates. In addition, new developments on the path to a multi-layer prototype Active Target detector system with sensor and readout electronics will be presented.

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*Speaker on behalf of PIONEER collaboration

1. Introduction

In the standard model of particle physics, the gauge interactions are lepton flavor universal, and the precise test of the lepton flavor universality is important to look for new physics. There are several experimental results which might be able to be considered as hints of the lepton flavor universality violation. Experiments to study B flavor physics like Belle/Belle II, BaBar, and LHCb measure the R(D) or R(D*) = $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)$ / $\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$ parameter, and the world average of those experimental results deviates from the standard model expectation by more than 3σ[1]. This deviation can be interpreted as a lepton flavor universality violation if it is induced by the difference between τ and μ. The long standing muon anomalous magnetic moment result, $(g\text{-}2)_\mu$[2] can also be a hint of lepton flavor universality violation between μ and e because the deviation of $(g\text{-}2)_e$ is in the opposite direction between the theoretical prediction and the experimental result. In the CKM matrix in the standard model, a Unitary equation $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2=1$ should be held. Since the parameter $|V_{ub}|$ is tiny ($< 10^{-5}$), it is simplified to two parameters of $|V_{ud}|$ and $|V_{us}|$ which are correlated by a two-generation mixing angle originally known as the Cabibbo angle. This unitarity is checked by several measurements of super-allowed nuclear beta decay, neutron beta decay for $|V_{ud}|$, and of $K \to \pi l \nu$ and $K^\pm \to l^\pm \nu$ decays for $|V_{us}|$, and the current measured average value is deviated from the theoretical prediction by about 3σ which is called "Cabibbo Angle Anomaly"[3]. This can also be interpreted as a lepton universality violation because the $|V_{ud}|$ measurements are basically coming from the electron measurements, and the $|V_{us}|$ measurements are from the muon ones.

The PIONEER experiment will measure the ratio of the branching fraction of $\pi^+ \to e^+\nu$ and

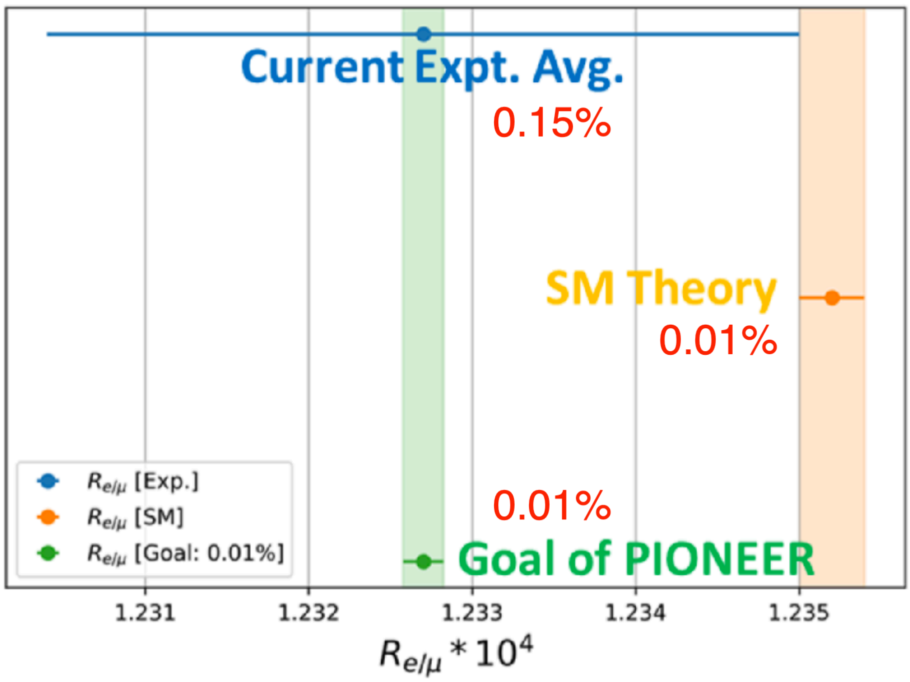

Figure 1: Sensitivity goal of PIONEER experiment

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$\pi^+ \rightarrow \mu^+\nu$ with the precision of 0.01 % in the phase I[4][5], which is to improve the previous result by a factor of 15 and is comparable to the theoretical precision from the standard model (Fig. 1). This precision will correspond to the new physics probe with the PeV energy scale. In the phase II & III, the pion beta decay of $\pi^+ \rightarrow \pi^0 e^+\nu$ will be measured with the improvement by a factor of three(II) or ten(III). This measurement will allow to verify $|V_{ud}|$ in the CKM unitarity equation with a theoretically cleanest way. The PIONEER experiment can perform the exotic search for the heavy neutral leptons such as $\pi \rightarrow l\nu_H$ in the low mass region of 10–120 MeV with an order of higher sensitivity. The PIONEER experiment is approved by Paul Scherrer Institute in Switzerland in 2022[6].

2. PIONEER experiment

The PIONEER experiment will measure the ratio ($R^{\pi}_{e/\mu} = \Gamma(\pi^+ \rightarrow e^+\nu(\gamma))/\Gamma(\pi^+ \rightarrow \mu^+\nu(\gamma))$) using different masses and lifetimes of pions and muons. Most pions will decay into muons via this reaction of $\pi^+ \rightarrow \mu^+\nu$ which branching ratio is 0.999877±0.0000004, and the branching ratio of $\pi^+ \rightarrow e^+\nu$ is (1.2327±0.0023)×10^{-4} which is suppressed by the helicity.

The statistical uncertainty is one of the largest uncertainties in the previous experiments, and the intense pion beam is important to reach 0.01 % precision. The 590 MeV proton accelerator

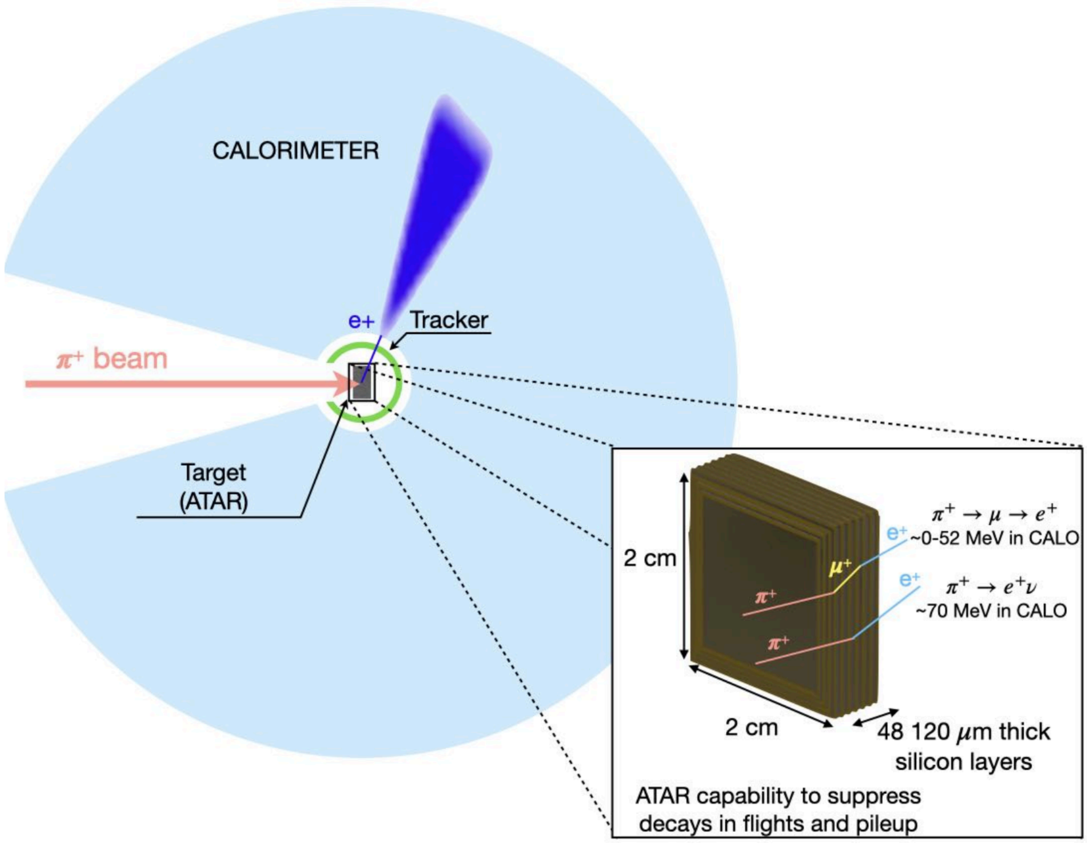

Figure 2: Schematic view of PIONEER experiment

at Paul Scherrer Institute (PSI) in Switzerland can provide the world most intense pion beam, and the requirement ($> 3 \times 10^5 \pi^+$/s) can be fulfilled in the $\pi E5$ beamline at PSI. The remaining requirements such as the beam size of 1 cm, momentum bite less than 2 %, the background contamination (< 10 %)

Fig. 2 shows the concept of the experiment. The pion beam is injected to the active target where the pion will stop decaying into a positron or a muon with a neutrino. The muon will decay to a positron and two neutrinos also in the target. The energy deposit and the time of each particle and the track information are extracted from the active target. A calorimeter surrounding the active target will measure the time and the energy of the emitted positrons. To connect the positron direction between the active target and the calorimeter, a tracker detector will be placed between them.

The active target must stop the pions and the muons efficiently, track all the particles and measure the energy deposits from them precisely, and avoid any dead region[7]. The large dynamic range for the energy measurement is required from the 30 keV minimum ionizing particles to 4 MeV μ^+ Bragg peak. The fine granularity in all directions is required because for example 4 MeV μ^+ only travels in silicon by 0.8 mm. To separate π/μ hits for 300 kHz counting rate, the time separation should be able to be by 1.5 ns. The current baseline technology in our application is a high granularity Low Gain Avalanche Diode (LGAD) because of a high signal to noise ratio, full fast collection time, and good time resolution. In X-Y plane, 100 silicon strips of a dimension of 200 μm $\times$ 2 cm with a thickness of 120 μm are stacked. In the next plane, the strip direction is rotated by 90°, and in total 48 layers are placed. The total size of the actice target is $2 \times 2 \times 0.576$ cm^3. In search of minimal cross-talk, small gain saturation, and large dynamic range, the active target using the technology based on AC-LGAD, TI-LGAD are currently under development.

The calorimeter should have high uniformity and large coverage (3π) to increase the statistics, and radiation length of ~20 X_0 to reduce the low energy tail region, sub-ns timing resolution, energy resolution of 1.5–2 %, high rate tolerance, and good pileup separation. There are two options for the

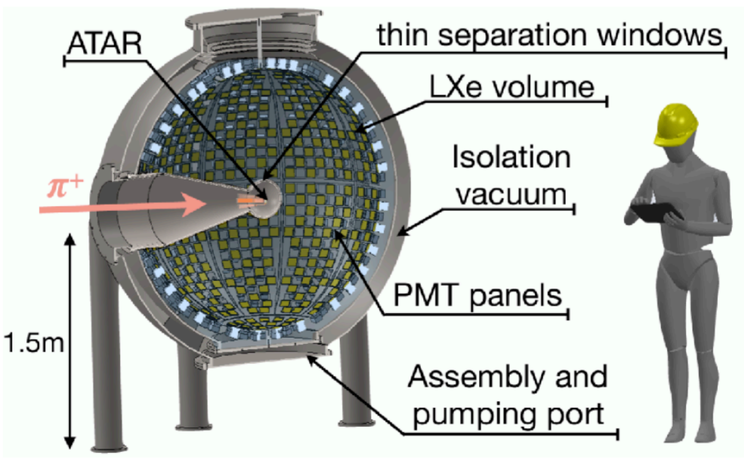

Figure 3: Schematic view of liquid xenon calorimeter

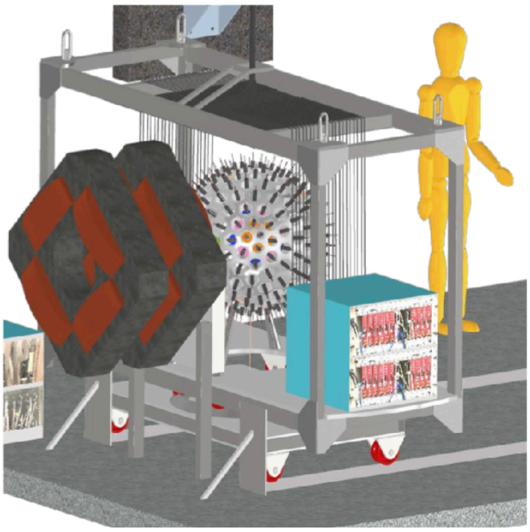

Figure 4: Schematic view of LYSO calorimeter

calorimeter, LXe of 4 t (Fig 3) and 311 LYSO crystals (Fig 4), and the preparation for the prototype test is underway.

The PSI has a beam intensity upgrade plan in 2027 and 2028, and there is a long shutdown in that period. The PIONEER experiment will continue the detector R&D until 2026 including some beam test measurements at PSI, and will aim at the detector construction during the shutdown period, and the detector installation starting from 2029 followed by the data taking for three years.

3. Conclusion

The PIONEER experiment will measure the ratio of the branching ratio of $\pi^+ \to e^+\nu$ and $\pi^+ \to \mu^+\nu$ with the precision of 0.01 % in the phase I which is to improve the previous result by a factor of 15 and is comparable to the theoretical precision. The experiment was approved with high priority by the PSI review committee in 2022. The experimental challenges requires state-of-the-art technology including active target, high resolution, deep and fast electromagnetic calorimeter, advanced trigger. The detailed simulation is necessary to evaluate the experimental sensitivity. The PIONEER collaboration grows internationally and new ideas and different expertise are necessary to realize the experiment. The experiment will continue the detector R&D for a couple of years and aim at finishing the detector construction by 2028 and start the installation work in 2029 followed by the data taking for three years.

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