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The PIONEER experiment to explore lepton universality using rare pion decays

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Recently, several measurement results suggesting a violation of lepton universality in B meson decays have been published, attracting attention as possible evidence of new physics. In the PIONEER experiment, the charged pion decay $\pi^+ \to e^+\nu$ will precisely be measured to obtain the decay ratio $R_{e/\mu} = B(\pi^+ \to e^+\nu)/B(\pi^+ \to \mu^+\nu)$ with a precision of 0.01%, which is an order of magnitude better than the previous measurements, to verify lepton universality to the limit of theoretical sensitivity. This corresponds to the search for new particles with PeV-scale masses through quantum effects.

In the second stage of the PIONEER experiment, we will also perform a precise measurement of the beta decay $\pi^+ \to \pi^0 e^+\nu$ of charged pions to verify the CKM unitarity.

The excellent measurement accuracy required for the experiment will be achieved by making full use of the liquid xenon total absorption calorimeter technology developed for the MEG experiment at the University of Tokyo and KEK. In addition, the development of an active target using the latest LGAD technology is underway internationally in order to accurately identify the reaction near the decay point.

The proposal for the PIONEER experiment was approved by the Paul Scherrer Institute (PSI) in Switzerland in 2022, and is being developed and prepared in international collaboration with Japan, the United States, Canada, Switzerland, Germany, and other countries.

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1. Introduction

The particle physics phenomena are described by the standard model. In quark and in lepton sectors, there are three flavors or generations. The electroweak interactions in the standard model are described as lepton universal, with universal couplings of W, Z and photons with respect to lepton flavor, which is called lepton flavor universality.

There are several results which show deviations from the lepton universality. One is the so-called R(D/D^*) ratio measuring the ratio of the B meson decays to τ and μ leptons. This can be considered to be the difference between τ and μ which may be a hint of the lepton flavor universality violation (LFUV). Another hint is from the (g-2)$_\mu$ measurements. There is a longstanding (g-2)$_\mu$ deviation from the theory that can be considered as another hint of LFUV when we compared with (g-2)$_e$.

Finally, let's mention the hint of LFUV coming from the unitarity check of the CKM matrix. The equation $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=0$ is one of the unitarity equations of the CKM matrix, and since $|V_{ub}|^2 < 10^{-5}$ is tiny, many experimental results are discussed in (V_{ud}, V_{us}) two dimensional plane. The current best fit result deviates from the unitarity expectation by roughly 3 σ, which can also be interpreted as a LFUV since the $|V_{ud}|$ measurements are mainly derived from the electron measurements while the $|V_{us}|$ ones are from the muon measurements.

2. PIONEER experiment

The PIONEER experiment which proposes to explore lepton universality using rare pion decays is a new experiment approved by Paul Scherrer Institute in 2021[1]. In the phase I, the ratio of $R^{\pi}_{e/\mu}$ between $\pi \to e\nu_e(\gamma)$ and $\pi \to \mu\nu_\mu(\gamma)$ decays will be measured with the precision of 0.01% representing a factor of 15 improvement with respect to the previous experiments. In the phase II the branching ratio of $\pi^+ \to \pi^0 e^+\nu$ decays will be measured with a precision of 0.2%, which is three times better than the previous results, and the CKM matrix unitarity check can be done with 10 times improvement in the phase III. Theoretically cleaner V_{ud} measurements will be possible with this mode.

There are mainly three basic π decay modes considered in the PIONEER experiment. The main decay is described by $\pi^+ \to \mu^+\nu_\mu(\gamma)$, which has almost a branching ratio of 1. The $\pi^+ \to e^+\nu_e(\gamma)$'s branching ratio is around 10^{-4}. To distinguish these two decays, the π/μ lifetimes and the mass differences are used. The μ will be identified directly from its decay products $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$. Finally the third decay mode considered is the beta decay $\pi^+ \to e^+\nu_e\pi^0$, which has a tiny branching ratio of 10^{-8}.

The signal considered dring the phase I is the $\pi^+ \to e^+\nu$ which will be detected by the active target (ATAR) with a single energy deposit, and the monochromatic energy deposit in a calorimeter. The background is the $\pi^+ \to \mu^+\nu$, with the following $\mu^+ \to e^+\nu\bar{\nu}$ decays. The muon deposits more energy in ATAR, and the Michel decay positron deposits less energy in the calorimeter. To distinguish these decays, the ATAR and the calorimeter signals will be used. For the precise measurements, the tail correction of the signal positron spectrum going into the Michel positron spectrum region is important to reduce the systematics in the ratio measurements.

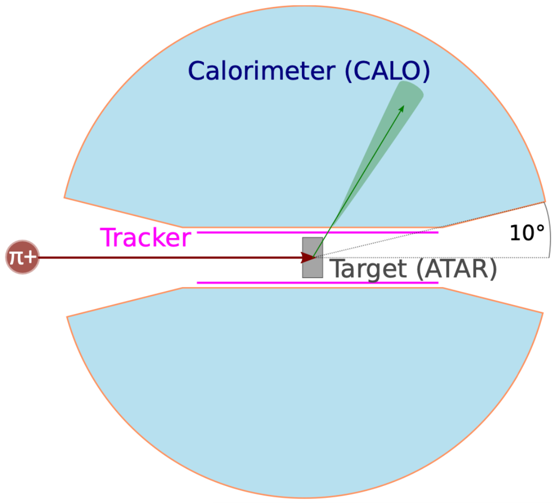

Figure 1: The concept of the PIONEER experiment

Figure 1 shows the concept for the PIONEER experiment. A lot of pion decays are necessary to increase the statistics, and the intense pion beam of $3{\times}10^5\pi^+$/s at Paul Scherrer Institute (PSI) will be used. The pion beam is stopped in the active target used to track $\pi \to e\nu$ or $\pi \to \mu\nu$ events. Energy, time, and the particle direction will be measured in the ATAR with an expected position resolution around 100 μm and a time resolution around 1 ns. This should work under a high event rate environment. The calorimeter will measure the positron energy and time. 25 radiation lengths to reduce the low energy tail region and 3π coverage to increase the statistics will be necessary. This should work also under high event rate environment. The positron direction between ATAR and the calorimeter will be measured by the tracker installed in between them.

The requirements for the pion beam are summarized here. The momentum of the pion is 65 MeV/c, the rate should be more than $3{\times}10^5\pi^+$/s, the beam size should be less than 10 mm, momentum dispersion dp/p less than 2%, and the contamination by e and μ should be less than 10%. The most important aspect is the rate, and this is currently only available at the πE5 beam line at PSI. The beam profile of the πE1 beam line will also be tested for the detector R&D because the MEG and the Mu3e will occupy the πE5 at least until 2026.

The requirements for the active target are as follows. Energy measurement is necessary from the MIP region of 30 keV up to the muon Bragg peak of 4 MeV. Good energy resolution over a large dynamic range is necessary. High granularity in (X, Y, Z) is required for tracking of π/μ/e, and the time resolution should be better than 1.5 ns for 300 kHz measurement. The current chosen sensor for ATAR is the high granularity low gain avalanche diode (LGAD) which has a high S/N, a fast collection time, and a good time resolution. This represents the current possible layout of the ATAR, which is composed of 2×2×0.6 cm^3 with 48 layers, with strip width of 0.2 mm and alternating strip planes by 90° for (X, Y) tracking. The combined information of tracking, timing, and energy deposit reduces the Michel e$^+$ contamination from the $\pi^+ \to \mu^+ \to e^+$ decay significantly.

The requirements for the calorimeter are large acceptance, uniformity, good timing, good energy resolution, long radiation lengths, high counting rate tolerance, and good pileup separation. The liquid xenon calorimeter is the current baseline design for the PIONEER experiment because the technology and the performance are well proven by the MEG II LXe detector. The current conceptual design utilizes 7 t of LXe, and the outer/inner radius is considered to be 80 cm/7 cm. Photo sensors are planned to be installed only on the outer face, and the incident position is extracted from the tracker. The simulation work is intensively progressing to determine the whole detector design. The requirements for the calorimeter and the ATAR energy resolution are determined based on the simulations to reduce the number of tail components, and the background events.

Statistics and systematics improvements are necessary to achieve the precision of the PIONEER experiment. The intense, high quality π^+ beam improves the statistics. The ATAR and calorimeter will improve the tail correction which was the dominant source of the systematic uncertainty in the previous experiments. Detector prototypes will be used to demonstrate the experimental sensitivity in three years, and the results will be summarized in a technical design report. After a construction work lasting several years, the physics run will be started.

3. Conclusion

The PIONEER experiment approved by the PSI scientific committees will explore the lepton flavor universality violation with the measurements of $\mathrm{R}^{\pi}_{e/\mu}$. The measurement of the pion beta decay ($\pi^+ \to \pi^0 e^+ \nu$) is an important input to check the CKM unitarity. There are three key points to improve the sensitivity with the PIONEER experiment, namely, the intense pion beam, the active target, and the calorimeter. The PIONEER experiment will aim at preparing the TDR in the next three years, and starting the run after a construction period of around three years.

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References

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