TESTING LEPTON UNIVERSALITY WITH RARE PION AND KAON DECAYS

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ABSTRACT

Rare pion and kaon decays provide highly sensitive experimental probes for new physics beyond the Standard Model via the theoretically pristine $\pi / K \to l\nu$ decay channels (where l=e or μ) which allow high precision tests of the hypothesis of electron-muon universality. These studies confront the Standard Model with unrivaled precision and have the potential to uncover new interactions at the 1000 TeV mass scale. Pion and kaon beams with high intensity, high purity, and high duty factor are needed to pursue measurements to their ultimate sensitivities.

INTRODUCTION

The absence of an explanation for the generation puzzle i.e. why do we have exactly three versions of each quark and lepton, is a major flaw in the highly successful Standard Model (SM). Electron-muon universality, within the context of the SM, refers to the hypothesis that charged leptons have identical electroweak gauge interactions and they differ only in their masses and coupling to the Higgs. However, there could be additional "New Physics" effects, such as non-universal gauge interactions, or scalar or pseudoscalar bosons with couplings not simply proportional to the lepton masses which would cause apparent violations of universality.

One of the most sensitive approaches to seeking such new interactions is the study of the ratio of decay rates of pions [1] $R^{\pi}_{e/\mu} \equiv \dfrac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$ which is predicted with $\pm 0.02\%$

[1] See Rare Pion and Kaon Decays, D. Bryman, W. Marciano, R. Tschirhart, T. Yamanaka, Ann. Rev. Nucl. Part. Sci., in press (2011) and references therein.

uncertainty in the SM to be $R^{\pi}_{e/\mu} = 1.2351(2)\times10^{-4}$ [2,3,4] and for which experiments can aim to approach similar sensitivities. "New Physics" at scales as high as $1000\ TeV$ can be constrained or conceivably unveiled by measurement of this ratio. For example [1], consider the case of a charged physical Higgs boson with couplings $\frac{g}{2\sqrt{2}}\lambda_{ud}$ to the $\bar{u}\gamma_5 d$ pseudoscalar current and $\frac{g}{2\sqrt{2}}\lambda_{l\nu}$ to $\bar{l}(1-\gamma_5)\nu_l$, $l = e,\mu$ where g is the $SU(2)_L$ gauge coupling and λ represents chiral breaking suppression factors. One finds $m_{H^\pm} \cong 200TeV \times \lambda_{ud}^{1/2}(\lambda_{e\nu} - \frac{m_e}{m_u}\lambda_{\mu\nu})^{1/2}$. If $\frac{\lambda_{e\nu}}{\lambda_{\mu\nu}} = \frac{m_e}{m_\mu}$, as in the minimal 2-Higgs doublet model, there is no sensitivity to new physics. However, in more general multi-Higgs models such a chiral relationship is not necessary and λ may not be too suppressed. For example, in the case of loop induced charged Higgs couplings $\lambda_{e\nu} \cong \lambda_{\mu\nu} \cong \lambda_{ud} \cong \frac{\alpha}{\pi}$, one finds $m_{H^\pm} \approx 400GeV$ is probed for $R^{\pi}_{e/\mu}$ sensitivity of $\pm 0.1\%$. If a discrepancy between theory and experiment is found in $R^{\pi}_{e/\mu}$, some type of charged Higgs explanation would be quite natural; however, it could also point to additional charged axial-vector interactions or loop effects due to "New Physics." It could also be interpreted as an effect of heavy neutrino mixing damping one of the π_{l2} decay modes.

Analogous K decays, $R^{K}_{e/\mu} \equiv \frac{\Gamma(K\to e\nu(\gamma))}{\Gamma(K\to \mu\nu(\gamma))}$ can also probe high scales and have the added appeal of being particularly sensitive to the lepton flavor violating $K^+ \to e^+\nu_\tau$ decay which might be induced through loop effects [5].

EXPERIMENTAL STUDY OF $\pi \to e\nu$ and $K \to e\nu$ DECAYS

The most recent $\pi^+\to e^+\nu$ (π_{e2}) branching ratio measurements and subsequent determination of the ratio $R^{\pi}_{e/\mu}$ were done at TRIUMF [6] and PSI [7] in the 1990s. The results from the two experiments were consistent and in agreement with the SM expectation previously discussed:

$$R^{\pi-TRIUMF}_{e/\mu} = 1.2265(34)(44)x10^{-4}\ ;\ \text{and}\ R^{\pi\text{-PSI}}_{e/\mu} = 1.2346(35)(36)x10^{-4}$$

for TRIUMF and PSI respectively, where the first and second uncertainties were due to statistical and systematic effects. The PDG average value is $R^{\pi-\mathrm{expt}}{}_{e/\mu} = 1.230(4)\times 10^{-4}$ [8] including results from [9]. Two new experiments are underway at TRIUMF [10] and PSI [11] which aim to improve the precision of $\mathrm{R}_{e/\mu}^{\exp\pi}$ by a factor of 5 or more, thereby confronting the SM prediction to better than ±0.1%. At that level, new physics effects could appear as a deviation from expectations or in the absence of a deviation strong new constraints on new physics hypotheses will be placed.

The PIENU experiment [10] is a refinement of the technique used in the previous TRIUMF experiment[6]. The branching ratio will be obtained from the ratio of positron yields from the $\pi \to e\nu$ decay and from the $\pi \to \mu \to e$ decay chain. By measuring positrons from the decays $\pi \to e\nu$ and $\pi \to \mu \to e$ in a non-magnetic spectrometer many normalization factors, such as the solid angle of positron detection, cancel to first order and only small energy-dependent effects, such as those for multiple Coulomb scattering (MCS) and positron annihilation, need to be corrected for. Major improvements in precision stem from the use of an improved geometry, a superior calorimeter, high speed digitizing of all pulses, Si strip tracking, and higher statistics. The improvements lead to an expected precision on the $\mathrm{R}_{e/\mu}^{\exp\pi}$ branching ratio <0.06 %, which corresponds to a 0.03 % uncertainty in the ratio of the gauge boson-lepton coupling constants g_e/g_μ testing electron-muon universality.

At PSI, the PIBETA CsI spectrometer [12] built for a determination of the $\pi^+ \to \pi^0 e\nu$ branching ratio and other measurements [13] has been upgraded and enhanced for the PEN [11] measurement of the $\pi \to e\nu$ branching ratio. The PEN technique is similar to that employed in the previous PSI experiment [7] which used a nearly 4π-sr BGO spectrometer. PEN began operation since 2007 and has observed $>10^7$ $\pi \to e\nu$ decays. PEN completed data acquisition 2010 and expects to obtain an improved precision measurement of $\mathrm{R}_{e/\mu}^{\exp\pi}$ at the level <0.05%.

Recent progress on $\mathrm{R}^{K}{}_{e/\mu}$ has been made by KLOE [14] and NA62 [15] with current efforts at NA62 aimed at reaching 0.4% precision. KLOE collected a data set of 3.3 billion K^+K^- pairs, observing decay products in a drift chamber in a 0.52 T axial magnetic field surrounded by an electromagnetic calorimeter. The measurement of $\mathrm{R}_{e/\mu}^{\exp K}$ consisted of comparing the corrected numbers of decays observed from the $K \to e\nu(\gamma)$ and $K \to \mu\nu(\gamma)$ channels. The result found was $\mathrm{R}_{e/\mu}^{\exp K-KLOE} = (2.493\pm 0.025(\mathrm{stat}) \pm 0.019(\mathrm{syst})\times 10^{-5}$ [14] in agreement with the SM prediction at the 1% level.

NA62 at CERN using the setup from NA48/2 has embarked on a series of $K_{e2}/K_{\mu 2}$ measurements [15]. A K^+ beam is produced by the 400 GeV/c SPS. Positively charged particles within a narrow momentum band of (74.0 ± 1.6) GeV/c are selected by an achromatic system of four dipole magnets and a muon sweeping system, enter a fiducial decay volume contained in a 114 m long cylindrical vacuum tank producing a secondary beam. The $K \to e\nu(\gamma)$ and $K \to \mu\nu(\gamma)$ detection system includes a magnetic spectrometer, a plastic scintillator hodoscope (HOD) and a 27 X_0 liquid krypton electromagnetic calorimeter (LKr). As in KLOE, the experimental strategy is based on counting the numbers of reconstructed $K \to e\nu(\gamma)$ and $K \to \mu\nu(\gamma)$ events concurrently eliminating dependence on the absolute beam flux and other potential systematic uncertainties. The result was $R_{e/\mu}^{\exp K-NA62} = (2.487 \pm 0.011\text{stat.} \pm 0.007\text{syst.}) \times 10^{-5} = (2.487 \pm 0.013) \times 10^{-5}$ [15] in agreement with the SM prediction. This result is based on 40% of the data sample acquired in 2007. The full data sample may allow a statistical uncertainty of 0.3% and a total uncertainty of 0.4-0.5% .

FUTURE PROSPECTS

If PIENU and PEN achieve their sensitivity goals there will still be a considerable window for new physics to appear without complication from SM prediction uncertainties. To reach the ultimate levels of uncertainty ~0.02% presented by the SM calculations would require a new generation of experiments and experimental techniques capable of providing control of systematic uncertainties at the 0.01% level or below. High precision measurements of $R^{\pi/K}_{e/\mu}$ would be important to confront theories which may arise from discoveries of high mass effect at the LHC. High intensity beams with 100% duty factor and ultra-high intensity and purity may be the key elements enabling ultra-high precision experiments on $\pi / K \to e\nu$ decays resulting in breakthroughs in understanding of $e-\mu$ universality and elucidation of subtle non-SM effects. Such beams would be available for pions and kaons at Project X and for pions at PSI or TRIUMF.

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