The transverse lepton polarization asymmetry in $\pi \rightarrow e\nu\gamma$ decay may probe T-violating interactions beyond the Standard Model. Dalitz plot distributions of the expected effects are presented and compared to the contribution from the Standard Model final state interactions. We give an example of a phenomenologically viable model, where a considerable contribution to the transverse lepton polarization asymmetry arises.

1 Introduction

T-violation beyond the Standard Model is usually searched for in decays forbidden by time reversal symmetry. Another way to probe T-violation is measurement of T-odd observables in allowed decays of mesons. Widely considered T-odd observables are transverse muon polarizations ($P_T$) in $K \rightarrow \pi \mu \nu$ and $K \rightarrow \mu \nu \gamma$ decays. There is no tree level SM contribution to $P_T$ in these decays, so they are of a special interest for search for new physics. Unfortunately, $P_T$ is not exactly zero in these decays even in T-invariant theory — electromagnetic loop corrections contribute to $P_T$ and should be considered as a background. There are no experimental evidence for nonzero $P_T$ in these processes at present time, but the sensitivity of the experiments has not yet reached the level of SM loop contributions.

In this talk we discuss the decay $\pi \rightarrow e\nu\gamma$. Within the Standard Model, T-violation in this process does not appear at tree level, but interactions, contributing to it, emerge in various extensions of SM. We shall demonstrate that $\pi_{e2\gamma}$ decay is an attractive probe of new physics beyond the Standard Model. Depending on the model, $\pi_{e2\gamma}$ decay may be even more attractive than usually considered $K_{l2\gamma}$ decays. The similar decay $\pi_{\mu2\gamma}$ is analized in the article, where one can also find the detailed bibliography.

Though $\pi_{e2\gamma}$ decay has very small branching ratio (it is of order $10^{-7}$), we find that the distribution of the transverse electron polarization over the Dalitz plot significantly overlaps
with the distribution of differential branching ratio, as opposed to the situation with $K_{\mu 2\gamma}$ decay. Moreover, the contribution of FSI (final-state interactions related to SM one-loop diagrams) to the observable asymmetry, being at the level of $10^{-3}$, becomes even smaller in that region of the Dalitz plot, where the contribution from new effective T-violating interaction is maximal. Thus, $\pi e_{2\gamma}$ decay is potentially quite interesting probe of T-violation.

To demonstrate that pion decays may be relevant processes where the signal of new physics may be searched for, we present a simple model of heavy pseudoscalar particle exchange leading in the low energy limit to the T-violating four fermion interaction. We find the constraints on the parameters of this model coming from various other experiments and describe regions of the parameter space which result in large T-violating effects in $\pi e_{2\gamma}$ decays. Depending on the parameters of the model, an experiment measuring transverse lepton polarization with pion statistics of $10^5 \div 10^{10}$ pions for $\pi e_{2\gamma}$ decay and $10^8 \div 10^{13}$ pions for $\pi e_{2\gamma}$ decay is needed to detect the T-violating effects (taking into account statistical uncertainty only and assuming ideal experimental efficiencies).

## 2 T-violating effect in $\pi e_{2\gamma}$ decay

Let us consider the simplest effective four-fermion interaction

$$L_{\text{eff}} = G_F^e \bar{d} \gamma_5 u \cdot \bar{\nu}_e (1 + \gamma_5)e + h.c.$$  \hspace{1cm} (1)

that may be responsible for the T-violating effects in pion physics beyond the Standard Model. Indeed, the imaginary part of the constant $G_F^e$ contributes to transverse lepton polarization.

For the transverse electron polarization asymmetry (polarization in the direction $\bar{e}_T = \vec{q} \times \vec{p}_l/|\vec{q} \times \vec{p}_l|$)

$$P_T(x, y) = \frac{d\Gamma(\bar{e}_T) - d\Gamma(-\bar{e}_T)}{d\Gamma(\bar{e}_T) + d\Gamma(-\bar{e}_T)} = [\sigma_V(x, y) - \sigma_A(x, y)] \cdot \Im[\Delta_P]$$

$$\Delta_P^e = \frac{\sqrt{2} G_F^e}{G_F \cos \theta_c} \cdot \frac{B_0}{m_t}, \quad B_0 = -\frac{2}{(f_{\pi})^2} \langle 0|\bar{q}q|0\rangle = \frac{m_e^2}{m_u + m_d} \approx 2\text{GeV}.$$  \hspace{1cm} (2)

The contour-plot of $[\sigma_V - \sigma_A]$ as a function of $x$ and $y$ is presented in the Figure (a).

As one can see, in a large region of kinematic variables, $[\sigma_V - \sigma_A]$ is about 0.5. This means that transverse electron polarization $P_T$ for this process, is of the same order as $\Im[\Delta_P^e] \approx 5 \times 10^{-3} \cdot \Im[G_F^e/G_F]$. It is worth noting that the region of the Dalitz plot where large T-violating effect might be observed, significantly overlaps with the region where the partial decay width $\Gamma(\pi e_{2\gamma})$ is saturated (cf. Figures (a) and (b)). This is in contrast to the situation with T-violation in $K_{\mu 2\gamma}$ decay, where the analogous overlap is small, so the differential branching ratio in the relevant region is smaller than on average.

Theoretical background to the observation of $P_T$ caused by interaction of the type (1) appears from the contribution from final-state interactions (FSI) — one-loop diagrams with virtual photons. The value of this contribution in the Standard Model is presented in Figure (b).
For the $\pi e_2 \gamma$ decay, the $(x, y)$-distributions of FSI contribution and the contribution from the four-fermionic interaction differ in shape. Specifically, part of the region with maximal $P_T$ from four-fermion interaction corresponds to the region of small $P_T$ from FSI. This implies that if measured, $P_T$ distribution could probe T-violating interaction with an accuracy higher than $\text{Im}[\Delta P] \sim 10^{-3}$ ($\text{Im}[G_P^e/G_F] \sim 2 \times 10^{-7}$). Again, this is not the case for $K_{\mu2\gamma}$ decay.

2.1 Constraint from $\pi \to l\nu$ decays

The interaction term not only gives rise to T-violation in $\pi \to e\nu_\gamma$ decay but also contributes to the rate of $\pi \to l\nu_l$ decays. Since the ratio of leptonic decays of the pion has been accurately measured, the coupling constants $G_P^e$ is strongly constrained. This constraint can be evaded by introducing a similar coupling to muon and muon neutrino with the corresponding constant $G_P^\mu = \frac{m_\mu}{m_e} G_P^e$.

Note that to the leading order in $\Delta P$, only the real parts of the coupling constants $G_P^\mu$ and $G_P^e$ are constrained, while constraints on imaginary parts are weaker. Thus, for general $G_P^\mu$ and $G_P^e$ (if the mentioned hierarchy does not hold) one obtains $|\text{Re}[\Delta P]| \lesssim 10^{-3}$ and $|\text{Im}[\Delta P]| \lesssim 0.03$. Hence in this case experiments aimed at searching for T-violation in $\pi e_2 \gamma$ decays should have sufficiently large statistics: the total number of charged pions should be $N_\pi \gtrsim 10^{11}$.

In models with $\text{Re}[G_P] \sim \text{Im}[G_P]$ and without $\mu - e$ hierarchy, the bound from $\pi \to l\nu$ decays implies $|\text{Im}[\Delta P]| \lesssim 10^{-3}$, which significantly constrains possible contribution of the new interaction to T-odd correlation in $\pi e_2 \gamma$ decay. Namely, the contribution to the $\pi e_2 \gamma$ decay should be of the same order or weaker than one from the Standard Model FSI. Nevertheless, as we discussed, in the case of $\pi e_2 \gamma$ the difference in $(x, y)$ distributions of FSI and four-fermion contributions may allow one to discriminate between the two if they are of the same order of magnitude, and even if the contribution of four-fermion interaction is somewhat weaker. To test four-fermion interaction at the level allowed by $\pi \to e\nu_e$, i.e., at the level of $10^{-3}$, one has to collect not less than $10^{13}$ charged pions, assuming statistical uncertainty only.

Overall, in the case of the hierarchy muon and electron couplings, decays $\pi \to l\nu$ do not constrain new T-violating interactions which can be searched for in relatively low statistics experiments, $N_\pi \gtrsim 10^8$ for $\pi e_2 \gamma$ and $N_\pi \gtrsim 10^5$ for $\pi \mu_2 \gamma$. In the worst case of no hierarchy and $\text{Re} G_P \sim \text{Im} G_P$, new T-violating interactions have little chance to be observed, and need high statistics experiments.

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