Highlights on Rare Charged Kaon Decays

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We review recent experimental results on radiative rare charged kaon decays. The results from ISTRA+ and KEK E-460 experiments are considered. The obtained branching fractions are compared with theoretical predictions. For K$l3\gamma$ decays the estimations of T-odd asymmetry are given.

1. Introduction

Radiative kaon decays are dominated by long distance (low energy) physics. For low energy processes we don't have predictions from SM and use effective theories such as Chiral pertubation theory (ChPT). ChPT gives decay rates for most decay modes. That's why radiative kaon decays provide a testing ground for ChPT. Moreover these decays are sensitive to New Physics, e.g. one can study T-odd asymmetries in radiative K$l3$ decays.

2. ISTRA+ recent results

2.1. Experimental setup

The experiment has been performed at the IHEP 70 GeV proton synchrotron U-70. The experimental setup "ISTRA+" (Fig. 1)has been described in some details elsewhere[1].

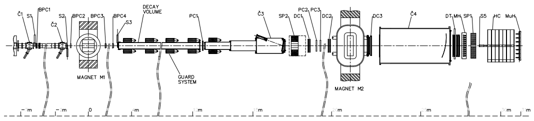

Figure 1. *Elevation view of the "ISTRA+" detector*

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2.2. $K^- \to \mu^- \nu_\mu \gamma$ decay

The decay $K^- \to \mu^- \nu_\mu \gamma$ is sensitive to hadronic weak currents in low-energy region. The decay amplitude includes two terms - internal bremsstrahlung (IB) and structure dependent term (SD). IB contains radiative corrections from $K^- \to \mu^- \nu_\mu$. SD allows to probe electroweak structure of kaon.

The differential decay rate is calculated within ChPT and can be written in terms of standard kinematical variables x=$2E^\star_\gamma/M_k$ and $y = 2E^\star_\mu/M_k$ (see [2],[3] for details).

The event selection criteria are: one charged track, μ flag in HCAL; one shower in ECAL not associated with a charged track; z-coordinate of the decay vertex within interval 300 $<$ z_{vertex} $<$1650 cm. Additional cuts are applied to suppress backgrounds:

- missing energy $>$ 1GeV;
- no photons in SP2 calorimeter;
- missing momentum points to ECAL aperture.

Main background comes from 2 decay modes - $K^- \to \mu^- \nu \pi^0$ and $K^- \to \pi^- \pi^0$ with one gamma lost from $\pi^0 \to \gamma\gamma$ and π misidentified as μ. Distribution over M($\mu\nu\gamma$) is used for signal observation. $M^2(\mu\nu\gamma) = (P_\mu + P_\nu + P_\gamma)^2$ where P_μ, P_ν, P_γ are 4-momenta of corresponding particles; missing mass is supposed to be equal to 0 so that $\vec{p}_\nu = \vec{p}_K - \vec{p}_\mu - \vec{p}_\gamma; E_\nu = |\vec{p}_\nu|$. M($\mu\nu\gamma$) peaks at K^- mass for signal.

To extract signal, the following procedure is applied:

- all kinematical (x,y) region is divided into little bins;

- we look at M($\mu\nu\gamma$) in each bin;
- bins with signal peak are selected(see fig. 2).The selected kinematical region is $30 < E^{\star}_{\gamma} < 120 MeV; 150 < E^{\star}_{\mu} < 230 MeV$(fig.3, red);
- Fitting M($\mu\nu\gamma$) gives the number of $K^- \to \mu^-\nu\gamma$ events (the shape of background distribution is taken from MC).

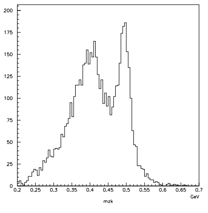

Figure 2. *M($\mu\nu\gamma$) for (x,y) bin, real data*

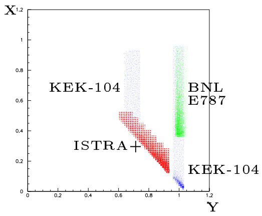

Figure 3. *x=2$E^{\star}_{\gamma}/M_k$, $y = 2E^{\star}_{\mu}/M_k$ ISTRA+(red); BNL E787(green);KEK-104(blue)*

Total number of $K^- \to \mu^-\nu\gamma$ events is 22472±465. To measure BR($K^- \to \mu^-\nu\gamma$), we normalize on BR($K^- \to \mu^-\nu\pi^0$). Supposing PDG04 value for BR($K\mu 3$) we obtain BR($K^- \to \mu^-\nu\gamma$) $= [1.25 \pm 0.04(stat) \pm 0.02(norm)] \times 10^{-3}$ which is in good agreement with theory: BR$_{th} \sim 1.28{*}10^{-3}$. Our kinematical region is complementary to that of previous experiments[2],[3] (see fig. 3).

2.3. Radiative Kl3 decays

Radiative Kl3 decays ($K\mu 3\gamma, Ke3\gamma$) are interesting to test ChPT and search for New Physics using T-odd kinematical variable $\xi = \frac{1}{M_K^3}\overrightarrow{p}_{\gamma} \cdot [\overrightarrow{p}_{\pi} \times \overrightarrow{p}_{l}]$.

In SM the expected value for asymmetry $A_{\xi} = \frac{N(\xi>0)-N(\xi<0)}{N(\xi>0)+N(\xi<0)}$ is less than that in SM extensions ($K\mu 3\gamma : A_{\xi} \sim 1.14\times 10^{-4}$ for SM, $A_{\xi} \sim 2.6\times 10^{-4}$ for SM extensions[4]; $Ke3\gamma : A_{\xi} \sim 0.6 \times 10^{-4}$ for SM, $A_{\xi} \sim 0.8 \times 10^{-4}$ for SM extensions[5]).

$K^- \to \mu^-\nu\pi^0\gamma$

Radiative $K\mu 3$ decay was observed in K_L-decays. Here we present first observation of $K^-_{\mu 3\gamma}$ mode[6].

Standard selection criteria are used:
- 1 charged track;
- 3 showers in ECAL;
- effective mass m($\gamma\gamma$) within $\pm 20 MeV/c^2$ from π^0 mass.

Some additional cuts are applied to suppress backgrounds:
- $400 < z_{vertex}$ <1650 cm;
- missing energy > 1GeV;
- no photons in veto system.

Main background comes from $K\mu 3, K\pi 2, K\pi 3$ decays with 1γ lost or accidental γ. Invariant mass M($\mu\nu\pi^0$) is used for signal observation (it peaks at K^- mass for signal). We separated our signal region into 2 parts: $5 < E^{\star}_{\gamma} < 30 MeV$ (low background) and $30 < E^{\star}_{\gamma} < 60 MeV$ (large background).

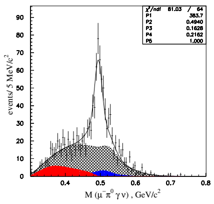

Figure 4. *$K\to \mu\nu\pi^0\gamma$, 1-st kinematical region $5 < E^{\star}_{\gamma} < 30 MeV$*

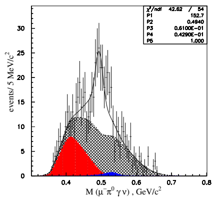

Figure 5. *$K\to \mu\nu\pi^0\gamma$, 2-nd kinematical region $30 < E^{\star}_{\gamma} < 60 MeV$*

In the 1-st kinematical region (see fig. 4) we observe 384±41 events. To obtain BR($K\mu 3\gamma$) we normalize on BR($K\mu 3$). Using PDG04 value for BR($K\mu 3$) we get BR($K\mu 3\gamma$)=[8.82±0.94($stat$) $\pm$ 0.80($syst$)] $\times 10^{-5}$. Theory gives BR($K\mu 3\gamma$) $\sim 6.86 \times 10^{-5}$. For T-odd asymmetry we get $A_{\xi} = -0.03 \pm 0.13$ which is far from theoretical predictions.

In the 2-nd region (fig. 5) an additional cut is applied to suppress strong background from $K\pi2$ and $K\pi3$: $0.1 < p^{\star}_{\pi} < 0.185 GeV/c$. 153±39 events are observed. $BR(K\mu3\gamma) = [1.46 \pm 0.22(stat) \pm 0.32(syst)] \times 10^{-5}$. Theory gives 1.53×10^{-5}.

$K^- \rightarrow e^-\nu\pi^0\gamma$

Radiative Ke3 decay was observed both for neutral and charged modes. Our result on $K^-_{e3\gamma}$ decay improves statistics significantly. Also the best estimation for A_ξ is obtained[7].

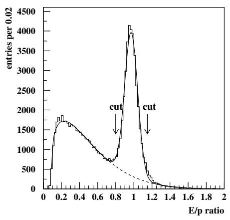

Figure 6. *E/P ratio for the real data*

Selection criteria and cuts are very similar to that of $K^-_{\mu3\gamma}$. The only difference is 4 showers in ECAL instead of 3 and additional E/p cut for electron identification (E - shower energy, p - track momentum). E/p distribution is shown in fig. 6.

Several kinematical cuts are applied to suppress background from $K^- \rightarrow \pi^-\pi^0\pi^0, K^- \rightarrow \pi^-\pi^0, K^- \rightarrow \pi^-\pi^0\gamma, K^- \rightarrow e^-\nu\pi^0\pi^0$. The most dangerous background from Ke3 with brem γ is effectively rejected by the following requirement: $0.002 < \theta_{e\gamma} < 0.030$ (See [7] for details).

Resulting spectra for $E^{\star}_{\gamma}$ and $cos\theta^{\star}_{e\gamma}$ are shown in fig. 7. 5378 events are selected. The estimated background is 1526 events.

To measure BR(Ke3γ), we normalize on BR(Ke3): $R=\frac{BR(Ke3\gamma, E^{\star}_{\gamma}>10MeV)}{BR(Ke3)}$ is measured. For comparison with other experiments additional cut is applied: $0.6 < cos\theta^{\star}_{e\gamma} < 0.9$.The final result is

$R_1 = [0.48 \pm 0.02(stat) \pm 0.03(syst)] \times 10^{-2}$
(PDG04 value: $R_1 = [0.54 \pm 0.04] \times 10^{-2}$)

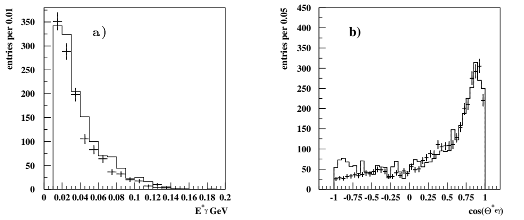

Figure 7. *E^*_γ and $cos\theta^{\star}_{e\gamma}$. Histogram - data, points with errors - MC*

To compare our result with theory, we apply another cuts: $E^{\star}_{\gamma} > 30MeV, \theta^{\star}_{e\gamma} > 20°$. Supposing PDG04 value for BR(Ke3) BR(Ke3γ,theor.cuts)$=(3.05 \pm 0.09) \times 10^{-4}$. Theory gives 2.8×10^{-4} (tree level) and 3.0×10^{-4} ($O(p^4)$ level).

For T-odd asymmetry, we get $A_\xi = -0.015 \pm 0.021$. This estimation is better than that of $K\mu3\gamma$ but still far from theoretical predicitons.

3. Recent result from KEK E470 on $K^+ \rightarrow \pi^+\pi^0\gamma$

Two terms give contribution to the decay amplitude: IB (inner bremsstrahlung) and DE (direct emission). For DE component, ChPT gives BR(DE)$=3.5\times10^{-6}$ while $1/N_c$ approach gives BR(DE)$=19.4\times10^{-6}$. Ambiguous situation exists both in theory and experiment(see [8] for details). Average BRs differ: BR(*old exp.*)$=(1.8 \pm 0.4) \times 10^{-5}$; BR(*new exp.*)$=(0.44 \pm 0.07) \times 10^{-5}$.

Recently an improved KEK E470 result on DE measurement has appeared[8]. E470 experimental setup is shown in fig. 8. Signal extraction procedure includes kaon identification, charged particle separation by TOF method, analysis of 3 photon events in CsI(Tl) calorimeter and background suppression. Total number of $K^+ \to \pi^+\pi^0\gamma$ events extracted for $115 < p^\star_\pi < 180 MeV/c$ is 10154.

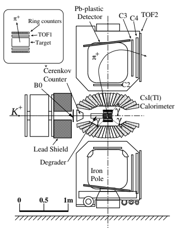

Figure 8. *KEK E470 setup*

To search for DE, it is suitable to use the variable W=$\frac{(p_k \times q_\gamma)(p_\pi \times q_\gamma)}{m^2(\pi^+) \times M^2(K^+)}$. Comparison of experimental data with MC for IB copmponent (fig. 9a) shows a strong evidence for DE. W-spectrum normalized on IB is shown in fig. 9b.

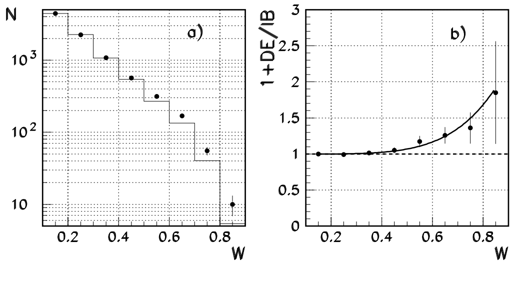

Figure 9. *W spectrum for $K^+ \to \pi^+\pi^0\gamma$*

The measurement of BR(DE) was carried out assuming zero interference between DE and IB. For the kinematical region $55 < T^\star(\pi^+) < 90MeV$ ($T^\star(\pi^+)$ being pion kinematical energy) BR(DE)=$[3.8\pm0.8(stat)\pm0.7(syst)]\times10^{-6}$ which is in good agreement with ChPT (3.5×10^{-6}) and disfavours 1/N$_c$ prediction.

4. conclusion

Now we summarize recent results on rare charged kaon decays from ISTRA+ and KEK E470:

- $K^- \to \mu^-\nu\gamma$ has been studied in a new kinematical region ($30 < E^\star_\gamma < 120MeV, 150 < E^\star_\mu < 230MeV$);
- $K^- \to \mu^-\nu\pi^0\gamma$ has been observed for the first time (~550 events);
- T-odd asymmetries are estimated for $K\mu3\gamma$ ($A_\xi = -0.03 \pm 0.13$) and $Ke3\gamma$ ($A_\xi = -0.015 \pm 0.021$);
- Precise measurement of BR(DE) in $K^+ \to \pi^+\pi^0\gamma$ (BR(DE)=$(3.8 \pm 1.1) \times 10^{-6}$) favours ChPT;
- The measured branching fractions are in reasonable agreement with theory.

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