Charm and beauty of pions and kaons: looking for chiral anomaly in $K\gamma \to K\pi$ reactions

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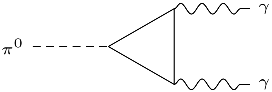
based on M.I.Vysotsky, E.V.Zhemchugov, : Phys. Rev. D 93, 094029 (2016)

IHEP experiment

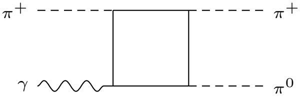
Charged and neutral pions photoproduction in charged kaons beam close to the threshold.

Firm theoretical prediction for neutral pion photoproduction near threshold from chiral anomaly.

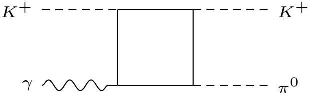
V. S. Burtovoy, Yadernaya Fizika i Inzhiniring 2014, 5, 724 [in Russian].



$$= -\frac{ie^2}{16\pi^2 F_\pi}\varepsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta} \qquad (F_\pi = 93 \text{ MeV})$$



$$= -\frac{ie}{8\pi^2 F_\pi^3}\varepsilon^{\mu\nu\alpha\beta}F_{\mu\nu}\partial_\alpha\pi^+\partial_\beta\pi^-\pi^0 \qquad \left(\times\frac{1}{eF_\pi^2}\right)$$



$$= -\frac{ie}{8\pi^2 F_\pi^3}\varepsilon^{\mu\nu\alpha\beta}F_{\mu\nu}\partial_\alpha K^+\partial_\beta K^-\pi^0$$

S. Adler, 1969, crucial for establishing QCD with 3 quark colors: $3 * (Q_u^2 - Q_d^2)$

Anomaly in $\pi\gamma \to \pi\pi$ amplitude:

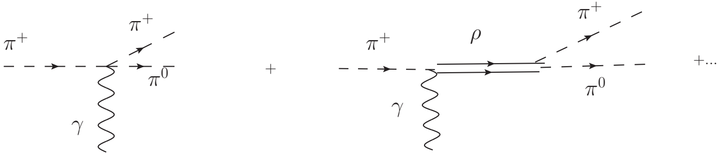
M.V.Terent'ev, Pisma ZhETF 14 (1971) 140

J.Wess, B.Zumino, Phys.Lett. 37B (95) 1971;
S.L.Adler, B.W.Lee, S.B.Treiman, A.Zee, Phys.Rev. D 4 (1971) 3497.

Process $\pi^\pm \to \pi^0\pi^\pm$ in the nuclear Coulomb field, M.V.Terent'ev, Phys. Lett. 38B (1972) 419.

$$M = A[1 + \frac{f_{\rho\pi\gamma} f_{\rho\pi\pi}}{h(0)} \frac{s}{(s - m_\rho^2) m_\rho^2} + ...]$$

subtraction at zero momenta are performed; "..." corresponds to the contributions of ρ in t- and u-channels and ω contribution.


π^+
π^+
π^0
γ
+
π^+
ρ
π^+
π^0
γ
+...

Experimental verification: Yu.M.Antipov et al.,Phys.Rev.D 36 (1987) 21.

40-GeV pion beam of the IHEP accelerator.

Theory:

$$h(0) = \frac{e}{4\pi^2 F_\pi^3} = 10\mathrm{GeV}^{-3}$$

Experiment, $s < 10m_\pi^2$,

$$F^{3\pi}(0) = 12.9 \pm 0.9 \pm 0.5 \pm 1.0\mathrm{GeV}^{-3},$$

VERY IMPORTANT: The last error is from the unknown phase of the ρ exchange contribution.

$$h \equiv F^{3\pi}$$

IHEP: $K^+\gamma \to K\pi$

Modern experiment: 18 GeV K^+ beam from U 70, coherent $(K\pi)$ production in forward region in the Coulomb field of a copper (Cu) nucleus.

2 theor papers: R.N.Rogalev, Yad Fiz 64 (2001) 72;
V.S.Burtovoy, Yad Fiz 76 (2013) 488.

Pions: only one amplitude: $\gamma \to \pi^+\pi^0\pi^-$ (C-parity, charge conservation)

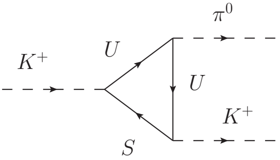
two amplitudes in case of charged kaons:

$K^+\gamma \to K^+\pi^0$ $\qquad$ $K^+\gamma \to K^0\pi^+$

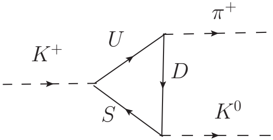
Only the first one has an anomaly: J.Wess, B.Zumino, Phys.Lett. 37B (95) 1971:

$$A = \frac{e}{4\pi^2 F_\pi^3}\epsilon_{\mu\nu\rho\sigma}F_{\mu\nu}\pi^0[\partial_\rho\pi^+\partial_\sigma\pi^- + \partial_\rho K^+\partial_\sigma K^-]$$

Why?

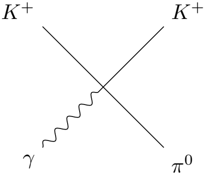


$2/3 + 2/3 - 1/3 = 1$

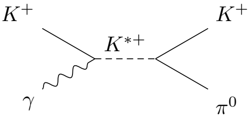


$2/3 - 1/3 - 1/3 = 0$

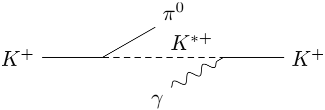
$K^+\gamma \to K^+\pi^0$



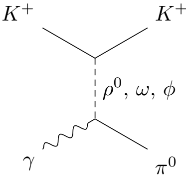
anomaly



s channel

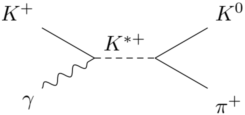


u channel

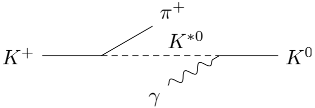


t channels

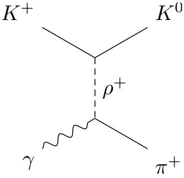
$K^+\gamma \to K^0\pi^+$



s channel



u channel



t channel

$$f_{K^{*+}K^+\pi^0} =$$
$$f_{K^{*+}K^0\pi^+} =$$
$$f_{K^{*0}K^+\pi^+} =$$
$$f_{\rho^0 K^+K^+} =$$
$$f_{\rho^+ K^+K^0} =$$
$$f_{\omega K^+K^+} =$$
$$f_{\phi K^+K^+} =$$
$$f_{K^{*+}K^+\gamma} =$$
$$f_{K^{*0}K^0\gamma} =$$
$$f_{\rho^0\pi^0\gamma} =$$
$$f_{\rho^+\pi^+\gamma} =$$
$$f_{\omega\pi^0\gamma} =$$
$$f_{\phi\pi^0\gamma} =$$

$\lvert f_{K^{*+}K^+\pi^0}\rvert$	$=$	3.10
$\lvert f_{K^{*+}K^0\pi^+}\rvert$	$=$	4.38
$\lvert f_{K^{*0}K^+\pi^+}\rvert$	$=$	4.41
$f_{\rho^0 K^+K^+}$	$=$	
$f_{\rho^+ K^+K^0}$	$=$	
$f_{\omega K^+K^+}$	$=$	
$\lvert f_{\phi K^+K^+}\rvert$	$=$	4.47
$\lvert f_{K^{*+}K^+\gamma}\rvert$	$=$	0.240 GeV^{-1}
$\lvert f_{K^{*0}K^0\gamma}\rvert$	$=$	0.385 GeV^{-1}
$\lvert f_{\rho^0\pi^0\gamma}\rvert$	$=$	0.252 GeV^{-1}
$\lvert f_{\rho^+\pi^+\gamma}\rvert$	$=$	0.219 GeV^{-1}
$\lvert f_{\omega\pi^0\gamma}\rvert$	$=$	0.696 GeV^{-1}
$\lvert f_{\phi\pi^0\gamma}\rvert$	$=$	0.040 GeV^{-1}

Decay widths:

$$\Gamma(K^* \to K\pi) \Longrightarrow |f_{K^*K\pi}|,$$
$$\Gamma(K^* \to K\gamma) \Longrightarrow |f_{K^*K\gamma}|,$$
$$\Gamma(\phi \to K^+K^+) \Longrightarrow |f_{\phi K^+K^+}|$$
$$\Gamma(\rho^+ \to \pi^+\gamma) \Longrightarrow |f_{\rho^+\pi^+\gamma}|,$$
$$\Gamma(\rho^0 \to \pi^0\gamma) \Longrightarrow |f_{\rho^0\pi^0\gamma}|,$$
$$\Gamma(\omega \to \pi^0\gamma) \Longrightarrow |f_{\omega\pi^0\gamma}|,$$
$$\Gamma(\phi \to \pi^0\gamma) \Longrightarrow |f_{\phi\pi^0\gamma}|,$$

$f_{K^{*+}K^+\pi^0}$	$=$	3.10
$f_{K^{*+}K^0\pi^+}$	$=$	4.38
$f_{K^{*0}K^+\pi^+}$	$=$	4.41
$f_{\rho^0K^+K^+}$	$=$	3.16
$f_{\rho^+K^+K^0}$	$=$	-4.47
$f_{\omega K^+K^+}$	$=$	3.16
$f_{\phi K^+K^+}$	$=$	-4.47
$f_{K^{*+}K^+\gamma}$	$=$	$0.240\ \text{GeV}^{-1}$
$f_{K^{*0}K^0\gamma}$	$=$	$-0.385\ \text{GeV}^{-1}$
$f_{\rho^0\pi^0\gamma}$	$=$	$0.252\ \text{GeV}^{-1}$
$f_{\rho^+\pi^+\gamma}$	$=$	$0.219\ \text{GeV}^{-1}$
$f_{\omega\pi^0\gamma}$	$=$	$0.696\ \text{GeV}^{-1}$
$\lvert f_{\phi\pi^0\gamma}\rvert$	$=$	$0.040\ \text{GeV}^{-1}$

Decay widths:

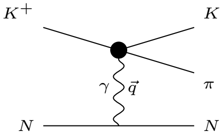
$$\Gamma(K^* \to K\pi) \implies |f_{K^*K\pi}|,$$
$$\Gamma(K^* \to K\gamma) \implies |f_{K^*K\gamma}|,$$
$$\Gamma(\phi \to K^+K^+) \implies |f_{\phi K^+K^+}|$$
$$\Gamma(\rho^+ \to \pi^+\gamma) \implies |f_{\rho^+\pi^+\gamma}|,$$
$$\Gamma(\rho^0 \to \pi^0\gamma) \implies |f_{\rho^0\pi^0\gamma}|,$$
$$\Gamma(\omega \to \pi^0\gamma) \implies |f_{\omega\pi^0\gamma}|,$$
$$\Gamma(\phi \to \pi^0\gamma) \implies |f_{\phi\pi^0\gamma}|,$$

$SU(3)$ symmetry:

$$\sqrt{2}f_{K^{*+}K^+\pi^0} = f_{K^{*+}K^0\pi^+} = f_{K^{*0}K^+\pi^+} = -f_{\rho^+K^+K^0}$$
$$= \sqrt{2}f_{\rho^0K^+K^+} = \sqrt{2}f_{\omega K^+K^+} = -f_{\phi K^+K^+}$$

$$f_{K^{*+}K^+\gamma} = f_{\rho^+\pi^+\gamma} = f_{\rho^0\pi^0\gamma} = \frac{1}{3}f_{\omega\pi^0\gamma} = -\frac{1}{2}f_{K^{*0}K^0\gamma}$$

Sign ambiguity.



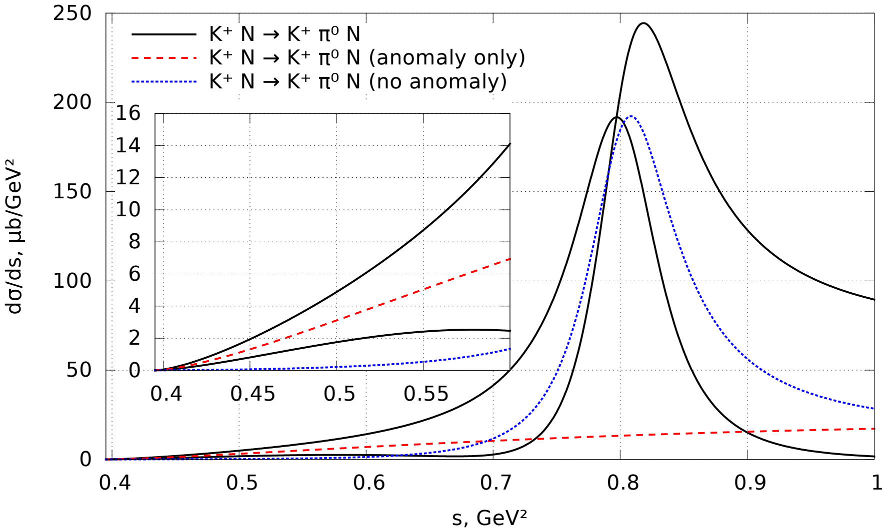
Equivalent photons approximation:

$$\frac{d\sigma(K^+N \to K\pi N)}{dt\ ds\ dq_\perp^2} = \frac{Z^2\alpha}{\pi(s-m_{K^+}^2)} \frac{q_\perp^2}{\left(q_\perp^2 + \left(\frac{s-m_{K^+}^2}{2E_K}\right)^2\right)^2} \frac{d\sigma(K^+\gamma \to K\pi)}{dt} |F(\vec{q}^{\,2})|^2$$

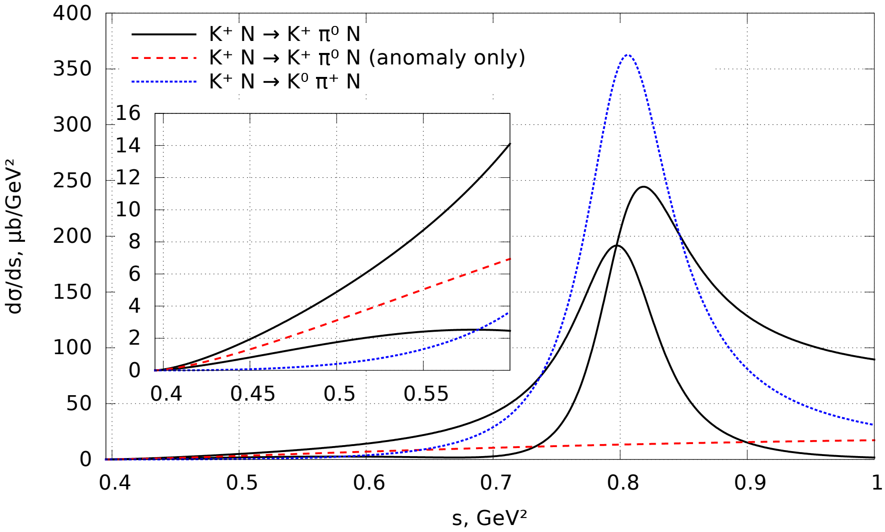
$$F(\vec{q}^{\,2}) = \exp\left(-\frac{\langle r^2\rangle q_\perp^2}{6}\right)$$

$$\frac{d\sigma(K^+N \to K\pi N)}{dt\ ds} = \frac{Z^2\alpha}{\pi} \frac{E_1(a)-1}{s-m_{K^+}^2} \frac{d\sigma(K^+\gamma \to K\pi)}{dt}$$

$$E_1(a) = \int\limits_a^\infty \frac{\mathrm{e}^{-z}}{z} dz,\ a = \frac{\langle r^2\rangle}{3}\left(\frac{s-m_{K^+}^2}{2E_K}\right)^2.$$



K+ N → K+ π0 N
K+ N → K+ π0 N (anomaly only)
K+ N → K+ π0 N (no anomaly)
dσ/ds, μb/GeV²
s, GeV²
250
200
150
100
50
0
0.4
0.5
0.6
0.7
0.8
0.9
1
16
14
12
10
8
6
4
2
0
0.4
0.45
0.5
0.55



K⁺ N → K⁺ π⁰ N
K⁺ N → K⁺ π⁰ N (anomaly only)
K⁺ N → K⁰ π⁺ N
dσ/ds, μb/GeV²
s, GeV²
400
350
300
250
200
150
100
50
0
0.4
0.5
0.6
0.7
0.8
0.9
1
16
14
12
10
8
6
4
2
0
0.4
0.45
0.5
0.55

Conclusions

Comparing experimental data on cross sections of
$K^+N \longrightarrow K^+\pi^0 N$ and $K^+N \longrightarrow K^0\pi^+ N$
reactions close to the threshold in forward direction it should be possible to single out the effect of anomaly in
$K^+\gamma \to K^+\pi^0$ reaction.