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Study of the $K^- \to \pi^0 e^- \nu$ decay

I.V. Ajinenko, S.A. Akimenko, G.A. Akopdzhanov, K.S. Belous, I.G. Britvich, G.I. Britvich, A.P. Filin, V.N. Govorun, A.V. Inyakin, V.F. Konstantinov, A.S. Konstantinov, I.Y. Korolkov, V.A. Khmelnikov, V.M. Leontiev, V.P. Novikov, V.F. Obraztsov, V.A. Polyakov, V.I. Romanovsky, V.M. Ronjin, V.A. Senko, N.A. Shalanda, M.M. Shapkin, V.I. Shelikhov, N.E. Smirnov, A.A. Sokolov, O.G. Tchikilev, E.V. Vlasov, O.P. Yushchenko.

Institute for High Energy Physics, Protvino, Russia

V.N. Bolotov, S.V. Laptev, A.Yu. Polyarush, V.E. Postoev

Institute for Nuclear Research, Moscow, Russia

S.V. Yaschenko, B.Zh. Zalikhanov, V.Z. Serdyuk.

Joint InstituteforNuclearResearch, Dubna, Russia

Abstract

The decay $K^- \to \pi^0 e^- \nu$ has been studied using in-flight decays detected with "ISTRA+" setup operating at the 25 GeV negative secondary beam of the U-70 PS. About 130K events were used for the analysis. The λ_+ parameter of the vector formfactor has been measured: $\lambda_+ = 0.0293 \pm 0.0015(stat) \pm 0.002(syst)$. The limits on the possible tensor and scalar couplings have been derived:

$$f_T/f_+(0) = -0.044^{+0.059}_{-0.057} \text{ (stat)}$$

$$f_S/f_+(0) = -0.020^{+0.025}_{-0.016} \text{ (stat)}$$

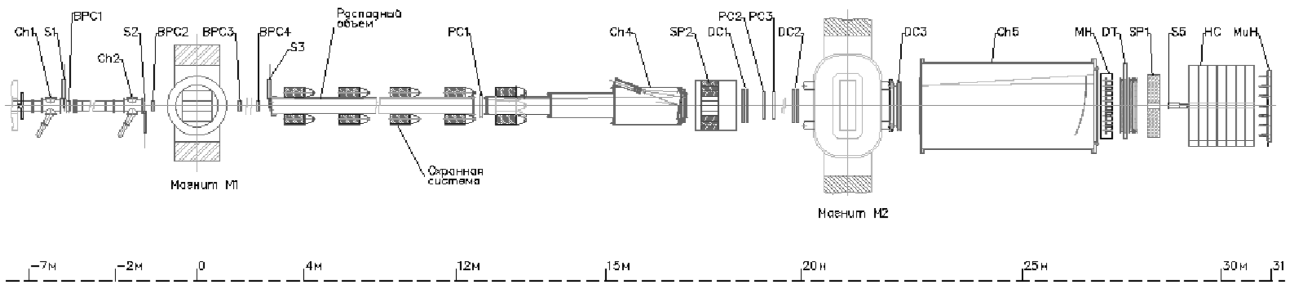

Figure 1: The layout of the "ISTRA+" setup.

1 Introduction

The decay $K \to e\nu\pi^0(\mathrm{K}_{e3})$ is known to be a promising one to search for an admixture of scalar (S) or tensor (T) interactions to the Standard Model (SM) V-A . This topic has been attracting significant interest during resent years and moreover some previous experiments with charged and neutral kaon beams have reported indications for some anomalous S and T signals [1], [2]. On the other hand, resent KEK [3, 4] experiment with stopped K^+ beam has reported negative results of the searches.

In our analysis we present new search for S and T couplings based on the statistics of about 130K Ke3 events. Another result of our study is the measurement of the V-A $f_+(t)$ formfactor slope λ_+.

2 Experimental setup

The experiment is performed at the IHEP 70 GeV proton synchrotron U-70. The experimental apparatus "ISTRA+" is the result of the modification of "ISTRA-M" [5], which, in turn, evolved from "ISTRA" that yielded important results on π^- and K^- decays in the late 1980's [6]. The setup is located at the 4A negative unseparated secondary beam. The beam momentum in the measurements is ~ 25 GeV with $\Delta p/p \sim 2\%$. The admixture of K^- in the beam is $\sim 3\%$. The beam intensity is $\sim 3 \cdot 10^6$ per 1.9 sec. U-70 spill. A schematic view of the detector is shown in Fig.1. The momentum of the beam particle deflected by M_1 is measured by $BPC_1 \div BPC_4$ PC's with 1mm wire step, the kaon identification is done by $\check{C}_1 \div \check{C}_3$ threshold $\check{C}$–counters. The 9 meter long vacuumated decay volume is surrounded by 8 lead glass rings $LG_1 \div LG_8$ used to veto low energy photons. The same role is played by SP_2– a 72–cell lead glass calorimeter. The decay products deflected in M2 with 1Tm field integral are measured with $PC_1 \div PC_3$– 2mm step proportional chambers; $DC_1 \div DC_3$– 1cm cell drift chambers and finally with 2cm diameter drift tubes $DT_1 \div DT_4$. A wide aperture threshold Cerenkov counter $\check{C}_4$ is filled with He and used to trigger the electrons. SP_1 is a 576-cell lead glass calorimeter, followed by HC – a scintillator-iron sampling hadron calorimeter, subdivided into 7 longitudinal sections 7×7 cells each. MH is a 11×11 cell scintillating hodoscope, used to solve the ambiguity for multitrack events and improve the time resolution of the tracking system, MuH is a 7×7 cell

muon hodoscope.
The trigger is provided by $S_1 \div S_5$ scintillation counters, $\check{C}_1 \div \check{C}_3$ Cerenkov counters, analog sum of amplitudes from the last dinodes of the SP_1 and is very loose: $T = S_1 \cdot S_2 \cdot S_3 \cdot \bar{S}_4 \cdot \check{C}_1 \cdot \bar{\check{C}}_2 \cdot \bar{\check{C}}_3 \cdot \bar{S}_5 \cdot \Sigma(SP_1)$, here S4 is a scintillator counter with a hole to suppress beam halo ; $S5$ is a counter downstream the setup at the beam focus; $\Sigma(SP_1)$ – a requirement for the analog sum of amplitudes from SP_1 to be larger than ∼700 MeV – a MIP signal. The last requirement surveys to suppress the $K \rightarrow \mu\nu$ decay. Some complementary triggers: $T_e = S_1 \cdot S_2 \cdot S_3 \cdot \bar{S}_4 \cdot \bar{S}_5 \cdot \check{C}_4$ – the electron trigger and prescaled "decay" trigger $T_d = S_1 \cdot S_2 \cdot S_3 \cdot \bar{S}_4 \cdot \bar{S}_5$ were used to cross-check the efficiency of the main one.

The main difference between "ISTRA-M" and "ISTRA+" is in the electronics and DAQ: all the CAMAC based electronics was changed by IHEP developed MICC [7] ECL-based electronics. "ISTRA+" has now 12 MICC crates with ADC's, TDC's and latches. The DAQ, described in some details in [8] is based on IHEP-developed VME master V-08 [9], which writes the MICC stream into standard VME memory. Between the spills, the information is written into PC through BIT-3 VME-PCI interface. The saturated event rate is ∼ 6500 of 1 Kb events per 1.9 sec. spill.

3 Event selection

During physics runs in November–December 1999 and March–April 2001, 206M and 363M events were logged on DLT's. This information is supported by about 100M MC events generated with Geant3 [10]. MC generation includes realistic description of the setup: decay volume entrance windows, track chambers windows, gas, sense wires and cathode structure, Cerenkov counters mirrors and gas, shower generation in EM calorimeters etc.

The usual first step of the data processing is the EM calorimeter calibration, using special runs with 10 GeV electrons; track system alignment, HCAL and guard system calibration with muon beam runs. The data processing starts with the beam particle reconstruction in $BPC_1 \div BPC_4$, then the secondary tracks are looked for in $PC_1 \div PC_3$; $DC_1 \div DC_3$; $DT_1 \div DT_4$ and events with one good negative track are selected. The decay vertex is searched for, and a cut is introduced on the matching of incoming and decay track. The next step is to look for showers in SP_2 calorimeter. A method of shower parameters reconstruction based on the MC–generated patterns(∼ 2000 3×3 patterns) of showers is used. The matching of the charged track and a shower in SP_2 is done on the basis of the difference between the track extrapolation and the shower coordinates. The electron identification is done using E/P ratio – of the energy of the shower associated with the track and the track momentum, see Fig.2. The selection of events with the two extra showers results in $M_{\gamma\gamma}$ spectrum shown in Fig.3. The π^0 peak has a mass of $M_{\pi 0} = 134.8 MeV$, and a resolution of 8.6 MeV. Another important variable for the $K^- \rightarrow e\nu\pi^0$ selection is the missing mass squared: $(P_K - P_e - P_{\pi^0})^2$, where P are the corresponding four-momenta, see Fig.4. The cut is ±0.01 GeV^2. The further selection is done by the requirement that the event passes 2C $K \rightarrow e\nu\pi^0$ fit. At the same time, similar 2C fit $K \rightarrow \pi^-\pi^0$ should fail. The missing energy $E_K - E_e - E_{\pi^0}$ after this selection is shown in Fig.5 The peak at low E_{miss} corresponds to the remaining $K^- \rightarrow \pi^-\pi^0$ background. The

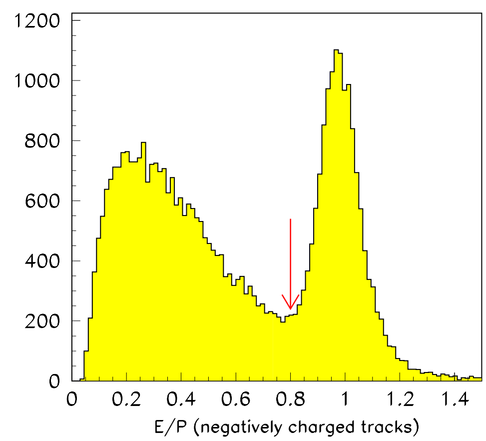

Figure 2: The E/p plot – the ratio of the energy of the associated cluster in ECAL to the momentum of the charged track. The arrow shows the cut used for the electron separation.

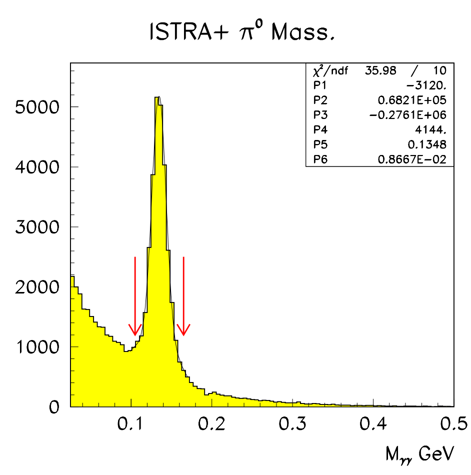

Figure 3: The $\gamma\gamma$ mass spectrum for the events with the identified electron and two extra showers.

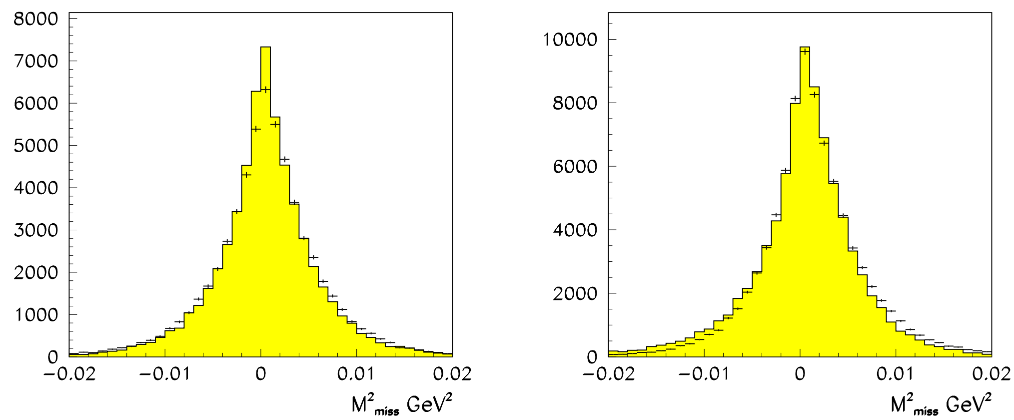

Figure 4: The missing four-momentum squared $(P_K - P_e - P_{\pi^0})^2$ for the selected events for 1999 run (left) and 2001 run (right). The points with errors are the data, the histogram – MC.

corresponding cut is $E_{miss} > 1GeV$. The surviving background is estimated from MC to be less than 3%.

The detailed data reduction information is shown in Table.1.

4 Analysis

The event selection described in the previous section results in selected 54K events in 1999 data and 79K events in 2001 data. The distribution of the events over the Dalitz plot is shown in Fig.6. The variables $y = 2E_e/M_K$ and $z = 2E_\pi/M_K$, where E_e, E_π are the energies of the electron and π^0 in the kaon c.m.s are used. The background events, as MC shows, occupy the peripheral part of the plot.

The most general Lorentz invariant form of the matrix element for the decay $K^- \to l^- \nu \pi^0$ is [11]:

$$M = \frac{G_F sin\theta_C}{\sqrt{2}} \bar{u}(p_\nu)(1+\gamma^5)[m_K f_S - \frac{1}{2}[(P_K + P_\pi)_\alpha f_+ + (P_K - P_\pi)_\alpha f_-]\gamma^\alpha + i\frac{f_T}{m_K}\sigma_{\alpha\beta}P_K^\alpha P_\pi^\beta]v(p_l) \quad (1)$$

It consists of scalar, vector and tensor terms. $f_S, f_T, f_\pm$ are the functions of $t = (P_K - P_\pi)^2$. In the Standard Model (SM) the W-boson exchange leads to the pure vector term. The "induced" scalar and/or tensor terms, due to EW radiative corrections are negligible small, i.e the nonzero scalar/tensor form factors indicate a physics beyond SM.

The term in the vector part, proportional to f_- is reduced(using Dirac equation) to a scalar formfactor. In the same way, the tensor term is reduced to a mixture of a scalar and a vector

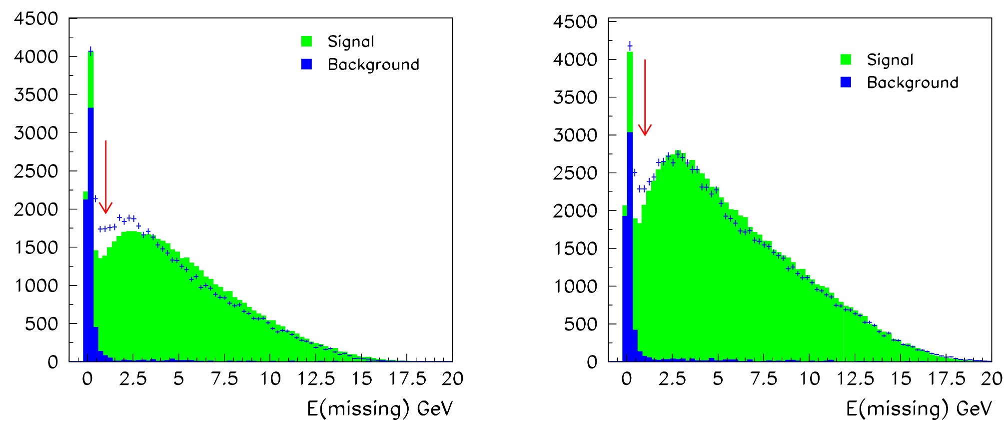

Figure 5: The missing energy for the $e\pi^0$ events, for 1999 run (left) and 2001 run (right). The points with errors are the data, the histograms – MC. The dark(blue) peak at zero value corresponds to the MC-predicted $K \to \pi^-\pi^0$ background. The arrow indicates the cut value.

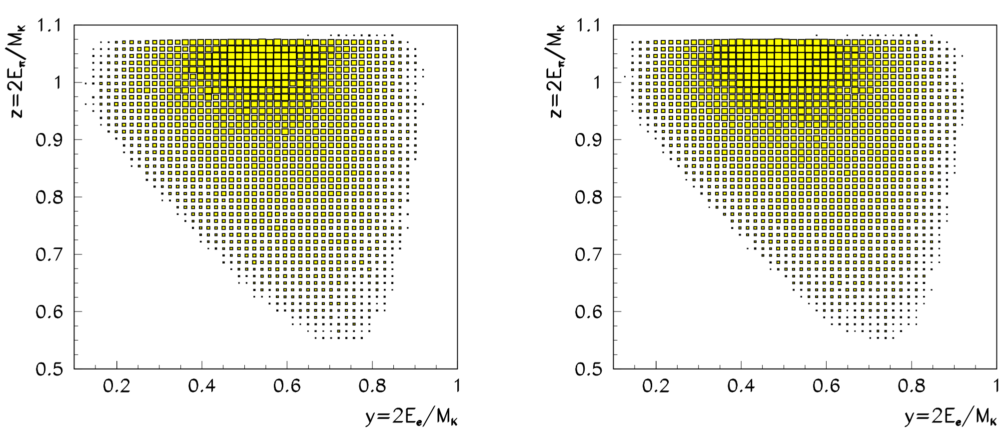

Figure 6: Dalitz plots ($y = 2E_e/M_K; z = 2E_{\pi^0}/M_K$) for the selected $K \to e\nu\pi^0$ events after the 2-C fit. Left – 1999 statistics, Right – 2001 statistics.

Table 1: Event reduction statistics. The main steps are shown for the 1999 and 2001 runs .

Run	1999	2001
N_{events} on tapes	206.544.909	363.002.105
Beam track reconstructed	159.459.629=77%	268.564.958 =74 %
One secondary track found	81.166.929=41%	134.227.095 =37%
Written to DST	70.015.610 =34%	107.215.783 =30 %
e^- identified	1.300.958	1.998.719
2 showers reconstructed	252.177	361.621
π^0 identified	186.850	251.489
$\lvert M^2_{miss}\rvert < 0.01$	96.652	144.642
$K \to \pi^-\pi^0$ rejected	79.660	117.566
$K \to e\nu\pi^0$ accepted	65.208	97.585
$E_{miss} > 1$ GeV	54.009	79.248

formfactors. The redefined f_+(V), F_S(S) and the corresponding Dalitz plot density in the kaon rest frame($\rho(E_\pi, E_l)$) are [12]:

$$\begin{aligned}
V &= f_+ + (m_l/m_K)f_T \\
S &= f_S + (m_l/2m_K)f_- + \left(1 + \frac{m_l^2}{2m_K^2} - \frac{2E_e}{m_K} - \frac{E_\pi}{m_K}\right) f_T \\
\rho(E_\pi, E_l) &\sim A \cdot |V|^2 + B \cdot Re(V^* S) + C \cdot |S|^2 \qquad (2) \\
A &= m_K(2E_l E_\nu - m_K \Delta E_\pi) - m_l^2(E_\nu - \frac{1}{4}\Delta E_\pi) \\
B &= m_l m_K(2E_\nu - \Delta E_\pi) \\
C &= m_K^2 \Delta E_\pi \\
\Delta E_\pi &= E_\pi^{max} - E_\pi
\end{aligned}$$

In case of Ke3 decay one can neglect the terms proportional to m_l; m_l^2. Then, assuming linear dependence of f_+ on t: $f_+(t) = f_+(0)(1 + \lambda_+ t/m_\pi^2)$ and real constants f_S, f_T we get:

$$\begin{aligned}
\rho(E_\pi, E_l) &\sim m_K(2E_l E_\nu - m_K \Delta E_\pi) \cdot (1 + \lambda_+ t/m_\pi^2)^2 \\
&+ m_K^2 \Delta E_\pi \cdot \left(\frac{f_S}{f_+(0)} + \left(1 - \frac{2E_e}{m_K} - \frac{E_\pi}{m_K}\right)\frac{f_T}{f_+(0)}\right)^2 \qquad (3)
\end{aligned}$$

The procedure for the experimental extraction of the parameters λ_+, f_S, f_T starts from the subtraction of the MC estimated background from the Dalitz plots of Fig.6. The background normalization was determined by the ratio of the real and generated $K^- \to \pi^-\pi^0$ events. Then the Dalitz plots were subdivided into 20×20 cells. The background subtracted distribution of the numbers of events in the cells (i,j) over Dalitz plots, for example, in the case of simultaneous extraction of λ_+ and $\frac{f_S}{f_+(0)}$, was fitted with the function:

$$\rho(i,j) \sim W_1(i,j) + W_2(i,j) \cdot \lambda_+ + W_3(i,j) \cdot \lambda_+^2 + W_4(i,j) \cdot \left(\frac{f_S}{f_+(0)}\right)^2 \tag{4}$$

Here W_l are MC-generated functions, which are build up as follows: the MC events are generated with constant density over the Dalitz plot and reconstructed with the same program as for the real events. Each event carries the weight w determined by the corresponding term in formula 3, calculated using the MC-generated values for y and z. The radiative corrections according to [13] were taken into account. Then W_l is constructed by summing up the weights of the events in the corresponding Dalitz plot cell. This procedure allows to avoid the systematics errors due to the "migration" of the events over the Dalitz plot because of the finite experimental resolution.

5 Results

The results of the fit are summarized in Table.2. The combination of the two runs is done by the simultaneous fit. The first line corresponds to pure V-A SM fit. In the second line the tensor and in the third the scalar terms are added into the fit. All the errors presented are from the "MINOS" procedure of the "MINUIT" program [14] and are larger than the Gaussian ones. At present, we estimate an additional systematics error in λ_+ to be ± 0.002. The estimate is done by comparing two runs, which differ a lot in amount of matter in the beamline and detector configuration and by varying cuts, cell size during the fit of the Dalitz plots etc.

The comparison of our results with the most recent $K^\pm$ data [1, 3, 4] shows that our statistics, at present, is the highest in the world and the statistical errors somewhat smaller than in [1, 3] and comparable with [4]. We do not confirm the observation of a significant f_S and f_T in [1]. Our data is in a good agreement with [3, 4] and with the theoretical calculations for λ_+: $\lambda_+ = 0.031$ [15], done in the context of the chiral perturbation theory.

6 Summary and conclusions

The K^-_{e3} decay has been studied using in-flight decays of 25 GeV K^-, detected by "ISTRA+" magnetic spectrometer. Due to the high statistics, adequate resolution of the detector and good sensitivity over all the Dalitz plot space, the measurement errors are significantly reduced as compared with the previous measurements. The λ_+ parameter of the vector formfactor has been measured to be:

$$\lambda_+ = 0.0293 \pm 0.0015(stat) \pm 0.002(syst).$$

Table 2: Results of the fit.

	1999	2001	1999+2001
λ_+	$0.0271^{+0.0023}_{-0.0023}$	$0.0310^{+0.0019}_{-0.0019}$	$0.0293^{+0.0015}_{-0.0015}$
λ_+	$0.0270^{+0.0023}_{-0.0023}$	$0.0310^{+0.0019}_{-0.0019}$	$0.0293^{+0.0015}_{-0.0015}$
$f_T = F_T/f_+(0)$	$-0.0388^{+0.0878}_{-0.0848}$	$-0.0487^{+0.0806}_{-0.0754}$	$-0.0445^{+0.0597}_{-0.0574}$
λ_+	$0.0268^{+0.0024}_{-0.0027}$	$0.0304^{+0.0022}_{-0.0024}$	$0.0289^{+0.0017}_{-0.0018}$
$f_S = F_S/f_+(0)$	$-0.0139^{+0.0338}_{-0.0259}$	$-0.0225^{+0.0355}_{-0.0187}$	$-0.0197^{+0.0252}_{-0.0163}$
χ^2/ndf	1.7	1.3	1.5
N_{bins}	225	228	

The limits on the possible tensor and scalar couplings have been derived:

$$f_T/f_+(0) = -0.044^{+0.059}_{-0.057};$$

$$f_S/f_+(0) = -0.020^{+0.025}_{-0.016}$$

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