SEMILEPTONIC $\mathrm{K_L}$ DECAYS AT NA48

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Preliminary results on $K_L \to \pi e \nu(\gamma)$ decays collected by the NA48 detector at the CERN SPS are reported. Using a sample of 6.8×10^6 reconstructed events $BR(\mathrm{K^0_{e3}}) = 0.4010 \pm 0.0028 \pm 0.0035$ was obtained. From the branching ratio the value of $|V_{us}| = 0.2187 \pm 0.0028$ was extracted. The same data sample has provided also a high precision measurement of the slope λ_+ of the form factor of the $\mathrm{K^0_{e3}}$ decay. Investigating the $\mathrm{K^0_{e3\gamma}}$ decay, from a sample of 18977 reconstructed events, $BR(\mathrm{K^0_{e3\gamma}})/BR(\mathrm{K^0_{e3}}) = (0.964 \pm 0.008^{+0.012}_{-0.011})\%$ was determined.

1 Introduction

The NA48 experiment at the CERN SPS has been exploited in a rich program of kaon physics. The existence of direct CP violation in the decay of two pions was demonstrated and many rare kaon decay searches as well as high precision measurements have been carried out.
Here will be reported three recent measurements of semileptonic $\mathrm{K_L}$ decays, namely the $\mathrm{K^0_{e3}}$ branching ratio together with a determination of the CKM matrix element $|V_{us}|$, the $\mathrm{K^0_{e3}}$ form factors and the $\mathrm{K^0_{e3\gamma}}$ branching ratio.
The most relevant component of the NA48 detector [1] are a high resolution liquid–krypton electromagnetic calorimeter and a magnetic spectrometer consisting of 4 drift chambers and a dipole magnet located inside a helium tank. Other components are a hodoscope for precise track time determination, a hadronic calorimeter and a muon veto.
The data sample used for all the three analyses was taken in 1999 during a dedicated minumum bias run without K_S beam; similar selection criteria were adopted throughout in order to select the events.

2 Physics Motivations for the Study of Kaon Semileptonic Decays

The renewed interest in the study of the semiletponic $\mathrm{K_L}$ decays is related to the long standing problem about the unitarity of the CKM matrix. The unitarity of the CKM matrix requires for the first row that:

$$|V_{ud}|^2 \ + \ |V_{us}|^2 \ + \ |V_{ub}|^2 \ = \ 1 \tag{1}$$

a significant departure from unity in this relation would imply the breaking of unitarity and the existence of new physics. PDG 2004 [2] values indicates a 2.2 σ deviation from unity and $|V_{us}|$ is responsible for about 50% of the error. $|V_{us}|$ can be extracted from the kaon semileptonic decays ($K_{\ell 3}, \ell = e, \mu$) width via the relation:

$$\Gamma_{K\ell 3} \ = \ \frac{G_F^2 M_K^5}{192\pi^3} \ S_{EW}(1+\delta_K^\ell) \ C^2 \ |V_{us}|^2 \ f_+^2(0) \ I_K^\ell(\lambda_+, \lambda_0) \tag{2}$$

where G_F is the Fermi coupling constant, M_K the kaon mass, S_{EW} and δ_K^ℓ the short and the long distance radiative corrections, C^2 is 1 for K_L^0 and 1/2 for $K^\pm$ decays, $f_+(0)$ is the calculated form factor at zero momentum transfer and finally $I_K^\ell(\lambda_+, \lambda_0)$ is the phase space integral which depends on the two form factors which describe the decay. Being pure vector transitions the $K_{\ell 3}$ decays suffer only from second order corrections in the simmetry breaking and therefore are the most accurate and theoretically cleanest way to extract $|V_{us}|$.
Recent measurements from K_{e3}^+ [3] and $\mathrm{K_{e3}^0}$ (KTeV [4], KLOE [7] for K_S) are significantly above PDG values "restoring" unitarity, however their branching ratio are not in agreement with PDG averages. New experimental (and theoretical) inputs are therefore needed to clarify the situation.

3 $\mathrm{K_L} \rightarrow \ \pi^\pm \ \mathrm{e}^\mp \ \nu_\mathrm{e}$ Branching Ratio and Extraction of $|V_{us}|$

The determination of the $BR(K_{e3})$ proceeds through the measurement of the ratio R of the decay rate of $\mathrm{K_{e3}^0}$ relative to all decays with two charged particles in the final state ($2T$), namely $\pi e \nu$, $\pi e \mu$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-$, and 3 π^0 with Dalitz decay of one π^0.

$$R \ = \ \frac{\Gamma(K_{e3})}{\Gamma(2T)} \ = \ \frac{N_{Ke3}/A_{Ke3}}{N_{2T}/A_{2T}} \tag{3}$$

N_i and A_i being the number of reconstructed events and the acceptance, respectively. Since the BRs of the neutral channels have been measured, the sum of BRs of all $\mathrm{K_L}$ decay modes with two charged tracks $BR(2T)$ is experimentally known:

$$BR(2T) = 1 - BR(All \ Neutral) = 1.0048 - BR(3\pi^0) \tag{4}$$

and $BR(K_{e3})$ can be derived from R : $BR(K_{e3}) \ = \ R \times BR(2T)$. The $\mathrm{K_{e3}^0}$ events were selected using exactly the same selection as the $2T$ events with in addition the requirement of e identification from the LKr calorimeter. This was done (see Fig. 1a) requiring $E/p > 0.93$ where E is the energy released in the calorimeter and p is the track momentum measured in the spectrometer. The number of $\mathrm{K_{e3}^0}$ accepted events amounts to 6.8 10^6. The background from $K_{\mu 3}/K_{3\pi}$ events with a π misidentified as an electron was estimated from $\mathrm{K_{e3}^0}$ data with identified e ($E/p > 1$) and is 5.8 10^{-3}. The inefficiency of electron ID is determined from $\mathrm{K_{e3}^0}$ data with identified π ($0.3 < E/p < 0.7$) and its value is 4.9 10^{-3}. The detector response was reproduced using a GEANT based simulation. The average two track acceptance was obtained from a mean of the individual acceptances weighted with their BR. These were evaluated combining together PDG and the recent KTeV [5] results. We obtained [6] $R = 0.4975 \pm 0.0035$ and $BR(K_{e3}) = 0.4010 \pm 0.0028_{exp} \pm 0.0035_{norm}$ where the first error is the complete experimental

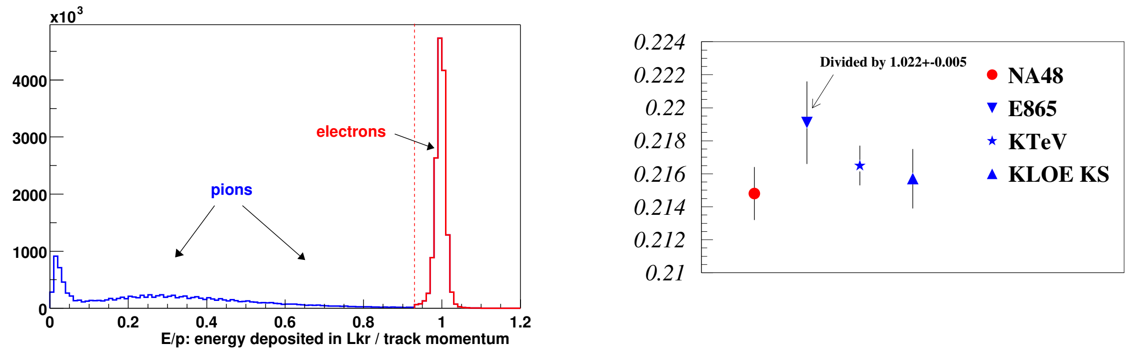

Figure 1: (a) E/p distribution of selected K^0_{e3} events. (b) Recent experimental results for $|V_{us}|f_+(0)$.

error and the second one is from the normalization. To determine $|V_{us}|$ we followed the prescription of Ref. [8] obtaining $|V_{us}|f_+(0) = 0.2146 \pm 0.0016$. Using their value of $f_+(0) = 0.981 \pm 0.010$ we get:

$$|V_{us}| \;=\; 0.2187 \pm 0.0016_{exp} \pm 0.0023_{theo} \tag{5}$$

The experimental number of $|V_{us}|f_+(0)$ is in agreement with the recent KTeV results [4] but larger than the PDG one. The result on $|V_{us}|$ is still 2.4 σ lower than what required by CKM unitarity and it is dominated by the theoretical uncertainties.

4 $\mathrm{K_L} \to \pi^{\pm}\, \mathrm{e}^{\mp}\, \nu_{\mathrm{e}}$ Form Factors

Assuming that only the vector coupling contributes to the decay, the matrix element can be written in terms of two dimensionless form factors $f_\pm(t)$:

$$\mathfrak{M} = G_F/\sqrt{2}\; V_{us}\; [f_+(t)\,(P_K + P_\pi)^\mu\, \bar{u}_\ell \gamma_\mu (1+\gamma_5) u_\nu + f_-(t)\; m_\ell \bar{u}_\ell (1+\gamma_5) u_\nu] \tag{6}$$

where m_ℓ is the lepton mass, $\bar{u}_\ell$ and u_ν are the lepton spinors and P_K and P_π are the kaon and pion four–momenta respectively. Since the contribution of f_- is proportional to the lepton mass squared it can be neglected in K^0_{e3} decays. The determination of the form factor is based on the measurement of the Dalitz plot density:

$$\rho(E^*_e, E^*_\pi) = \frac{dN^2(E^*_e, E^*_\pi)}{dE^*_e\; dE^*_\pi} \propto f^2_+(t)\; A \tag{7}$$

A is a kinematical term and E^*_e and E^*_π are the electron and pion energies in the kaon c.m., respectively. An usual assumption is that the form factor depends lineraly on t (the square of the four–momentum transferred to the lepton system): $f_+(t) = f_+(0)(1 + \lambda_+ t/m^2_\pi)$.
A fit comparing the data and the MC expectations was performed in order to extract the form factors. The results, allowing also for scalar (f_S) and tensor (f_T) contributions to the decay, are:

$$\begin{aligned} \lambda_+ &= 0.0284 \pm 0.0007_{stat} \pm 0.0013_{syst} \\ \left|\frac{f_S}{f_+(0)}\right| &= 0.015^{+0.007}_{-0.010}\,{}_{stat} \pm 0.012_{syst} \\ \left|\frac{f_T}{f_+(0)}\right| &= 0.05^{+0.03}_{-0.04}\,{}_{stat} \pm 0.03_{syst} \end{aligned} \tag{8}$$

The results do not support any evidence for scalar or tensor couplings, if the fit is done assuming only the vector contribution one gets:

$$\lambda_+ \;=\; 0.0288 \pm 0.0005_{stat} \pm 0.0011_{syst} \tag{9}$$

Figure 2b shows the comparison between the experimental results for the slope λ_+.

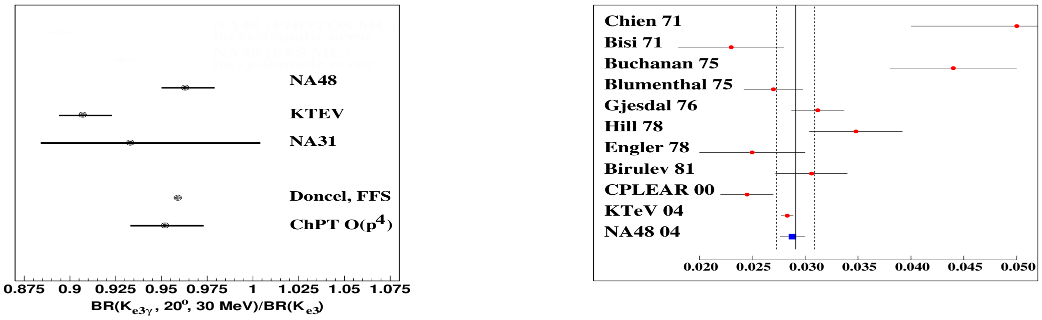

Figure 2: (a) Comparison between the measured values and theoretical predictions of the ratio $BR(\mathrm{K}^0_{e3\gamma})/BR(\mathrm{K}^0_{e3})$. (b) Experimental results for the slope λ_+ of K^0_{e3} decays.

5 $\mathrm{K_L} \to \pi^{\pm} \mathrm{e}^{\mp} \nu_{\mathrm{e}}\gamma$ Branching Ratio

In total 18977 $\mathrm{K_L} \to \pi^{\pm} \mathrm{e}^{\mp} \nu_{\mathrm{e}}\gamma$ events have been reconstructed from the data sample. The events are selected in the same manner as the K^0_{e3} events adding the requirement of exactly one γ in the LKr calorimeter. To take into account the effect of the radiative corrections (real and virtual) the Monte Carlo events, generated with the PHOTOS [9] package, were modified in order to reproduce the data. This was achieved by weighting the MC events with the distribution, obtained from the data, of $\theta^*_{e\gamma}$ the angle between the electron and the photon in the kaon c.m. In this way the agreement between data and MC has been found very good for all the variables. The preliminary result of the branching ratio measurement is:

$$\frac{BR(K_L \to \pi^{\pm} e^{\mp} \nu_e\gamma,\ E^*_\gamma > 30MeV,\ \theta^*_{e\gamma} > 20^\circ)}{BR(K_{e3})} = (0.964 \pm 0.008^{+0.012}_{-0.011})\% \qquad (10)$$

As it can be seen in Fig. 2a, this is in good agreement with theoretical predictions [10,11] and recent ChPT calculations [12,13] and in disagreement with the other high precision measurement done by the KTeV collaboration [14].

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