K_S and Ξ^0 results from NA48/I

C. Lazzeroni[a],
on behalf of the NA48 collaboration

[a]High Energy Physics group, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK

1. Introduction

The NA48 experiment was originally designed to measure direct CP-violation effects in neutral-kaon decays to two pions. The experimental layout, described in detail elsewhere [1], includes a spectrometer (drift chambers and a dipole magnet), an electromagnetic calorimeter, and arrangements of scintillators for vetoing photons outside the calorimeter acceptance. The upgrade of the NA48 $\mathrm{K_S}$ beam, in the absence of the $\mathrm{K_L}$ beam, by a factor of several hundred in intensity was undertaken in 2002. A large sample of $\mathrm{K_S}$ and neutral hyperon decays were collected.

2. $\mathrm{K_S} \to \pi^0\mathrm{e^+e^-}$

Decays of the type $\mathrm{K_L} \to \pi^0 l\bar{l}$ are of considerable interest because of their sensitivity to direct CP violation [2]. However, in $\mathrm{K_L} \to \pi^0\mathrm{e^+e^-}$ decays, CP-conserving and indirect CP-violating amplitudes also contribute. The CP-conserving contribution can be evaluated by measuring the low-$m_{\gamma\gamma}$ component of the decay $\mathrm{K_L} \to \pi^0\gamma\gamma$ [3]. The direct and indirect CP violating (CPV) contributions interfere, and their contribution to the branching ratio can be written as [4]:

$$B(\mathrm{K_L} \to \pi^0\mathrm{e^+e^-})_{\mathrm{CPV}} \times 10^{12} \simeq$$
$$15.3\, a_S^2 - 6.8\, a_S \frac{\mathrm{Im}(\lambda_t)}{10^{-4}} + 2.8 \left(\frac{\mathrm{Im}(\lambda_t)}{10^{-4}}\right)^2,$$

where $\lambda_t = V_{ts}^* V_{td}$ is the relevant combination of CKM matrix elements describing the short distance CP violation. The parameter a_S describes the strength of the indirect CP violating component in the decay $\mathrm{K_L} \to \pi^0\mathrm{e^+e^-}$, and is related to the branching ratio of $\mathrm{K_S} \to \pi^0\mathrm{e^+e^-}$ via [4]:

$$\mathrm{B}(\mathrm{K_S} \to \pi^0\mathrm{e^+e^-}) = 5.2 \times 10^{-9}\, a_S^2.$$

From dimensional analysis in chiral perturbation theory, $a_S \sim \mathcal{O}(1)$. A precise measurement of the $\mathrm{K_S} \to \pi^0\mathrm{e^+e^-}$ branching fraction is clearly important for placing a bound on the indirect CP violating term in the $\mathrm{K_L}$ decay.

A search for $\mathrm{K_S} \to \pi^0\mathrm{e^+e^-}$ has been made using the 2002 data, taken with a high-intensity $\mathrm{K_S}$ beam. For the analysis of the data, signal and control regions were defined as:

$$\begin{aligned} \textit{signal}: \quad & |m_{\gamma\gamma} - M_{\pi^0}| < 2.5 \times \sigma_{\gamma\gamma} \\ & |m_{ee\gamma\gamma} - M_K| < 2.5 \times \sigma_{ee\gamma\gamma} \end{aligned}$$

$$\begin{aligned} \textit{control}: \quad & 3 \times \sigma_{\gamma\gamma} < |m_{\gamma\gamma} - M_{\pi^0}| < 6 \times \sigma_{\gamma\gamma} \\ & 3 \times \sigma_{ee\gamma\gamma} < |m_{ee\gamma\gamma} - M_K| < 6 \times \sigma_{ee\gamma\gamma} \end{aligned}$$

where $\sigma_{\gamma\gamma} = 1$ MeV/c^2 and $\sigma_{ee\gamma\gamma} = 4.7$ MeV/c^2. These regions were masked while cuts to reject the background were tuned, using both experimental data and simulated events.

A large number of possible sources of background has been studied, taking into account single kaon and hyperon decays and fragments from two decays accidentally coincident in time. The background contribution was minimised by imposing the requirements: $m_{e\gamma} > m_{\pi^0} +$ 30 MeV/c^2, to reject events where two photons from different π^0s converted; and $m_{ee} >$ 165 MeV/c^2, to reject events where one or more photons from a single π^0 converted. In addition, the background from Ξ^0 and Λ^0 decays was reduced to a negligible level by exploiting the large momentum asymmetry. The main residual background contributions were from $\mathrm{K_S} \to \pi^0_D\pi^0_D$,

Source	Control region	Signal region
$K_S \to \pi^0{}_D\pi^0{}_D$	0.03	0.007
$K_L \to e^+e^-\gamma\gamma$	0.11	0.075
$\pi^{\pm}e^{\mp}\nu + (\pi^0\pi^0(\pi^0))$	0.19	0.069
Total	0.33	0.15

Table 1
Contributions to the background for $K_S \to \pi^0 e^+e^-$.

$K_L \to e^+e^-\gamma\gamma$ and $\pi^{\pm}e^{\mp}\nu + (\pi^0\pi^0(\pi^0))$ decays, and the total background was estimated to be $0.15^{+0.10}_{-0.04}$ events (Table 1).

When the signal region was unmasked, 7 events were found (Fig. 1), corresponding to a signal of $6.85^{+3.8}_{-1.8}$. The number of K_S decays in the fiducial volume was evaluated by counting $K_S \to \pi^0\pi^0_D$ decays. The acceptance for the $K_S \to \pi^0e^+e^-$ channel was calculated using the amplitude [4] predicted by Chiral Perturbation Theory and a unit form factor. A measurement of the branching ratio was then obtained [5]:

$$B(K_S \to \pi^0e^+e^-, m_{ee} > 165\ \mathrm{MeV/c^2}) = (3.0^{+1.5}_{-1.2}(stat) \pm 0.1(syst)) \times 10^{-9}$$

$$B(K_S \to \pi^0e^+e^-) = (5.8^{+2.8}_{-2.3}(stat) \pm 0.8(syst)) \times 10^{-9}.$$

The systematic uncertainty includes the uncertainty on the flux measurement and on the acceptance. The parameter $|a_S|$ was derived from $K_S \to \pi^0e^+e^-$ to be:

$$|a_S| = (1.06^{+0.26}_{-0.21}(\mathrm{stat}) \pm 0.07(\mathrm{syst})).$$

This measurement of $|a_S|$ allows the K_L branching ratio to be calculated as a function of $Im(\lambda_t)$, with a sign ambiguity. Taking the value $Im(\lambda_t) = (1.36 \pm 0.12) \times 10^{-4}$ [6] from a global fit to b-decays, the CP-violating part of $K_L \to \pi^0e^+e^-$ can be predicted to be:

$$B(K_L \to \pi^0e^+e^-)_{\mathrm{CPV}} \simeq (17_{\mathrm{indirect}} \pm 9_{\mathrm{interference}} + 5_{\mathrm{direct}}) \times 10^{-12},$$

.

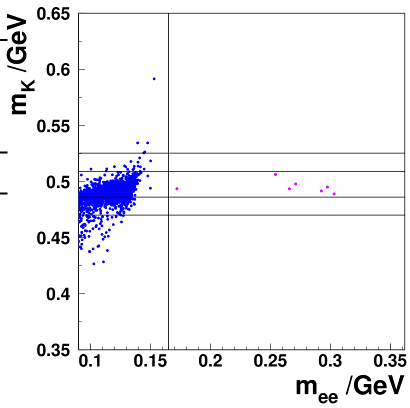

Figure 1. Scatter plot of $m_{ee\gamma\gamma}$ versus m_{ee} for $K_S \to \pi^0e^+e^-$ events. The $m_{ee} > 165$ MeV/c^2 cut is shown. The regions at $3\sigma_K$ and $6\sigma_K$ are indicated. The inset shows an enlargement of the signal box.

2.1. $K_S \to \pi^0\mu^+\mu^-$

An estimate of the ratio of the muon to electron branching ratios can be obtained within the framework of the Vector Meson Dominance model [4]. A measurement of both the branching ratios can therefore test the theory.

The data were taken in the same run as that used for the observation of the $K_S \to \pi^0e^+e^-$ decay. The analysis has proceeded in a similar way to the $K_S \to \pi^0e^+e^-$ analysis. Events which contain two photons and two muons were selected. The invariant mass of the muon pairs is limited by kinematics to be between 0.210 GeV and 0.363 GeV.

A blind analysis has been performed. A signal and a control region have been defined in similar ways to the $K_S \to \pi^0e^+e^-$ analysis, with the exception that here $\sigma_{\gamma\gamma} = 1.0$ MeV/c^2 and $\sigma_{\mu\mu\gamma\gamma} = 3.0$ MeV/c^2. These regions were masked while cuts to reject the background were tuned, using both experimental data and simulated events.

The main residual background contributions were from $K_L \to \mu^+\mu^-\gamma\gamma$, and from $\pi^{\pm}\mu^{\mp}\nu + (\pi^0\pi^0)$ decays where one pion decays in flight, or from $\pi^+\pi^- + (\pi^0\pi^0)$ decays where two pions decay in flight. The total background was estimated to be $0.22^{+0.19}_{-0.12}$ events (Table 2).

When the signal region was unmasked, 6 events were found (Fig. 2), corresponding to a signal of $5.78^{+3.0}_{-2.5}$ events. The number of $\mathrm{K_S}$ decays in the fiducial volume was evaluated by counting $\mathrm{K_S} \rightarrow \pi^+\pi^-$ decays from a minimum bias trigger. The acceptance for the $\mathrm{K_S} \rightarrow \pi^0\mu^+\mu^-$ channel was calculated using the amplitude [4] predicted by Chiral Perturbation Theory and a unit form factor; the trigger efficiency of 0.77 ± 0.02 and and the 2μ identification efficiency have been taken into account in the acceptance of 0.0814 ± 0.004. A measurement of the branching ratio was then obtained [7]:

$$B(\mathrm{K_S} \rightarrow \pi^0\mu^+\mu^-) = (2.8^{+1.5}_{-1.2}(stat)^{+0.2}_{-0.2}(syst)) \times 10^{-9}.$$

The systematic uncertainty includes the uncertainty on the flux measurement and on the acceptance. The parameter $|a_S|$ was derived from $\mathrm{K_S} \rightarrow \pi^0\mu^+\mu^-$ to be:

$$|a_S| = (1.53^{+0.38}_{-0.32}(\mathrm{stat}) \pm 0.05(\mathrm{syst})).$$

in agreement with the value obtained from the $\mathrm{K_S} \rightarrow \pi^0\mathrm{e^+e^-}$ analysis. In a similar way as for $\mathrm{K_S} \rightarrow \pi^0\mathrm{e^+e^-}$, this measurement of $|a_S|$ allows the $\mathrm{K_L}$ branching ratio to be calculated as a function of $Im(\lambda_t)$, with a sign ambiguity. Taking again the value $Im(\lambda_t) = (1.36 \pm 0.12) \times 10^{-4}$ [6] from a global fit to b-decays, the CP-violating part of $\mathrm{K_L} \rightarrow \pi^0\mu^+\mu^-$ can be predicted to be:

$$B(\mathrm{K_L} \rightarrow \pi^0\mu^+\mu^-)_{\mathrm{CPV}} \simeq (9_{\mathrm{indirect}} \pm 3_{\mathrm{interference}} + 1_{\mathrm{direct}}) \times 10^{-12},$$

where here the direct CP violation is small compared with the indirect component, but part of the sensitivity is retained through the interference term.

3. $\Xi^0 \rightarrow \Lambda\gamma$

The $\Xi^0 \rightarrow \Lambda\gamma$ decay asymmetry plays an important role in solving a long standing discrepancy between the Hara theorem [8] and the observed decay asmmetries of weak radiative hyperon decays. The Hara theorem states that the parity-violating amplitude of the weak radiative

Source	Events
$\mathrm{K_L} \rightarrow \pi^0\pi^+\pi^-$	$0^{+0.02}_{-0.00}$
$\mathrm{K_L} \rightarrow \mu^+\mu^-\gamma\gamma$	0.04 ± 0.04
$\pi^\pm\mu^\mp\nu(\pi^+\pi^-) + \pi^0\pi^0$	$0.18^{+0.18}_{-0.11}$
Total background	$0.22^{+0.19}_{-0.12}$

Table 2
Contributions to the background for $\mathrm{K_S} \rightarrow \pi^0\mu^+\mu^-$.

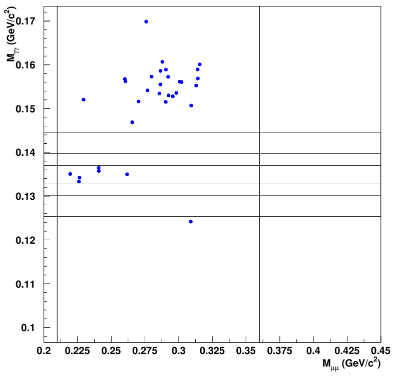

Figure 2. Scatter plot of $m_{\mu\mu\gamma\gamma}$ versus $m_{\mu\mu}$ for $\mathrm{K_S} \rightarrow \pi^0\mu^+\mu^-$ events. The regions at $2.5\sigma_K$ and $6\sigma_K$ are indicated.

hyperon decays vanishes in the SU(3) limit. Accordingly the decay asymmetries will vanish in this case. Allowing for a weak breaking of SU(3) symmetry, the observation of a small asymmetry is expected. In contrast to this, a large negative decay asymmetry has been measured [9] and models are being developed to account for this discrepancy [10].

The measurement is based on data from a special two-day period in 1999 where only the high-intensity K_S beam was present. The $\Lambda\gamma$ invariant mass distribution of the Ξ^0 candidates is shown in Fig. 3: 730 candidates were reconstructed with a background of 58.2 ± 7.8 events. The main sources of background were $K_L \rightarrow \pi^+\pi^-\pi^0$ events, time overlap of two events and hadronic interactions in the final collimator region.

The $\Xi^0 \to \Lambda\pi^0$ decays have been chosen as normalization channel, and 61828 events were selected with negligible background.

For the asymmetry measurement, the well-known decay asymmetry of the $\Lambda \to p\pi$ decay is used. The Λ hyperons are longitudinally polarised by the parent process $\Xi^0 \to \Lambda\gamma$ with a polarisation $\alpha(\Xi^0 \to \Lambda\gamma)$ in their rest frame. Effectively, the distribution of the angle θ_{lambda} between the incoming Ξ^0 (corresponding to the outgoing Λ direction in the Ξ^0 rest frame) and the outgoing proton in the Λ rest frame is measured:

$$dN/dcos\theta_\Lambda = N_0(1-\alpha(\Lambda \to p\pi)\alpha(\Xi^0 \to \Lambda\gamma)cos\theta_\Lambda)$$

In this way, the Λ is polarised by the Ξ^0 decay and analysed by its own decay into $p\pi$. The minus sign is purely conventional and arises from the fact that the photon carries spin 1, which leads to an opposite Λ spin to that in the process $\Xi^0 \to \Lambda\pi^0$. A Monte Carlo simulation with flat $cos\theta_\Lambda$ distribution has been used to correct for the detector acceptance. The effective asymmetry of the background was determined by fitting the mass side-bands. A fit was been perfomed to data in the range $-0.8 < cos\theta_\Lambda < 1$ and the parameter $\alpha(\Lambda \to p\pi)\alpha(\Xi^0 \to \Lambda\gamma)$ was extracted. After dividing by $\alpha(\Lambda \to p\pi) = 0.642 \pm 0.013$, the $\Xi^0 \to \Lambda\gamma$ decay asymmetry is obtained:

$$\alpha(\Xi^0 \to \Lambda\gamma) = -0.78 \pm 0.18_{stat} \pm 0.06_{syst}$$

where the largest systematic uncertainties come from the effective asymmetry of the background and the background normalization. This is the first evidence for a negative decay asymmetry in this channel. The only previous measurement was consistent with zero asymmetry [11].

As a check, the $\Xi^0 \to \Lambda\pi^0$ decay asymmetry was also measured and found in excellent agreement with published data [12].

Using the central value of the Ξ^0 decay asymmetry, a branching ratio has been obtained for $\Xi^0 \to \Lambda\gamma$ decays:

$$Br(\Xi^0 \to \Lambda\gamma) = (1.16 \pm 0.05_{stat} \pm 0.06_{syst}) \times 10^{-3}$$

where the systematic uncertainty is dominated by the uncertainty on the decay asymmetry. This is the most precise measurement of this decay rate so far, and it confirms the previous published measurement [11].

Much larger statistical sample from 2002 data is under analysis.

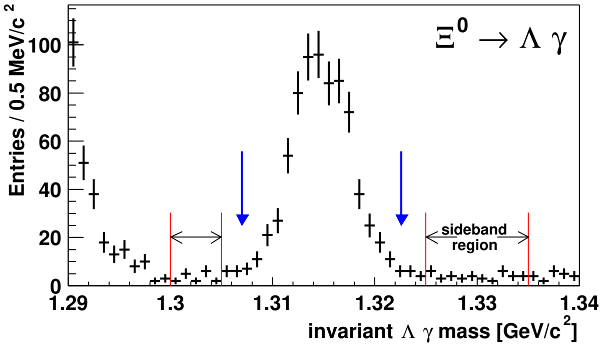

Figure 3. $\Lambda\gamma$ invariant-mass distribution.

REFERENCES

1. V. Fanti *et al*, Phys. Lett. B **465**, 335 (1999).
2. G. D'Ambrosio and G. Isidori, Int. Jour. Mod. Phys. **A13**, 1 (1998).
3. A. Lai *et al*, Phys. Lett. **B536**, 229 (2002).
4. G. D'Ambrosio, G. Ecker, G. Isidori and J. Portoles, JHEP 08(1998)004.
5. R.Batley et al., Phys. Lett. **B576** (2003).
6. S. H. Kettell, L. G. Landsberg, and H. Nguyen, hep-ph/0212321.
7. R.Batley et al., CERN PH-EP Preprint 2004-025 (2004).
8. Y.Hara, Phys. Rev. Lett. **12**, 378 (1964).
9. L.K.Gershwin et al., Phys. Rev. **188**, 2077 (1969).
10. P. Zenczykowski, Phys. Rev. **D62**, 014030 (2000).
    R.C.Veram and A.Sharma, Phys. Rev. **D38**, 1443 (1988).
11. C.James et al, Phys. Rev. Lett. **64**, 843 (1990).
12. R.Handler et al., Phys Rev **D25**, 639 (1982).