A high sensitivity investigation of K_S and neutral hyperon decays using a modified K_S beam

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Addendum 2 to P253
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Plan of the presentation

We propose to use the NA48 detector and a modified K_S beam line to search for rare K_S and neutral hyperon decays.

- Selected physics topics:
  - programme which does not require drift chambers (it can start in the year 2000)
    - K_S non-leptonic neutral decays
    - $K_S \rightarrow \pi^0\pi^0\pi^0$ (η_{000})
  - Programme which requires the drift chambers (after $\mathrm{Re}(\varepsilon'/\varepsilon)$ is completed)
    - $K_S \rightarrow \pi^0 e^+ e^-$
    - K_S decays with four tracks
    - neutral hyperon decays
- Modifications to the K_S beam
- Detector
- Trigger rates
- Read out systems
- Request of beam time

Sensitivities and number of events are quoted for 120 days of proton running, 50 % overall data taking efficiency

Physics case: Non-leptonic K_S decays

The non-leptonic $K_{S,L}$ decays are important for understanding the low energy hadron dynamics of Chiral Perturbation Theory (χPT), since they are sensitive to higher order loop effects.

Decay mode	BR (exp)	BR (th)	Evts/year
$K_S \to \gamma\gamma$	$(2.4 \pm 0.9) \times 10^{-6}$	2.1×10^{-6}	24000
$K_S \to \pi^0\gamma\gamma$		3.8×10^{-8}	114
$K_S \to \pi^0\pi^0\gamma\gamma$		5.6×10^{-9}	7
$K_S \to \pi^0\pi^0\gamma$		1.7×10^{-11}	
$K_L \to \gamma\gamma$	$(5.92 \pm 0.15) \times 10^{-4}$	$\sim 5 \times 10^{-4}$	$25000/c\tau_S$
$K_L \to \pi^0\gamma\gamma$	$(1.70 \pm 0.15) \times 10^{-6}$	1.5×10^{-6}	$23/c\tau_S$
$K_L \to \pi^0\pi^0\gamma\gamma$		2.0×10^{-7}	$1/c\tau_S$
$K_L \to \pi^0\pi^0\gamma$		1×10^{-8}	

The $K_S \to \gamma\gamma$ decay is especially interesting because χPT predicts unambiguously the branching ratio with an error of less than 10%.

Physics Case: Non-leptonic $\mathrm{K_S}$ decays, contd.

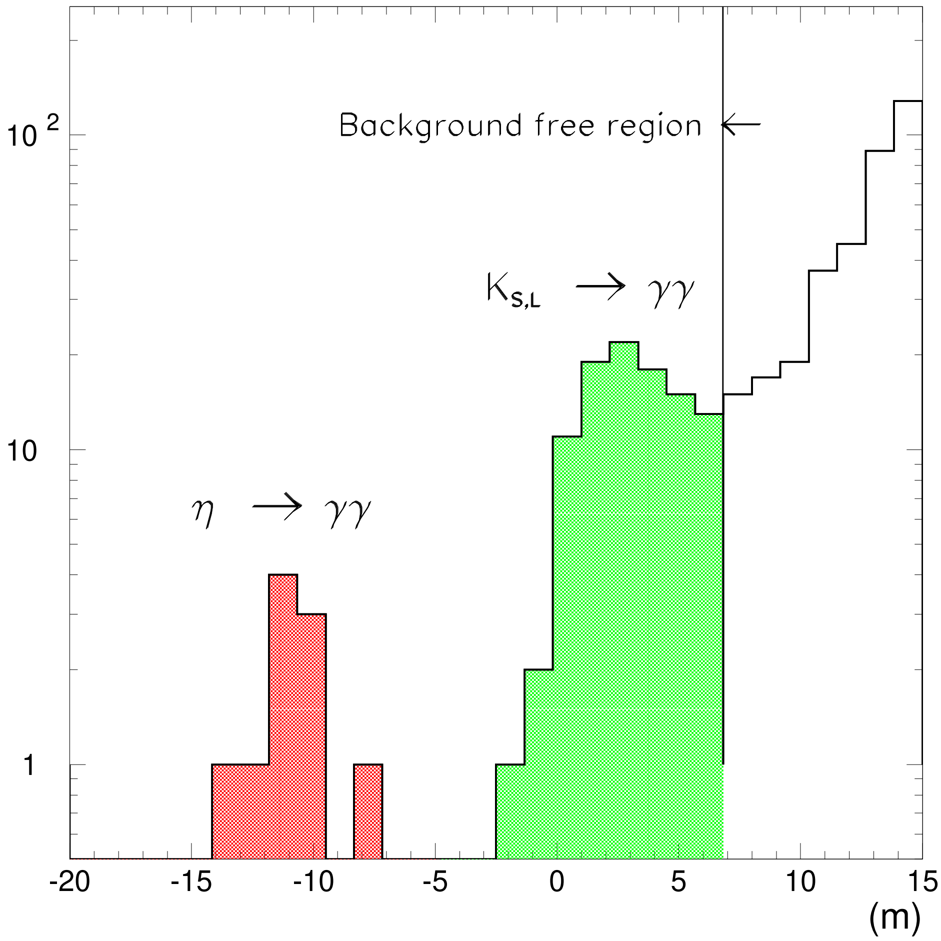
- $\mathrm{K_S} \to \pi^0\gamma\gamma$
  This decay probes the momentum dependence of the $\mathrm{K}\pi\pi$ vertex. Due to the large $\mathrm{K_S} \to \pi^0\pi^0$ background a cut around the π^0 mass hasto be applied.
- $K_{S,L} \to \pi^0\pi^0\gamma\gamma$
  These decays are finite at the one loop level and do not involve any unknown coupling constant[a]. The dominant contributions to $\mathrm{K_S} \to \pi^0\pi^0\gamma\gamma$ are basically flat over the physically accessible region. Any deviation from phase space would signal a breakdown of χPT.

Both decays are very challenging from the experimental point of view.

[a] R. Funck and J. Kambor, Nucl. Phys. B396, 53-80, (1993).

Example: $K_S \to \gamma\gamma$

KS test run, summer 1999



The first 7 m length after the K_S collimator is free from background coming from $K_S \to \pi^0\pi^0$ decays. The $K_L \to \gamma\gamma$ contamination in the signal is estimated precisely by measuring the K_L flux coming from $K_L \to \pi^0\pi^0\pi^0$ decays.

Physics case: CP violation in $K_S \to \pi^0\pi^0\pi^0$

$|K_S> \simeq |K_1> + \epsilon_S |K_2>$

$CP(|K_1>) = +1 \quad CP(|K_2>) = -1 \quad CP(\pi^0\pi^0\pi^0) = -1$

CP-violation in the K_S : $\eta_{000} = \frac{A(K_S \to \pi^0\pi^0\pi^0)}{A(K_L \to \pi^0\pi^0\pi^0)}$

Experiment	$\mathfrak{Re}(\eta_{000})$	$\mathfrak{Im}(\eta_{000})$	$BR(K_S \to \pi^0\pi^0\pi^0)$
Barmin et. al	-0.08 ± 0.27	-0.05 ± 0.27	$< 3.7 \times 10^{-5}$ 90 % CL
CPLEAR	0.18 ± 0.15	0.15 ± 0.20	$< 1.9 \times 10^{-5}$ 90% CL
SND			$< 1.4 \times 10^{-5}$ 95% CL

$\mathfrak{Re}(\eta_{000}) = \mathfrak{Re}(\epsilon) \sim 1.6 \times 10^{-3}$ is predicted by the CP violation in the K^0 -$\overline{K}^0$ mixing. The imaginary part is sensitive to direct CP violation. It is also an important input to CPT tests.

This proposal aims to reduce the error on $\mathfrak{Re}(\eta_{000})$ and $\mathfrak{Im}(\eta_{000})$ by a factor of 10, measuring $K_S - K_L$ interference near the production target.

Physics case: η_{000} and tests of CPT

- CPT test in the Wu-Yang plane

  Neglecting second order terms in CP violation, CPT conservation predicts[a] :

  $$\Delta\Phi - \frac{\mathrm{R_{dir}} \sin\phi_{\mathrm{SW}}}{|\eta_{\pm}|} = 0$$

  - $\Delta\Phi = 2/3\phi_{\pm} + 1/3\phi_{00} - \phi_{\mathrm{SW}} = (0.01 \pm 0.7)^{\circ}$
  - $\mathrm{R_{dir}}$ is the contribution from direct CP violation from channels other than the $\pi\pi$.

  If no further theoretical prejudice is used, the error from $\mathrm{R_{dir}}$ amounts to $\pm 1.5^{\circ}$ and it is limited by the poor knowledge of $\mathfrak{Im}(\eta_{000})$.

  CPT is tested only to $\sim 4\%$ of the CP violation strength!

[a] I.I. Bigi and A. I. Sanda, Phys. Lett. B466 33-40, (1999).

Physics case: η_{000} and tests of CPT, contd.

- CPT test using the unitarity constrain

  $\epsilon_{\mathrm{L}} = \epsilon - \delta$

  $\epsilon_{\mathrm{S}} = \epsilon + \delta$ ϵ is CP violating and δ is CP and CPT violating.

  The CPLEAR result [a] using the Bell-Steinberger (unitarity) relation:

  $M_{\mathrm{K}^0} - M_{\bar{\mathrm{K}}^0} = (-1.5 \pm 2.0) \times 10^{-18} GeV$

  $\Gamma_{\mathrm{K}^0} - \Gamma_{\bar{\mathrm{K}}^0} = (3.9 \pm 4.2) \times 10^{-18} GeV$ are obtained projecting $\mathfrak{Re}(\delta)$ and $\mathfrak{Im}(\delta)$ along the super-weak direction

  $\phi_{\mathrm{SW}} = \tan^{-1}(2\Delta m/\Delta\gamma) \approx 43.5°$.

  $\mathfrak{Re}(\delta) = (2.4 \pm 2.8) \times 10^{-4}$

  $\mathfrak{Im}(\delta) = (2.4 \pm 5.0) \times 10^{-5}$ η_{000} is the main limiting factor on $\mathfrak{Im}(\delta)$.

[a] CPLEAR Collaboration, CERN-EP/99-150

η_{000}: technique

The sensitivity to η_{000} comes from the $K_S - K_L$ interference term which is superimposed on a very large, flat $K_L \rightarrow \pi^0\pi^0\pi^0$ component. Most of the effect is contained within a few K_S lifetimes from the target.

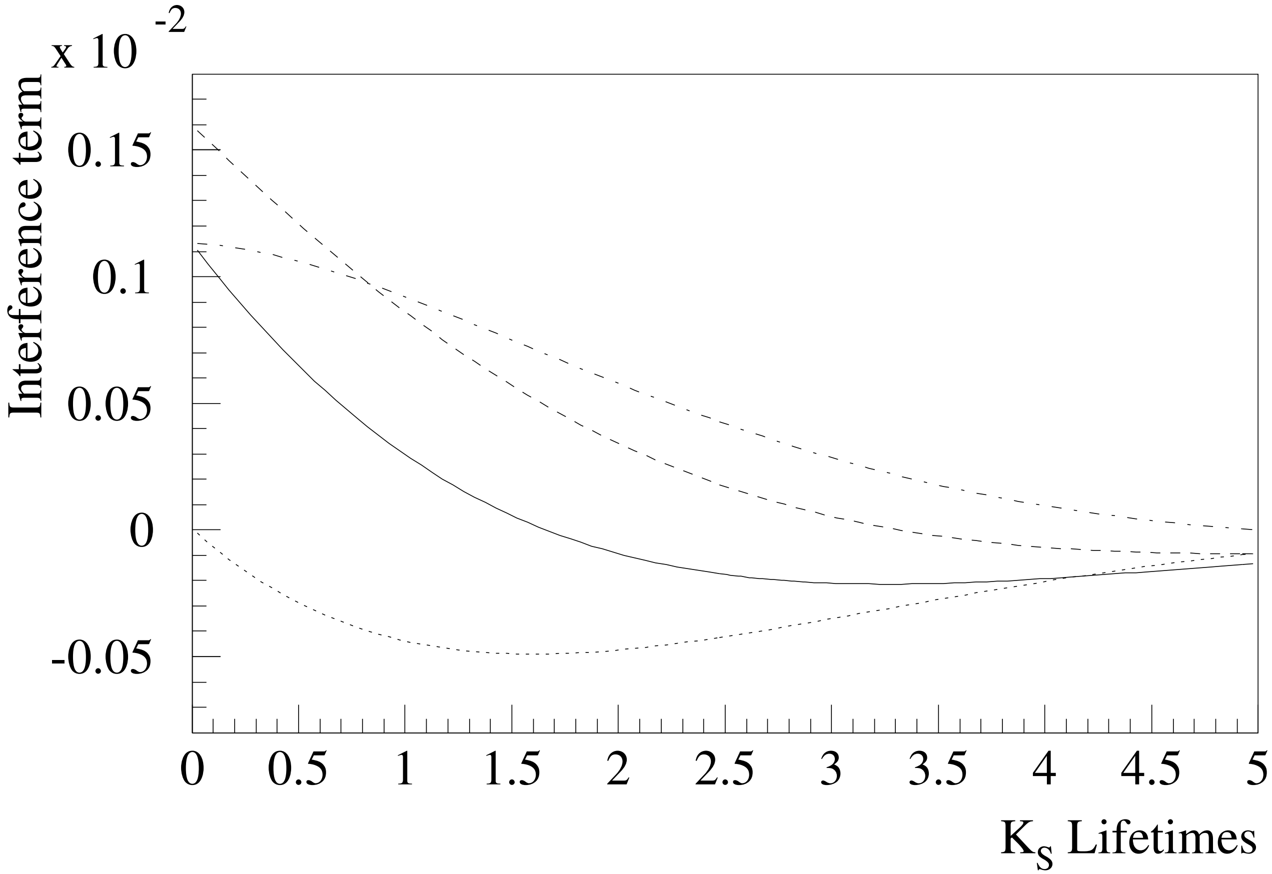
$$I_{3\pi^0} = K \times \Gamma(K_L \rightarrow \pi^0\pi^0\pi^0) \times$$

$$\left(e^{-t/\tau_L} + |\eta_{000}|^2 e^{-t/\tau_S} + 2D|\eta_{000}|e^{-t/2(1/\tau_S+1/\tau_L)}\cos(\Delta m t + \phi_{000})\right),$$

D is the $K^0\ \overline{K}^0$ (about 0.3 for NA48).

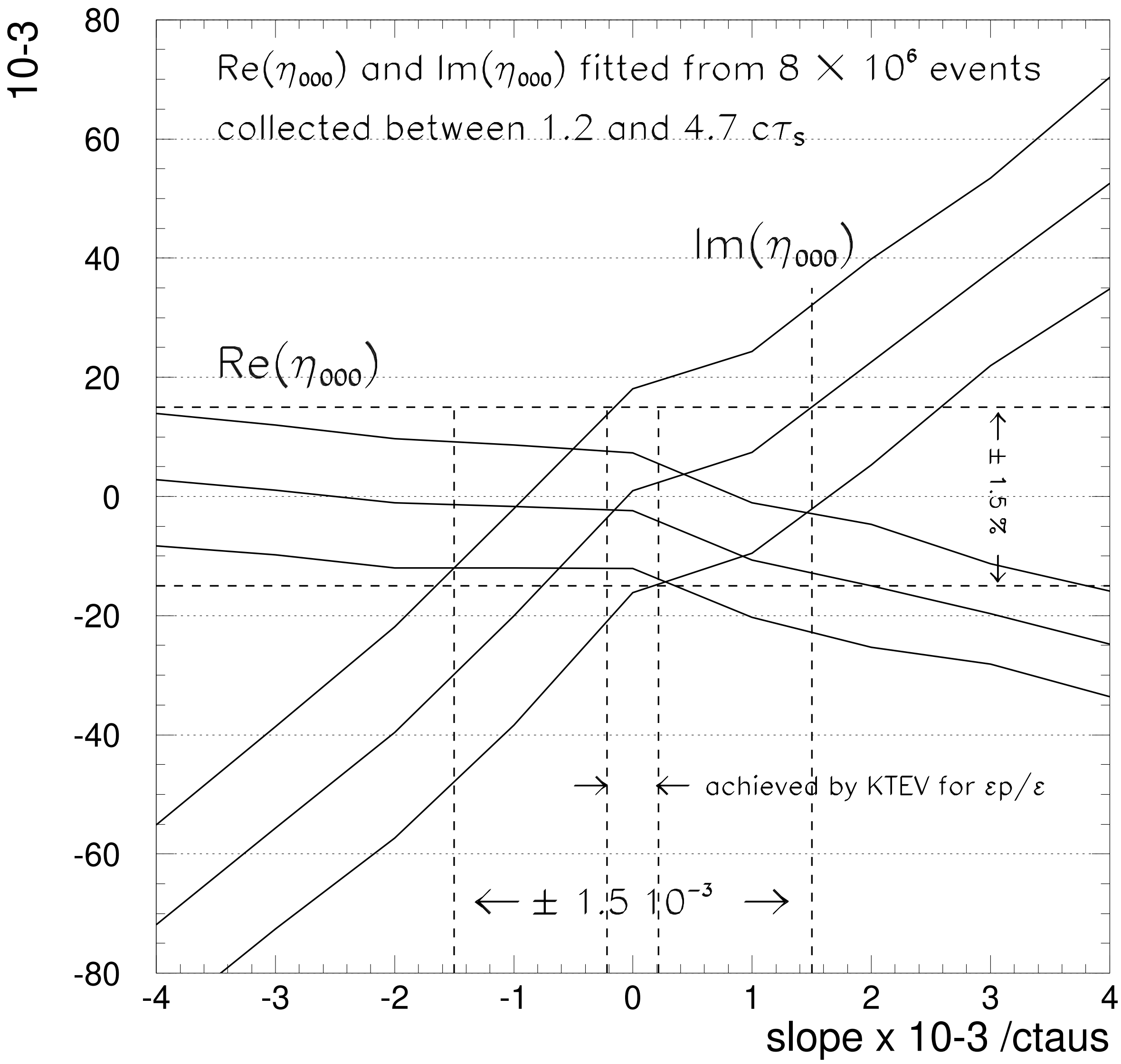
The disadvantage of losing the first lifetime due to the presence of the collimator is offset in part by the very good proper time resolution ($\sim 0.1\ c\tau_S$) provided by the combination of high energy kaons and high resolution calorimetry. To evaluate the sensitivity to η_{000}, we have used samples of $3\pi^0$ from a K_S -only high intensity run, and a Monte Carlo simulation.

$K_S \to \pi^0\pi^0\pi^0$: technique, contd.



The interference term for the first 5 K_S lifetimes. The phases are $\phi_{000} = 45^\circ$ (solid), $\phi_{000} = 0^\circ$ (dashed), $\phi_{000} = 90^\circ$ (dotted), and $\phi_{000} = -45^\circ$ (dash-dotted). $I_{3\pi^0}$ has been normalised to 1 at $t = 0$, assuming $\eta_{000} = \epsilon$.

Sensitivity to η_{000}



$\mathfrak{Re}(\eta_{000}), \mathfrak{Im}(\eta_{000})$: statistical and systematic error due to limited knowledge of the acceptance.

Physics case: $K_S \rightarrow \pi^0 e^+ e^-$

The interest in $K_S \rightarrow \pi^0 e^+ e^-$ is to measure the indirect CP violation in the $K_L \rightarrow \pi^0 e^+ e^-$ decay.

$K_L \rightarrow \pi^0 e^+ e^-$ is a place to look for direct CP violation within and beyond the standard model.

$$CP(K_L) \sim -1 \qquad CP(\pi^0 e^+ e^-)_{1\gamma} = +1$$

- The current upper limit[a] $BR(K_L \rightarrow \pi^0 e^+ e^-) < 5.64 \times 10^{-10}$ could be improved in the next few years by a factor of ≈ 2 by KTEV and more significantly by the KAMI (P804) proposal at FNAL.
- In the SM: $BR(K_L \rightarrow \pi^0 e^+ e^-)_{CPVdir} \sim 6.7 \times 10^{-11} A^4 \eta^2$ where η is the CP violating phase in the CKM matrix.
- The 2γ CP conserving component to $K_L \rightarrow \pi^0 e^+ e^-$ can be bound from the study of the low $m_{\gamma\gamma}$ component of the $K_L \rightarrow \pi^0 \gamma\gamma$ decay (NA48, KTEV).

[a] J. Whitmore, KAON-99 Conference, June 1999.

Physics case: $\mathrm{K_S} \rightarrow \pi^0 e^+ e^-$ contd.

$$\mathrm{BR}(\mathrm{K_L} \rightarrow \pi^0 e^+ e^-)_{\mathrm{CPVind}} = |\epsilon|^2 \frac{\tau_L}{\tau_S} \times BR(\mathrm{K_S} \rightarrow \pi^0 e^+ e^-)$$

$$\mathrm{BR}(\mathrm{K_S} \rightarrow \pi^0 e^+ e^-) \times 10^9 = 5.2|a_s|^2$$

1. for $\mathrm{BR}(\mathrm{K_S} \rightarrow \pi^0 e^+ e^-) < 10^{-9}$ the indirect CPV in $\mathrm{K_L} \rightarrow \pi^0 e^+ e^-$ is bound to $\sim 3 \times 10^{-12}$
2. for $\mathrm{BR}(\mathrm{K_S} \rightarrow \pi^0 e^+ e^-) > 10^{-9}$ one becomes sensitive to direc CPV also via the interference of the direct and indirect CPV amplitudes.

Since the a_s parameter cannot be predicted to any degree of confidence, a high sensitivity search for $\mathrm{K_S} \rightarrow \pi^0 e^+ e^-$ is needed.

Sensitivity to $K_S \to \pi^0 e^+ e^-$

The Single Event Sensitivity (SES) for 1 year, 120 days 50% efficiency, is: 6×10^{-10}.

It corresponds to 7 events for $BR(K_S \to \pi^0 e^+ e^-) = 5 \times 10^{-9}$.

Estimated backgrounds:

decay mode	background events in one year
$K_L \to e^+ e^- \gamma\gamma$	<0.15
$K_S \to e^+ e^- \gamma\gamma$	<0.10
$K_S \to \pi^0 \pi^0_D$ *	< 2.5

* Limited by present MC statistics

The physics case for $K_S \to \pi^0 \mu^+ \mu^-$ is the same as for the electron channel. However, the backgrounds to this channel are quite different and the decay rate is suppressed by a factor of 5 due to phase space.

K_S decays with four tracks

- $K_S \to \pi^+\pi^-e^+e^-$
  Unlike $K_L \to \pi^+\pi^-e^+e^-$, no CP asymmetry[a] in the distribution of the angle between the planes of decay of the $\pi^+\pi^-$ and e^+e^- pairs is foreseen for $K_S \to \pi^+\pi^-e^+e^-$. This decay is therefore important to measure the effect of final state interactions on the recently published large asymmetry for the $K_L \to \pi^+\pi^-e^+e^-$ decay[b].
- $K_S \to e^+e^-\mu^+\mu^-$
  This decay mode is predicted[c] to be 2.31×10^{-8}. The angular distribution is interesting to disentangle the CP violating and CP conserving $K\gamma^*\gamma^*$ form factors.

[a] L. M. Sehgal and J. van Leusen, Phys. Rev. Lett. 83, 4933 (1999).
[b] KTEV Collaboration, Phys. Rev. Lett. 84, 408 (2000).
[c] Z. E. U. Uy, Phys. Rev. Lett., 43, 802 (1991).

Neutral hyperon decays

Contribution from the 1997 NA48 run to neutral hyperons:

- Hyperon EM mass splitting
  $M(\Xi^-) - M(\Xi^0) = (6.50 \pm 0.25)$ MeV, at variance with the lattice result[a] 5.68 ± 0.24 MeV.
- Hyperon radiative decays
  Based on 31 and 20 events respectively:
  $\mathrm{BR}(\Xi^0 \to \Lambda\gamma) = (1.90 \pm 0.34(\mathrm{stat}) \pm 0.19(\mathrm{syst})) \times 10^{-3}$
  $\mathrm{BR}(\Xi^0 \to \Sigma\gamma) = (3.14 \pm 0.76(\mathrm{stat}) \pm 0.32(\mathrm{syst})) \times 10^{-3}$
  These agree with one model based on SU(6) symmetry and vector dominance[b].

[a] A. Duncan, E. Eichten and TH. Thacker, Nucl. Phys. B (Proc. Suppl.) 53, 299 (1997).

[b] P. Zenczykowski, Phys. Rev. D40, 2290 (1989).

Neutral hyperon decays

With the high intensity KS run, we will also contribute to:

- Hyperon β decays
  The β decay of the Ξ^0 hyperon ($\Xi^0 \to \Sigma^+ e^- \bar{\nu}$), with a branching ratio of 2.5×10^{-4}, can be detected in NA48 by identifying the electron in the LKr calorimeter and the Σ^+ by its decay to $\mathrm{p}\pi^0$ (51%). We expect to collect 25000 events to check the SU(3) symmetry and the Cabibbo model in hyperon decays.
- Search for $\boldsymbol{\Xi^0 \to \mathrm{p}\pi^-}$
  The present experimental limit on this decay with a double strangeness change ($\Delta\mathrm{S} = 2$) is $\leq 4\times10^{-5}$ at 90% CL. We plan to improve this limit by a factor of 100.

Competition

- K_S
  - The competition to this experiment comes from the KLOE detector. However, even at the full DAΦNE design luminosity of 5×10^{32} cm^{-2}s^{-1}, the sensitivity per annum for $K_S \to \pi^0 e^+ e^-$ is less than this proposal.
  - Unlike KLOE, we cannot tag our K_S , thus making the two experiments complementary.
- Neutral hyperons
  - The competition comes from the KTEV experiment which collects neutral hyperons from the vacuum beam. Only hyperons with very high energy decay in the fiducial region. This loss is offset in part by the capability to track the leading baryon in the beam (no hole in tracking chambers).
  - Overall this proposal is up to one order of magnitude more competitive than KTEV

The intense K_S beam

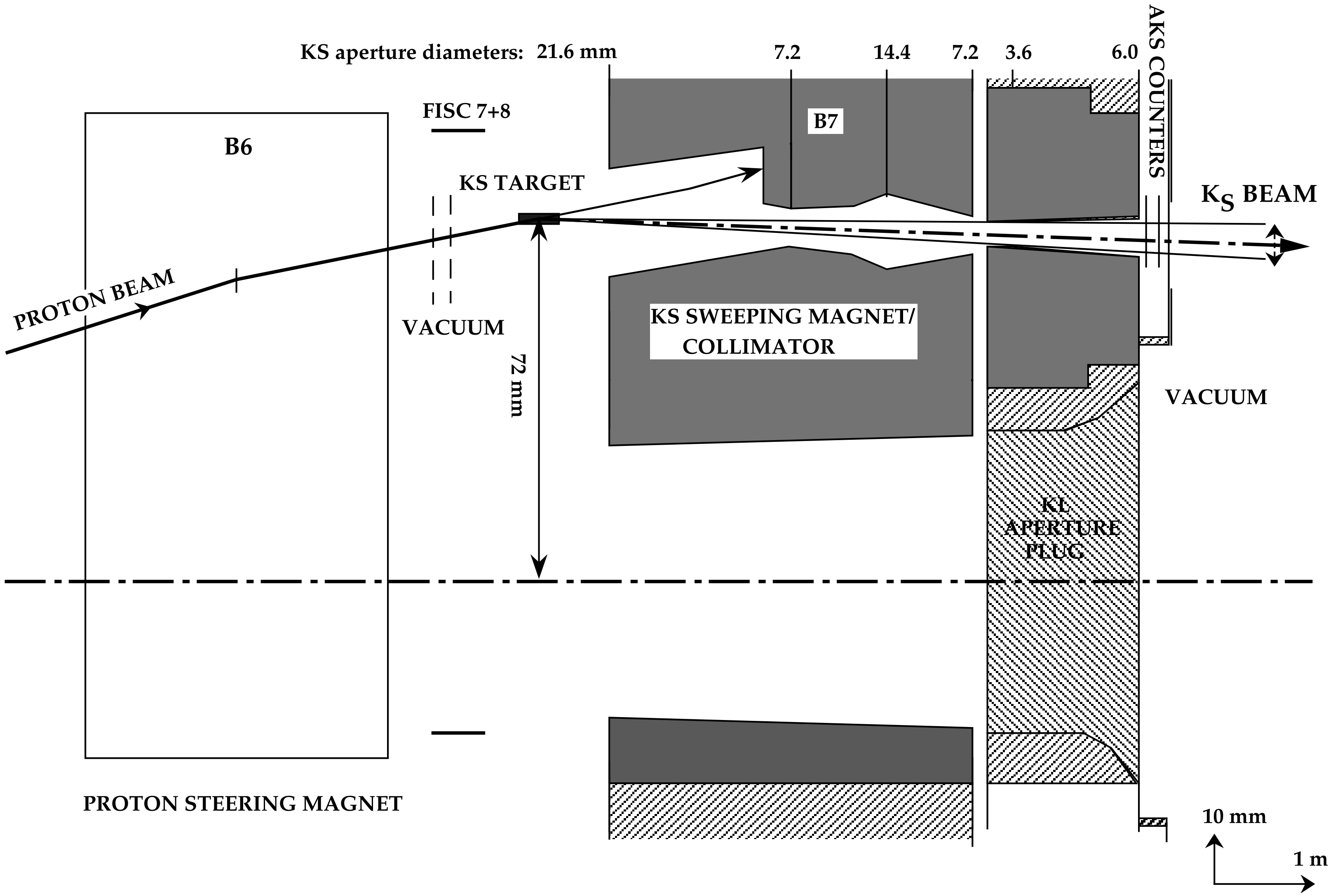
With respect to the present NA48 setup we propose to:

1. Dismount the whole AKS anti-counter array at the exit of the K_S collimator and establish a continuous vacuum along the passage of the beam;
2. Introduce a 1.5 m long absorber plug made of bronze into the present K_L -beam aperture below the K_S beam in the final collimator;
3. Exchange the proton steering magnet B6 just upstream of the K_S target by a stronger magnet, in order to reduce the production angle of the beam to $\sim$2.5 mrad compared to the present 4.2 mrad.

All of the above at no significant cost!

We request at least 50% longer SPS proton duty cycle at 400 GeV/c, for example: >3.75s./14.4s. or >5.s./19.2s.

The intense K_S beam, contd.



Detailed layout of the K_S target station and beam (vertical section)

K_S beam parameters

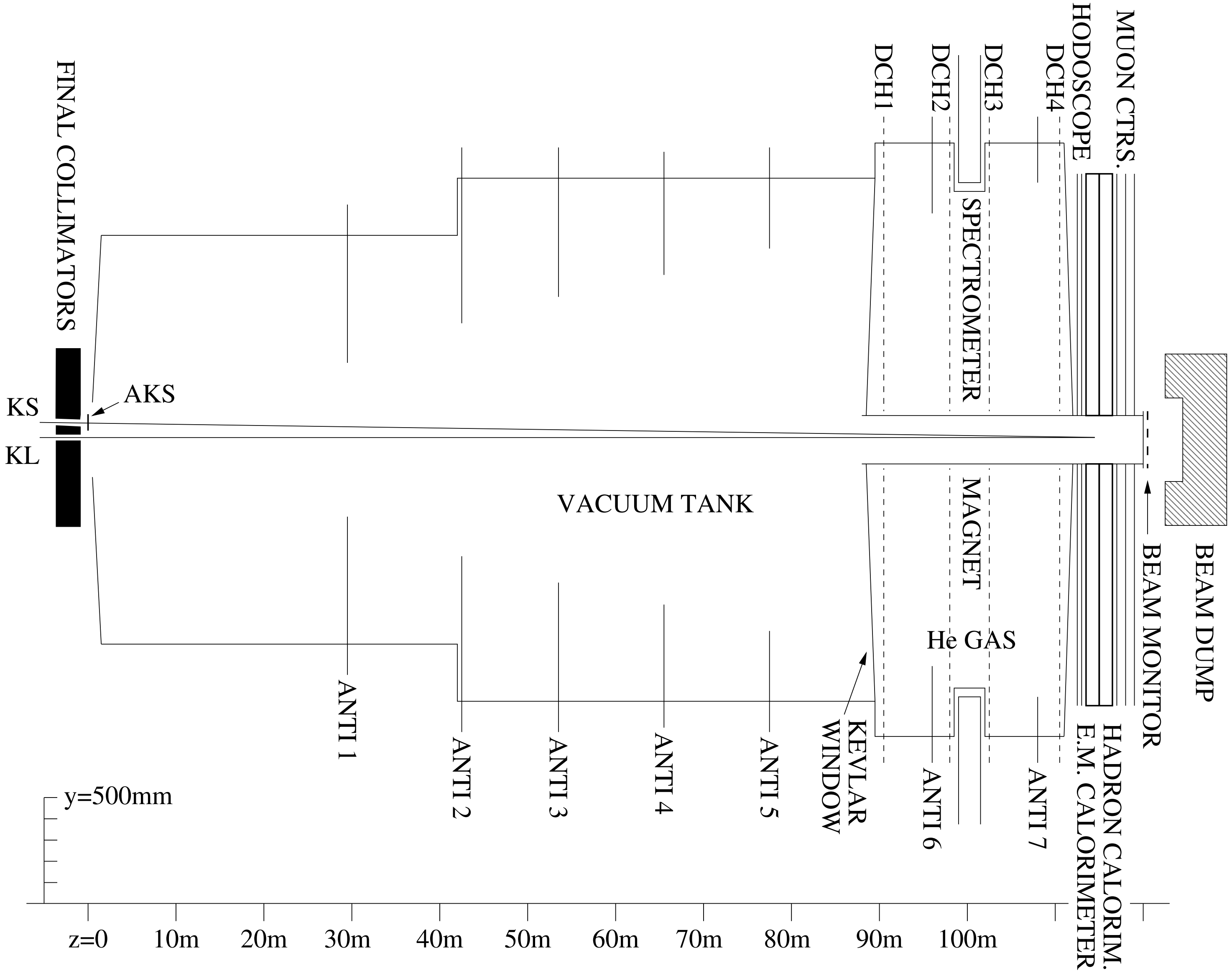
Beam	$K_L + K_S$ (Re(ε'/ε))		Intense K_S beam	
Year	1999		Phase I	Phase II
SPS momentum (GeV/c)	450		450	400
Duty Cycle (s/s)	2.5/14.4		2.5/14.4	5.0/19.2
Protons per pulse on target	1.5×10^{12}	3×10^{7}	5×10^{9}	1×10^{10}
Production angle α (mrad)	+2.4	-4.2	-4.2	-2.5
Total beam flux K's/pulse	$\sim 2\times10^{7} + \sim 3\times10^{2}$		$\sim 5\times10^{4}$	$\sim 1.5\times10^{5}$
K-decays in Δp_K /pulse	$1.0\times10^{5} + 1.8\times10^{2}$		4.0×10^{4}	1.1×10^{5}
K-decays in Δp_K /year ($\frac{1}{2} \times 120$ days)	$3.6\times10^{10} + 6.5\times10^{7}$		1.4×10^{10}	3.0×10^{10}

Detector

The following NA48 detectors will be used

1. A Liquid krypton EM calorimeter with good energy ($\sigma_{\mathrm{E}}/\mathrm{E} < 1\%$) time ($\sigma_t \sim 300ps$) and position ($\sigma_{x,y} < 1mm$) resolution for photons and providing highly selective neutral trigger;
2. a scintillating fibre hodoscope, embedded in the EM calorimeter, which generates control triggers;
3. a magnet spectrometer with a momentum resolution of:
   $\sigma_{\mathrm{p}}/\mathrm{p} = 0.48\% \oplus 0.009\% \times \mathrm{p}[GeV/c]$;
4. a plastic scintillator hodoscope to trigger on charged decays;
5. seven anti-counter rings (ANTI) to veto the photons and the charged particles escaping acceptance;
6. an hadron calorimeter;
7. a muon hodoscope consisting of three planes of plastic scintillator;
8. a beam counter to monitor the beam intensity and to trigger on random events.

Detector layout



Trigger rates

Decay mode	conditions	counts
(NUT)	$c\tau_S \leq 5.5$	7500
$K_S \rightarrow \pi^0\pi^0\pi^0$	NUT $\times$ (NPX>4 OR NPY>4)	1500
$K_S \rightarrow \gamma\gamma$	NUT $\times$ $Z < 9\ m$ NPX, Y $\leq 3 \times$ NPY, X ≤ 2	2500
$K_S \rightarrow \pi^0 e^+ e^-$	NUT $\times$ 1/2 tracks	4000
$K_S \rightarrow \pi^+\pi^- e^+ e^-$	MBX 4 tracks	2000
hyperon trigger	$\overline{\mathrm{MBX}}$	40000

L2 Trigger rates as measured in the September 1999 test run (5×10^9ppp).
The Hyperon trigger needs to be improved or deliberately downscaled.

- The current Level II read out limit is 8 KHz, i.e. $\sim$ 20000 events for a flat top of 2.5 s.
- The Online PC farm can take twice as many triggers.
- The use of the NA48 CDR facilities is assumed

Read out systems

All the read-out systems used in NA48 can be employed with no modification for this proposal. However with a software upgrade of the LKr read out and an upgraded drift chamber read out, the sensitivity of the experiment can be improved significantly.

System	Cost (KSfr)
LKr read out	
Upgrade of the DT/SLINK interfaces	25
Assembly of 10 CPD spares (4 for the HAC)	60
Reprogramming of CPD FPGA	20
DCH front end and read out	
Modification of preamplifier	40
New cables to TDC	30
Upgrade of the DCH read out	under evaluation

Beam time request

- Phase 1 (Year 2000):

  Request 50 days of protons at 450 GeV/c or 400 GeV/c with at least 20 % increase in duty cycle to get started with the $\mathrm{K_S}$ neutral decays, notably $\mathrm{K_S} \to \gamma\gamma$ and η_{000}.

  – No drift chambers, no beam-pipe and no kevlar window

  – Extend the vacuum into the Helium tank

  – The flux of protons can be significantly increased above 5×10^9 ppp since the limit due to the counting rate in the drift chambers does not apply.

- Phase 2 (after completion of $\mathrm{Re}(\varepsilon'/\varepsilon)$):

  Request 120 days of 400 GeV/c protons with the best possible duty cycle to finish off the neutral $\mathrm{K_S}$ decays and achieve the proposed sensitivities for the rest of the $\mathrm{K_S}$ programme, notably $\mathrm{K_S} \to \pi^0 e^+ e^-$.