An overall review of the Kaon Physics results from NA48

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SuGRA20
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on behalf of the NA48 Collaboration
Cagliari, Cambridge, CERN, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Orsay, Perugia, Pisa, Saclay, Siegen, Torino, Warsaw, Wien
Introduction

Results on CP violation ($\Re(\varepsilon'/\varepsilon)$, $\delta_L(e)$, $\eta_{000}$)

By-product analysis ($K_S$ lifetime, $K$ mass, $\eta$ mass)

Results on Rare Decays ($K \rightarrow \pi^+\pi^-e^+e^-$, $K \rightarrow \pi^0\gamma\gamma, \gamma\gamma$)

News from NA48/1 - 2002

Summary
The NA48 beam lines

SPS spill length: 5.2 s
Cycle time: 16.8 s
Proton momentum: 400 GeV/c

Proton momentum: 400 GeV/c
Cycle time: 16.8 s
SPS spill length: 5.2 s

Target

K target

Ks tagging station
(~ 40 m long)

Ks anticounter
(AKS)

Ks

6.8 cm

0.6 mrad

Last collimator

Decay Region
(~ 40 m long)

~ 126 m

~ 114 m

Ks

K L

Bent cristal

Muon sweeping

~ 2.4 \times 10^{12} \text{ protons per spill}
Magnetic spectrometer

\[ \sigma_{X,Y} \sim 100 \, \mu m \]
\[ \sigma_{K \, mass} \sim 2.5 \, MeV/c^2 \]
resolution on \((x,y)\) vertex \(\sim 2\) mm → allows for beams separation

Liquid Krypton em calorimeter

with high granularity \((\sim 13500\) cells\)
\[ \sigma_t \sim 220 \, ps \]
\[ \frac{\sigma(E)}{E} < 1 \% \text{ for } E_\gamma > 25 \, GeV \]
\[ \sigma_{\pi^0 \, mass} \sim 1.1 \, MeV/c^2 \]
**Resolutions plots**

**LKr calorimeter**

\[ M(\gamma_1 \gamma_2) \ (\text{GeV}/c^2) \]

\[ M(\gamma_3 \gamma_4) \ (\text{GeV}/c^2) \]

\[ \sigma = 0.42 \text{ MeV}/c^2 \]

\[ \sigma = 0.83 \text{ MeV}/c^2 \]

\[ m_{\gamma \gamma} \] invariant mass in \( K_S \rightarrow \pi^0 \pi^0 \) candidates

**Spectrometer**

\[ M(\pi^+ \pi^-) \ (\text{GeV}/c^2) \]

\[ \sigma = 2.5 \text{ MeV} \]

\[ \bullet \ 2001 \]

\[ - \ 98+99 \]

Kaon invariant mass in \( K_S \rightarrow \pi^+ \pi^- \) candidates

R. Arcidiacono - Results from NA48

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NA48 data taking overview

1997
$K_L + K_S$
$\varepsilon'/\varepsilon$ run

1998
$K_L + K_S$
$\varepsilon'/\varepsilon$ run
$K_S$ lifetime,
$K_L$ rare decays

1999
$K_L + K_S$
$\varepsilon'/\varepsilon$ run
$K_S$ lifetime,
$K_L$ rare decays

K_S high
intens.
test run

2002
K_S high
intensity
K_S and Hyperons

2000
$K_L$
$\varepsilon'/\varepsilon$ checks
$K^0$ mass,
$K_L \to \gamma\gamma$

and Hyperons

2001
$K_L + K_S$
$\varepsilon'/\varepsilon$ run
$\delta_L(e), \delta_L(\mu)$

no spectrometer

R. Arcidiacono - Results from NA48

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The $K_S$ events are identified by tagging the parent proton (measurement of the proton time in the tagging station).
Re($\varepsilon'/\varepsilon$): the NA48 method

All experiments so far used the **Double Ratio method**:

$$R = \frac{N(K_L \rightarrow \pi^0\pi^0)[0.0009]}{N(K_S \rightarrow \pi^0\pi^0)[0.314]} \frac{N(K_S \rightarrow \pi^+\pi^-)[0.686]}{N(K_L \rightarrow \pi^+\pi^-)[0.002]} \simeq 1 - 6 \times \text{Re} \left( \frac{\varepsilon'}{\varepsilon} \right)$$

**Accuracy** $2 \times 10^{-4} \rightarrow$ count a lot of events in the most unbiased way

To exploit cancellation of systematic effects

- the 4 decay modes are taken simultaneously
- cancellation of fluxes, dead-times, inefficiencies, accidental losses
- from the same fiducial region (lifetime $\leq 3.5 \tau_S$) and two quasi-collinear beams, with offline lifetime weighting applied to $K_L$ events to equalize distribution of $K_S$ and $K_L$ decay positions
- with similar energy spectra
  - performing the analysis in energy bins to minimize the remaining $K_S / K_L$ differences
- small acceptance correction
- with high resolution detectors
- small background level
### History of $\varepsilon'/\varepsilon$ data collected by NA48

<table>
<thead>
<tr>
<th>Year</th>
<th>Days</th>
<th>ppp on $K_L$ target</th>
<th>$K_L \rightarrow \pi^0\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>89</td>
<td>$1 \times 10^{12}$</td>
<td>0.49 million $\Re(\varepsilon'/\varepsilon) = (18.5 \pm 4.5 \pm 5.8) \times 10^{-4}$</td>
</tr>
<tr>
<td>1998</td>
<td>135</td>
<td>$1.4 \times 10^{12}$</td>
<td>1.05 million $\Re(\varepsilon'/\varepsilon) = (15.0 \pm 1.7 \pm 2.1) \times 10^{-4}$</td>
</tr>
<tr>
<td>1999</td>
<td>128</td>
<td>$1.4 \times 10^{12}$</td>
<td>2.24 million $\Re(\varepsilon'/\varepsilon) = (13.7 \pm 2.5 \pm 1.8) \times 10^{-4}$</td>
</tr>
<tr>
<td>2001</td>
<td>90</td>
<td>$2.4 \times 10^{12}$ *</td>
<td>1.55 million</td>
</tr>
</tbody>
</table>

* modified beam parameters
in 2001 we collected additional data under varied conditions to test the intensity related systematics of the measurement

- SPS spill length/cycle time: $2.4/14.4$ s → $5.2/16.8$ s
- Duty cycle: $0.17$ → $0.31$
- Proton beam energy: $450$ GeV → $400$ GeV
- Instantaneous intensity: ~30% lower
- Detector: new drift chambers

![Graph showing Good K_L Events / 100 ms over time within a burst for 1999 and 2001]
# Comparing 2001 and 98+99 Results

<table>
<thead>
<tr>
<th>Corrections and uncertainties on $R$ (Units = $10^{-4}$)</th>
<th>2001</th>
<th>1998/1999</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistical error</td>
<td>± 14.7</td>
<td>± 10.1</td>
</tr>
<tr>
<td>$\pi^0\pi^0$ reconstruction</td>
<td>± 5.3</td>
<td>± 5.8</td>
</tr>
<tr>
<td>Acceptance</td>
<td>21.9 ± 3.5 ± 4.0</td>
<td>26.7 ± 4.1 ± 4.0</td>
</tr>
<tr>
<td>$\pi^+\pi^-$ trigger inefficiency</td>
<td>5.2 ± 3.6</td>
<td>-3.6 ± 5.2</td>
</tr>
<tr>
<td>Acceptance</td>
<td>± 1.1</td>
<td>± 3.0</td>
</tr>
<tr>
<td>illumination diff.</td>
<td>± 3.0</td>
<td>± 3.0</td>
</tr>
<tr>
<td>$K_S$ in-time activity</td>
<td>± 1.0</td>
<td>± 1.0</td>
</tr>
<tr>
<td>Accidentals: intensity diff.</td>
<td>6.9 ± 2.8</td>
<td>8.3 ± 3.4</td>
</tr>
<tr>
<td>Tagging inefficiency</td>
<td>± 3.0</td>
<td>± 3.0</td>
</tr>
<tr>
<td>$\pi^+\pi^-$ background</td>
<td>14.2 ± 3.0</td>
<td>16.9 ± 3.0</td>
</tr>
<tr>
<td>$\pi^+\pi^-$ reconstruction</td>
<td>± 2.8</td>
<td>± 2.8</td>
</tr>
<tr>
<td>beam scattering</td>
<td>± 2.0</td>
<td>± 2.0</td>
</tr>
<tr>
<td>$\pi^0\pi^0$ background</td>
<td>± 2.0</td>
<td>± 2.0</td>
</tr>
<tr>
<td>AKS inefficiency</td>
<td>± 0.3</td>
<td>± 0.4</td>
</tr>
<tr>
<td>Total correction and systematic error</td>
<td>+35.0 ± 6.5 ± 9.0</td>
<td>+35.9 ± 8.1 ± 9.6</td>
</tr>
<tr>
<td>double ratio $R$</td>
<td>0.99181</td>
<td>0.99098</td>
</tr>
</tbody>
</table>
\[ \Re(\varepsilon'/\varepsilon) : \text{the final result} \]

From 2001 data:

\[ \Re(\varepsilon'/\varepsilon) = (13.7 \pm 3.1) \times 10^{-4} \]

in agreement with NA48 previous measurements.

Combining the four years of data taking

\[ \Re(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4} \]

⇒ 6.7 \( \sigma \) away from 0

proposed accuracy has been reached 😊
World average of $\varepsilon'/\varepsilon$

naive average $\Rightarrow \Re(\varepsilon'/\varepsilon) = (16.6 \pm 1.6) \times 10^{-4}$

with a $\chi^2 = 6.3/3$
Not only $\varepsilon'/\varepsilon$ ....
\[ \delta_l(e) = \frac{BR(K_L \to \pi^- e^+ \nu_e) - BR(K_L \to \pi^+ e^- \bar{\nu}_e)}{BR(K_L \to \pi^- e^+ \nu_e) + BR(K_L \to \pi^+ e^- \bar{\nu}_e)} = 2\text{Re}(\epsilon) \]

\[ 200 \times 10^6 K_{e3} \quad (2001) \]

Analysis in pion momentum bins
Fake asymmetries studied

Corrections:
- trigger: 26.2 ± 6.0
- pion ID: -1.4 ± 3.5
- punch thru: -17.1 ± 2.4

\[ \delta \cdot 10^{-3} \]

\[ \chi^2 / n.d.f = 0.90 \quad (n.d.f. = 9) \]

\[ P_\pi \text{ (GeV/c)} \]

\[ \Rightarrow \delta_L(e) = (3.317 \pm 0.070_{\text{stat}} \pm 0.072_{\text{syst}}) \times 10^{-3} \]

New World Average: \( \delta_L = (3.310 \pm 0.054) \times 10^{-3} \) with a \( \chi^2 = 4.2/7 \)
\( K_{e3} \) : measurements overview

![Graph showing \( \delta_L \times 10^3 \) for various experiments like Columbia 69, Col.-Harv.-CERN 70, SLAC 72, Princeton 73, CERN-Heidelberg 74, KTEV 02, and NA48 03.]
\[ \eta_{000} = \frac{A(K_S \rightarrow \pi^0 \pi^0 \pi^0)}{A(K_L \rightarrow \pi^0 \pi^0 \pi^0)} \]

if CPT symmetry assumed

\[ \Re \eta_{000} = \Re \epsilon \]

\[ \Im \eta_{000} \text{ sensitive to direct CP violation} \]

\[ f(E, t) = \frac{I_{\text{near } \pi^0 \pi^0 \pi^0}}{I_{\text{far } \pi^0 \pi^0 \pi^0}} = A(E) \left[ 1 + |\eta_{000}|^2 e^{t/\tau_L - t/\tau_S} + 2D(E)e^{t/2\tau_L - t/2\tau_S} (\Re \eta_{000} \cos(\Delta mt) - \Im \eta_{000} \sin(\Delta mt)) \right] \]

5.9 \times 10^6 \pi^0 \pi^0 \pi^0 (KSHI 2000)

acceptance corrected at 1st order using data (from the K_L only run 2000)

fit in energy bin of \( f(E, t) \) range 70-170 GeV

fit parameters: \( A(E), \Re \eta_{000}, \Im \eta_{000} \)

Systematic sources: \( K^0 - \bar{K}^0 \) dilution, acceptance, accidentals, energy scale, binning
**η_{000} measurement**

\[ \chi^2 / \text{ndf} = 415/405 \]

Fixing \( \text{Re } \eta_{000} = \text{Re } \epsilon \)

\[ \text{Im } \eta_{000} = (-1.2 \pm 0.7_{\text{stat}} \pm 1.1_{\text{syst}}) \times 10^{-2} \]

**Fit result**

\[ \text{Re } \eta_{000} = (-2.6 \pm 1.0_{\text{stat}} \pm 0.5_{\text{syst}}) \times 10^{-2} \]

\[ \text{Im } \eta_{000} = (-3.4 \pm 1.0_{\text{stat}} \pm 1.1_{\text{syst}}) \times 10^{-2} \]

**Br: \( K_S \to \pi^0 \pi^0 \pi^0 \)< \(3.0 \times 10^{-7} \)

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**NA48 Preliminary**

**CPLEAR**

\[ \text{Re } \eta_{000} = (18 \pm 14_{\text{stat}} \pm 6_{\text{syst}}) \times 10^{-2} \]

\[ \text{Im } \eta_{000} = (15 \pm 20_{\text{stat}} \pm 3_{\text{syst}}) \times 10^{-2} \]

\( \eta_{000} \) fixed

\[ \text{Im } \eta_{000} = (-1.2 \pm 1.3) \times 10^{-2} \]
By-products of the $\varepsilon'/\varepsilon$ analysis
- **98 + 99 $\varepsilon'/\varepsilon$ data**
- $K_S$ lifetime derived from the ratio $K_S/K_L$ of decay time distributions
  - detector acceptance cancels in first approximation
- $\tau_S \ll \tau_L$, the ratio is primarily sensitive to the $\tau_S$

$N_S/N_L$ of $K^0 \to \pi^+\pi^-, \pi^0\pi^0$:
- corrected for residual acceptance differences due to beams geometry [MC]
- background subtracted ($10^{-3}$ in $K_L$ sample) using data
- fitted in bins of energy [70-170 GeV] and lifetime [0.5-3.5 $\tau_S$]
**K_S lifetime measurement overview**

Data samples: 13.2M \( K_S \rightarrow \pi^+\pi^- \), 12.2M \( K_L \rightarrow \pi^+\pi^- \), 3.1M \( K_S \rightarrow \pi^0\pi^0 \), 2.8M \( K_L \rightarrow \pi^0\pi^0 \)

\[ \tau_S = (0.89592 \pm 0.00052_{\text{stat}} \pm 0.00054_{\text{syst}}) \times 10^{-10} \text{ s} \]

\[ \tau_S = (0.89626 \pm 0.00129_{\text{stat}} \pm 0.00100_{\text{syst}}) \times 10^{-10} \text{ s} \]

**Combined result:**

\[ \tau_S = (0.89598 \pm 0.00048_{\text{stat}} \pm 0.00027_{\text{MCstat}} \pm 0.00043_{\text{syst}}) \times 10^{-10} \text{ s} \]

Measurement of $\eta$ and $K^0$ masses

Year 2000

$K^0$ mass: data with only $K_L$ beam

$\eta$ mass: special $\eta$ runs

Method

Using the $3\pi^0 \rightarrow 6\gamma$ decay channel:

1) the $z_{\pi^0}$ position is inferred using the $\pi^0$ mass constraint via the relation

$$d\ [z_{\pi^0}, LKr] = \frac{1}{M_{\pi^0}} \sqrt{E_1 E_2 d_{12}}$$

2) using the $d$ average from the $3 \pi^0$, the 6-body invariant mass is

$$M = \frac{1}{d_{\pi^0}} \sqrt{\sum_{i,j,i<j} E_i E_j (d_{ij})^2}$$

$M$ is independent of the energy scale of the calorimeter!
Measurement of \( \eta \) and \( K^0 \) masses

Only symmetric decays used (photons \( \sim \) the same energy) to minimize sensitivity to residual nonlinearities

\( M_\eta/M_\pi^0 \) measured with an accuracy three times better than the PDG world average

\( M_{K^0}/M_{\pi^0} \) measured with an accuracy similar to the PDG

**PDG 2000 Values:**

\[ M_{K^0} = 497.672 \pm 0.031 \text{ MeV}/c^2 \]

\[ M_\eta = 547.30 \pm 0.12 \text{ MeV}/c^2 \]

\[
M_\eta = \begin{array}{c} 547.843 \pm 0.030_{\text{stat}} \pm 0.005_{MC\text{stat}} \pm 0.041_{syst} \text{ MeV}/c^2 \\
M_{K^0} = 497.625 \pm 0.001_{\text{stat}} \pm 0.003_{MC\text{stat}} \pm 0.031_{syst} \text{ MeV}/c^2
\end{array}
\]

On Rare Decays
Radiative $K^0$ decays

In the $K_L$ case, interference between CP violating Inner Brem. and CP conserving Direct Emission processes, produces an asymmetry in the distribution of $\Theta$ between $\pi^+\pi^-$ and $e^+e^-$ decay planes

$\sim 14\%$

- **DATA SAMPLE:** $98 + 99\, \Re\epsilon(\varepsilon'/\varepsilon)$ period + KSHI test runs of 99
- **$K_S$ $K_L$ decay rates** normalized to $K_L \rightarrow \pi^+\pi^-\pi^0_D$ coming from $K_S$ $K_L$ targets respectively
- detailed Montecarlo study to remove backgrounds and to compute the acceptances of signals and normalization
\[ K_L \rightarrow \pi^+\pi^-e^+e^- \]

1162 candidates, expected background of 36.9 events

\[ BR(K_L \rightarrow \pi^+\pi^-e^+e^-) = (3.08 \pm 0.20) \times 10^{-7} \]

\[ A^S_\Phi = (14.2 \pm 3.6)\% \]
621 candidates (99 data) + 56 (98 data - published), expected background of 0.7 events

\[ \text{BR}(K_S \rightarrow \pi^+\pi^-e^+e^-) = (4.69 \pm 0.30) \times 10^{-5} \]

\[ A_\Phi^S = (0.5 \pm 4.3)\% \]

The results are in good agreement with the theoretical predictions

Large asymmetry observed in the angular correlation between \( \pi^+\pi^- \) and \( e^+e^- \) decay planes \(
\rightarrow \text{manifestation of indirect CP violation}
\)

No asymmetry observed in the \( K_S \) channel (as expected)
\( \chi PT \) and \( K_L \to \pi^0\gamma\gamma \) and \( K_S \to \gamma\gamma \)

\( O(p^4) \) diagrams:

\[
\begin{align*}
2.1 \times 10^{-6} & \quad \text{\includegraphics[width=0.3\textwidth]{diagram1}} \\
0.6 \times 10^{-6} & \quad \text{\includegraphics[width=0.3\textwidth]{diagram2}}
\end{align*}
\]

Similarities in these two decays:

- \( O(p^2) = 0 \), \( O(p^4) \) is unambiguously predicted by \( \chi PT \) (<5% precision)
- at \( O(p^6) \):

\[
\begin{align*}
K_L & \to \pi^0\gamma\gamma \\
\text{“scalar” exchange} & \quad \text{similar} & \quad K_S & \to \gamma\gamma \\
\text{“scalar” exchange} & + & \text{“scalar” exchange} & + \\
O(p^4) \text{ correction to} & A(K_L \to \pi^0\pi^+\pi^-) & a_V \text{ can be extracted from exper.} & m_{\gamma\gamma} \text{ distribution}
\end{align*}
\]

R. Arcidiacono - Results from NA48
**$\text{K}_S \rightarrow \gamma \gamma$**

$\gamma \gamma$ normalized to $\pi^0 \pi^0 \rightarrow$ most systematics cancel

### 2000 KSHI data

- 7500 estimated events in the signal region
- $-1 \, \text{m} < z_{\text{vertex}} < 5 \, \text{m}$

Main background:
- $2\pi^0$ with only 2 reconstr. clusters
- Irreducible $\text{K}_L \rightarrow \gamma \gamma$ ($\sim 1.5$ times $\text{K}_S$)

Use $\text{K}_L \rightarrow 3\pi^0$ to estimate $\text{K}_L$ flux, and 2000 $\text{K}_L$ run to measure $\frac{\Gamma(\text{K}_L \rightarrow \gamma \gamma)}{\Gamma(\text{K}_L \rightarrow 3\pi^0)}$

$$BR(\text{K}_S \rightarrow \gamma \gamma) = (2.78 \pm 0.06_{\text{stat}} \pm 0.02_{\text{MC stat}} \pm 0.04_{\text{syst}}) \times 10^{-6}$$


This result differs by 30% from $O(p^4) \chi PT$ prediction $\implies$ indication of large $O(p^6)$ contribution
$K_S \rightarrow \gamma\gamma$ measurements

$\chi_{PT}$

$O(p^4)$ $O(p^6)$

NA31 NA48/99 NA48/00

$BR(K_S \rightarrow \gamma\gamma) \times 10^6$
**KL, KS → π⁰γγ measurements**

**π⁰γγ signals normalized to π⁰π⁰**

88 +99 ε'/ε data: KL

2500 events with 3.2% estimated background

vector-meson coupling of \( a_V = -0.46 \)

negligible CP-conserving contribution to KL → π⁰e⁺e⁻

**BR(K_L → π⁰γγ) = (1.36 ± 0.03_{stat} ± 0.03_{syst}) \cdot 10^{-6}**


2000 KSHI run: KS

KS → π⁰γγ first observation: 31 events with 13.2 estimated background

**BR(K_S → π⁰γγ)_{zq>0.2} = (4.9±1.6_{stat}±0.8_{syst}) \cdot 10^{-8}**

χPT prediction= 3.8 \times 10^{-8}

preliminary
The NA48/1 - phase II

NA48/1: high intensity neutral short beam experiment
(mainly dominated by $K_S$ and neutral Hyperons)

NA48 detector, modified $K_S$ beam line, more powerful DAQ

Physics motivations

- Search for $K_S \rightarrow \pi^0 e^+e^-$, $K_S \rightarrow \pi^0 \mu^+\mu^-$ decays
- Measure semi-leptonic and radiative Hyperons decays, improving experimental results on $\Xi^0 \rightarrow \Sigma^+ e^-\nu$, $\Xi^0 \rightarrow \Sigma^+ \mu^-\nu$, $\Xi^0 \rightarrow \Sigma^0 \gamma$, $\Xi^0 \rightarrow \Lambda\gamma$
- Study other $K_S$ and Hyperon rare decays

Proposal goal: reach a SES of $2 - 3 \times 10^{-10}$ for $K_S \rightarrow \pi^0 e^+e^-$

Experimental set-up

- $K_S$ beam produced by $\sim 5 \times 10^{10}$ proton per pulse (500 times more than $\epsilon'/\epsilon$ config.)
  Accidental rate reduced by photon converter + sweeping magnet after the target
- detector prepared to maximize the particles flux
- DAQ speed up by some upgrades $\rightarrow$ double bandwidth
From July 18th to September 18th:

- Successful data taking: data quality is good!
- Analysis well advanced, both in the Kaon and in the Hyperon sector.

\[ N_{K_S} = \frac{\text{Downscale} \times N_{\pi^0\pi^0}}{\text{Acceptance} \times \text{BR}(K_S \rightarrow \pi^0\pi^0)} \approx 4.4 \times 10^{10} \]

\[ \text{SES (5% acceptance)} \approx 4.5 \times 10^{-10} \]
In 4 years of data taking, NA48 measured the direct CP violation parameter \( \Re(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4} \), with the proposed accuracy. The result is 6.7 \( \sigma \) from 0.

\( \delta_L(e) \) has been measured with competitive precision, \( \eta_{000} \) improved by an order of magnitude.

\( K_S \) lifetime, \( K \) mass, \( \eta \) mass measured with similar or better precision. \( \eta \) mass 4.2 \( \sigma \) from current world average.

On rare decays, several measurements testing \( \chi PT \) predictions have been done. First observation of \( K_S \to \pi^0\gamma\gamma \).

Active program to measure \( K_S \) rare decays and CP violation in the \( K^\pm \) decays [NA48/2!].