Future NA48 programs for hyperon rare decays and CP violation measurements

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The NA48 Collaboration has submitted two proposals to extend its physics program after the completion of the ϵ'/ϵ measurement. The first will address several topics in rare hyperon and K_S decays, using an high intensity K_S beam. In the second proposal the focus is on the measurement of direct CP violation in charged kaon decay, using simultaneous $K^\pm$ beams.

1. The NA48 experiment

The main objective of NA48 is the measurement of direct CP violation in neutral kaon decays. Useful data has been collected in the years 1997-1999 and two results based on '97 and '98 data have been presented [1] [2]. The very good performances of the detector together with a flexible trigger system allowed to accumulate also data useful for other kinds of analyses.

An example is an hyperon trigger which allowed the collaboration to do several measurements, including [3] [4]:

- Tranverse polarization of the Λ^0
- Ξ^--Ξ^0 mass difference and Ξ^0 mass
- Branching ratios of the Ξ^0 radiative decays

Another physics case is the study of rare decays of K_S. For this purpose a special test run has been done during 1999 during which the intensity of the K_S beam was increased by 200 times for about 2 days. Several results have been published and/or presented [5]:

- First observation of the decay $K_S \rightarrow \pi^+\pi^-e^+e^-$
- Upper limit on the BR of $K_S \rightarrow \pi^0e^+e^-$
- $K_S \rightarrow \gamma\gamma$

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Two proposals [6] [7] have been submitted to the CERN SPSC, for experiments to be run after the completion of the ϵ'/ϵ program. The first is intended to study K_S and hyperon decays using a high intensity K_S beam. The second will use a setup with two simultaneous positive and negative kaon beams to study direct CP violation in three pion decays, the $q\bar{q}$ condensate in the K_{e4} and other rare $K^\pm$ decays. These two proposals, currently under discussion in the SPSC Committee, have a good physics potential well beyond other existing experiments (KTEV, KLOE).

2. High Intensity K_S proposal

Following the experience of the high intensity test in 1999, it will be possible with minor optimization of the beam to achieve 400 times the standard K_S intensity. In one year of data taking (120 days, 50% efficiency), this translates in a Single Event Sensitivity (SES) of 3 $\cdot 10^{-11}/\alpha$, where α is the acceptance for a given decay mode after all cuts. As an example, for the decay $K_S \rightarrow \pi^0e^+e^-$, with an acceptance of 0.05, the SES will be 6 $\cdot 10^{-10}$, 500 times better than the actual limit.

2.1. Neutral hyperon decays

The high statistics will improve the measurement of the decays already considered and will allow new searches. It will be possible to improve the statistical and systematic errors on the Ξ^--

Ξ^0 mass difference down to 0.1 Mev/c, the current error on the mass of Ξ^-. The systematic error on Ξ^0 radiative decays could be improved by a factor 2, achieving a global error of 5%.

The β decay of the Ξ^0 ($\Xi^0 \to \Sigma^+ e^- \bar{\nu}$) can be detected identifying the electron in the calorimeter and the Σ^+ via the pπ^- decay mode. 25000 events could be collected, for a new consistency check of the SU(3) symmetry and the Cabibbo model in hyperon decays.

The double strangeness decay $\Xi^0 \to p\pi^-$ has a present limit on the branching ratio of $4{\cdot}10^{-5}$ at 90% CL and it could be improved by a factor of at least 500.

The accumulated statistics will also allow to start looking into Σ physics, with Σ^0 from the decay $\Xi^0 \to \Sigma^0\gamma$.

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

The decay $\mathrm{K_S} \to \pi^0 \mathrm{e^+e^-}$ places a bound on the indirect CP violating term in the $\mathrm{K_L}$ decay. Of the three contributions to the $\mathrm{K_L}$ decay, the two CP violating ones interfere and a_s, the magnitude of the indirect CP violating component, is related to the BR of $\mathrm{K_S} \to \pi^0 \mathrm{e^+e^-}$ via the relation [8]

$$\mathrm{BR}(\mathrm{K_S} \to \pi^0 \mathrm{e^+e^-}) = 5.2{\cdot}10^{-9} \mid a_s \mid^2$$

A naive dimensional analysis gives $a_s \approx \mathrm{O}(1)$, but the degree of confidence is low, so it is important to measure the branching ratio experimentally. The proposal would yield about 7 events at $a_s = 1$. The backgrounds ($\mathrm{K_L} \to \mathrm{e^+e^-}\gamma\gamma$, $\mathrm{K_S} \to \mathrm{e^+e^-}\gamma\gamma$, $\mathrm{K_S} \to \pi^0\pi^0_{dalitz}$ with one lost photon) should be negligible with appropriate cuts.

2.3. CP violation in $\mathrm{K_S} \to \pi^0\pi^0\pi^0$

It is planned to improve the CPLEAR [9] and the SND [10] limits on η_{000} by a factor 10. Re(η_{000}) is given by the CP violation in the K^0-$\bar{K}^0$ mixing and Im(η_{000}) is in principle sensitive to direct CP violation. A better limit on η_{000} will also allow an improved test of CPT based on the Bell-Steinberger unitarity relation.

The experiment will measure the $\mathrm{K_L}$-$\mathrm{K_S}$ interference near the production target. The combination of high energy beam and good calorimeter resolution ($\approx 0.1\ c\tau_s$) will compensate, more than in CPLEAR, the loss of events in the first lifetime due to the presence of the collimator.

2.4. $\mathrm{K_S} \to \gamma\gamma$ and $\mathrm{K_S} \to \pi^0\gamma\gamma$

The study of these two decays is important for the understanding of the low energy hadron dynamics of the Chiral Perturbation Theory (ChPT) [11]. $\mathrm{K_S} \to \gamma\gamma$ is especially interesting because ChPT predicts that the BR is $2.25{\cdot}10^{-6}$ within 10% uncertainty.

The expected number of events (for $3{\cdot}10^{10}$ $\mathrm{K_S}$ decays in the decay region) will be $\approx$ 24000 for $\mathrm{K_S} \to \gamma\gamma$ and $\approx$ 1200 for $\mathrm{K_S} \to \pi^0\gamma\gamma$.

2.5. Competition

As far as $\mathrm{K_S}$ decays are concerned, the competition comes from KLOE. However, even at the full DAΦNE design luminosity of $5\times\ 10^{32}$ cm^{-2}s^{-1}, the sensitivity per year for $\mathrm{K_S} \to \pi^0 \mathrm{e^+e^-}$ is less than the NA48 proposal.

The competition for neutral hyperon decays comes from KTEV, which collects hyperons from the vacuum beam. However, the NA48 proposal is up to one order of magnitude better than KTEV.

3. The charged kaon proposal

The study of charged kaon decays, done with high statistics and systematic accuracy, can give new informations about direct CP violation, existence of $q\bar{q}$ condensate of the QCD vacuum, measurement of ChPT parameters and detection of possible deviations from V-A theory.

The NA48 proposal will use simultaneous $\mathrm{K^\pm}$ beams of a novel design and a transition radiation detector added to the NA48 apparatus.

3.1. Direct CP violation in $\mathrm{K^\pm}$ decays

The latest results from NA48 [1] [2] and KTEV [12] have confirmed the value of ϵ'/ϵ measured by NA31 at CERN [13]. The new world average is higher than the theoretical predictions, which could indicate disagreement with the SM or at least problems in the non-perturbative calculations of the decay matrix element. A measurement of direct CP violation in other processes could therefore be of great relevance. Direct CP violation could manifest itself in particular in an asymmetry of the slope of the Dalitz plot density of events as a function of the kinetic energy of the π^+ and π^- for $\mathrm{K^+} \to \pi^+\pi^+\pi^-$ and

$K^- \to \pi^-\pi^-\pi^+$.

The matrix element for these decays could be parametrized as

$$| M(u,v) |^2 \propto 1 + g \cdot u + h \cdot u^2 + k \cdot v^2$$

where $u = (s_3 - s_0)/m_\pi^2, v = (s_1 - s_2)/m_\pi^2, s_0 = (s_1 + s_2 + s_3)/3, s_i = (P_K - P_i)^2$ and i=3 is the odd pion. The coefficients g, h, k should be equal for the two K charges if CP is conserved. Direct CP violation will show up with a value different from zero of the asymmetry

$$A_g = \frac{g^+ - g^-}{g^+ + g^-}$$

where g^+ and g^- are the above defined coefficients for K^+ and K^- respectively.

Theoretical papers [14] [15] [16] [17] [18] predict values for A_g ranging from 10^{-5} to 10^{-4}. The only dedicated measurement, based on $1.6 \cdot 10^6$ events has given $A_g = (-7 \pm 5) \cdot 10^{-3}$ [19]. HyperCP at Fermilab [20] has $2 \cdot 10^8$ K^- decays and twice as many for K^+, but it is not specifically studied for high systematic accuracy in $K^\pm$ decays.

The experiment will measure the ratio

$$R(u) = \frac{\int dv |M^+(u,v)|^2}{\int dv |M^-(u,v)|^2} \approx 1 + u \cdot (g^+ - g^-)$$

as a function of the variable u.

In order to reduce at the minimum systematic effects which could simulate an A_g different from zero, we plan to take data using simultaneous overlapping K^+ and K^- beams derived from the same target, alternating in sign the spectrometer field to equalize the acceptances in the presence of possible localised imperfections in the detector, binning data in reconstructed kaon momentum and averaging the ratios measured with different magnetic field polarities.

In one year of SPS operation we expect to collect $2 \cdot 10^9$ $K^\pm \to \pi^\pm\pi^+\pi^-$ decays and also $1.2 \cdot 10^8$ $K^\pm \to \pi^\pm\pi^0\pi^0$ decays, giving respectively a statistical accuracy of $1.7 \cdot 10^{-4}$ and $3.1 \cdot 10^{-4}$.

To evaluate the slope difference induced by systematic errors, a Montecarlo simulation has been performed, considering the possible asymmetries in the beams and/or in the response of the detector. In addition, semileptonic decays of K_L have been used to set upper limits to effects due to difference in π^+ and π^- interactions in the material of the detector. The result of these studies is that the systematics could be kept at a level less than few parts in 10^{-5} if the data are taken and analyzed with the procedure mentioned above.

3.2. Study of $K^\pm \to \pi^+\pi^-e^\pm\nu$ decays

K_{e4} decays allows to verify the hypothesis that chiral symmetry is spontaneously broken by the formation of a strong $q\bar{q}$ condensate in the QCD vacuum. Up to now this hypothesis has no experimental confirmation. The dependence of the π mass on m_u and m_d is analyzed in ChpT [21] and leads to the prediction that in the low energy $\pi\pi$ scattering the S-wave is particularly sensitive to the condensate. The interesting parameter in K_{e4} decay is the the S-wave scattering amplitude a_0^0.

A CERN experiment in 1977 (30000 decays)[22] did not collect enough statistics to support unambiguosly the condensate. In Brookhaven a new experiment [23] is analysing about 10 times that statistics which still appears to be marginal. The NA48 proposal expects to collect more than 10^6 K_{e4} decays in one year, giving an accuracy of 0.01 on a_0^0.

3.3. Other decays

Radiative decays of $K^\pm$ can be used to test the validity of ChPT. With the available statistics will be possible to improve the accuracy or the upper limit of their BRs. The latest measurement of the decay $K^\pm \to \pi^0 e^\pm \nu(\bar{\nu})$ gives significant values of the scalar and tensor form factors, indicating a deviation from V-A theory. To test this, the proposed experiment is expected to be at least 3 times more precise than [24].

3.4. Competition

The competition for the direct CP violation is coming from HyperCP (completed, but with 10 times less statistics than proposed and with no comparable systematics control) and KLOE, which anyway will not collect more that one tenth of the NA48 statistics in one nominal year.

For the K_{e4}, KLOE could get of the order of $3 \cdot 10^5$ K_{e4} decays per year.

3.5. The beams

To compare K^+ and K^- with the minimum systematic error, a design to transport simultaneously positive and negative beams has been conceived. The primary proton beam hits a target at 0 degrees. The central momentum and the momentum bite are selected symmetrically with a system of magnets and collimators (so called achromats) which then recombine the beams onto a common axis. The optimum momentum will be 60 $\pm$ 6 GeV/c. There will be $1.9 \cdot 10^6$ K^+ and $1.1 \cdot 10^6$ K^- per pulse, which, in one year of running, will give in a 50 m decay region $5.5 \cdot 10^{10}$ K^+ and $3.1 \cdot 10^{10}$ K^-. A K_L beam (simultaneous or alternated with the $K^\pm$ beams) will be used to monitor potential systematic effects.

3.6. Detector upgrade

3.6.1. Beam Spectrometer

The measurement of the K_{e4} decay is unambiguosly determined if the kaon momentum is measured. To do so, it is proposed to install tracking detectors in three positions along the beams in the second achromat, to measure the position of the kaons to compute their momentum and direction. High rate capability is needed ($\approx 4 \cdot 10^7$ part/s) together with minimum material along the beam ($\leq 10^{-3} X_0$). It is planned to use a Micromegas like detector [25]. Simulations show that it is possible to get resolution in time better than 1 ns, in momentum better than 1% and in the angle of 10^{-2}, with a minimal amount of material.

3.6.2. Transition Radiation detector

To improve electron identification in K_{e4} decays, it is planned to add a transition radiation detector to the NA48 apparatus. A basic requirement is to have π/e rejection bigger than 100 with an electron efficiency of 90% between 1 and 50 GeV/c.

It is proposed to install in front of the LKr calorimeter 7 modules of the NOMAD TRD [26] with suitable modifications .

Simulation of this TRD in the NA48 environment shows that for $K^\pm \to \pi^\pm \pi^+ \pi^-$ (the main background to K_{e4}) the rejection factor is 345 at ϵ_e=90% and 111 at ϵ_e=95%.

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