Kaon identification in the NA62 experiment at CERN

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The main purpose of the NA62 experiment at the CERN SPS is to measure the Branching Ratio of the ultra-rare kaon decay $K^+ \to \pi^+\nu\bar{\nu}$ with 10% accuracy. This will be achieved by collecting about 100 events with a Signal to Background ratio of 10/1. NA62 will use a 75 GeV/c unseparated charged hadron beam and a kaon decay-in-flight technique. For the kaon identification a hydrogen gas-filled differential Cherenkov counter (CEDAR) is placed in the incoming beam. The CEDAR detector is required to achieve a kaon identification efficiency of at least 95% with a time resolution of about 100 ps.

Keywords: Kaon decays; Cherenkov detectors; Gas filled counters.

1. The NA62 experiment at CERN SPS

The NA62 experiment[1] at the CERN SPS is designed to use rare kaon decays to probe physics Beyond the Standard Model in a complementary way respect to the direct searches for potential new particles at the LHC. The main goal of NA62 is the measurement of the Branching Ratio (BR) of the decay $K^+ \to \pi^+\nu\bar{\nu}$ with 10% accuracy. The study of this process provides a determination of the CKM matrix element $|V_{td}|$ and the theoretical computations of its rate can reach an exceptionally high degree of precision[2]. The $K^+ \to \pi^+\nu\bar{\nu}$ decay is a flavor-changing neutral-current channel forbidden at a tree-level. The leading SM contribution to the matrix element is dominated by short-distance processes mediated by quark loops, where the top quark exchange is the dominant component. The required hadronic matrix elements can be extracted from the accurately measured leading semileptonic decay $K^+ \to e^+\pi^0\nu$ via isospin rotation[3]. The experimental status is based on 7 events collected by the E787/949 collaborations at BNL[4]: $BR(K^+ \to \pi^+\nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$. The measured value is compatible with the SM prediction[5]:$(7.81 \pm 0.80) \times 10^{-11}$. The NA62 strategy is to collect about 100 events of the rare kaon decay $K^+ \to \pi^+\nu\bar{\nu}$, keeping the background contamination lower than 10%, in two years of data taking starting after LHC shutdown in 2013.

2. The kaon identification in NA62

NA62 is a fixed-target experiment that uses 400 GeV/c protons from the SPS to produce a 75 GeV/c secondary unseparated hadron beam. The main beam components are pions ($\sim$ 60%) and protons ($\sim$ 20%), while kaons correspond to the 6%. NA62 exploits a kaon decay-in-flight technique free from the background due to multiple scattering of kaons impinging on the stopping target. The advantages of using a high energy beam is that the kaon production cross-section increases with the proton energy and that the background rejection improves for high energy decay products. The disadvantage is that kaons cannot be efficiently separated from pions and protons at the beam level: upstream detectors, which tag the kaons and measure their momentum and direction, are then exposed to a particle flux about 17 times larger than the useful (kaon) one. It is crucial to make a positive identification of the minority particles of interest, kaons, in the high rate beam environment before they decay. This is achieved by placing a *ChErenkov Differential counter with Achromatic Ring focus* (CEDAR) in the incoming beam; the CEDAR is insensitive to pions and protons with minimal accidental mis-tagging. The CEDAR detector is required to achieve a kaon identification efficiency of at least 95%. In addition, a time resolution of $\sim$ 100 ps, in conjuction with timing information from other detectors, is necessary to reconstruct the $K^+ \to \pi^+ \nu\bar{\nu}$ decay and ensure the rejection of the background due to the accidental overlap of events in the NA62 detector.

3. The CEDAR counter

The counter was built in the early 80s at CERN for application in the SPS secondary beams[6]. Two different versions exist: a "CEDAR-North" optimized for operation with helium gas and high energies (K/π separation up to 300 GeV/c); a "CEDAR-West" optimized for operation with nitrogen gas and used with low momentum beam (K/π separation up to 150 GeV/c). A simulation programme verified that the West version will function well for NA62 purposes. A test beam on a CEDAR-West counter was performed in 2006 and its results validated the counter ability to distinguish kaons from pions and protons in NA62.
The CEDAR counter (Fig. 1) is a $\sim$ 6 m long vessel filled with gas of controlled pressure. For a given beam momentum, the Cherenkov angle of

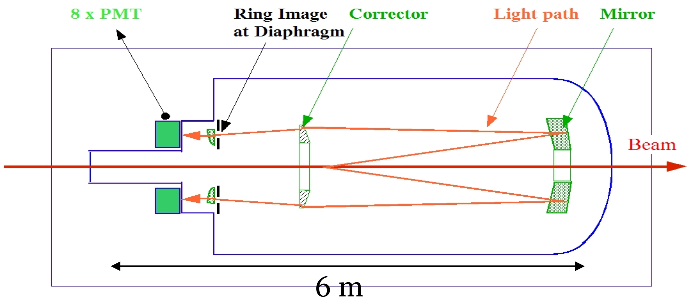

Fig. 1. The CEDAR layout

the light emitted by a charged particle traversing the radiator is a unique function of the mass of the particle and the wavelength of the emitted light. A spherical Mangin mirror, located at the end of the vessel, reflects the Cherenkov light back on a ring-shaped diaphragm with an adjustable aperture width. A chromatic corrector system reduces the severe effect of chromatic dispersion. Under the assumptions of a minimal beam divergence ($< 80\mu$rad) and a precise alignment of the optical and beam axis, the Cherenkov light produced by the particles of interest (kaons) is transmitted by the internal optics through the diaphragm aperture. Behind the diaphragm eight condenser lenses focus the light on eight photomultipliers (PMT). Although kaons are the minority particles ($\sim 6\%$) of the beam, the kaon rate in the high-intensity beam for NA62 will be ~ 50 MHz (average). The Cherenkov light yield expected at the exit windows of the CEDAR vessel is about 250 photons per kaon, which translates in a photon rate of $\sim$ few MHz/mm^2. The existing CEDAR PMT and readout electronics are inadequate to cope with this illumination and need to be replaced.

4. The CEDAR upgrade design

An upgraded CEDAR-West design has been proposed to positively tag incident kaons at the required rate of 50 MHz. It uses hydrogen instead of nitrogen as radiator to reduce the beam scattering in the gas and it is equipped with new photomultipliers (PMT) and readout electronics. The eight light spots produced by the internal optics on the exit windows of the vessel are projected onto new PMT planes by means of external spherical mirrors and a 90-degrees reflection (Fig. 2). The achieved light spots on new PMT planes are enlarged and uniform.

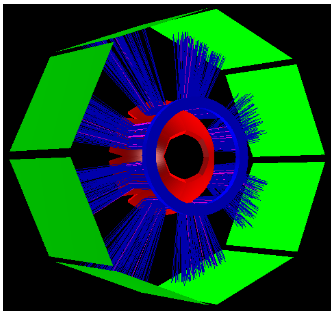

Fig. 2. New design of CEDAR external optics: exit windows (blue), spherical mirrors (red) and PMT planes (green)

The technology choice for the CEDAR photon detector consists of metal package photomultipliers of the HAMAMATSU R7400[7] series, U-03 (UV glass window) type, which were chosen for their smallness, capability of single photon counting, ability of standing at high rate per unit area, UV/blue light sensitivity with the highest efficiency, excellent time resolution, limited anode current, feasibility under radiation exposure. The light collection system design is an array of cones and PMTs packed in a compact configuration to reduce the effect of dead areas. A safety requirement resulting from the mechani cal modifications and the use of hydrogen gas is a nitrogen-filled environmental casing around the optical-readout electronics and HV, which is mandatory to eliminate any possibility of an explosion in the event of a hydrogen leak from the CEDAR.

5. The CEDAR simulation

In the proposed design the photon flux on single PMT device is ≤ 5 MHz and the PMT anode current is kept within a safe limit (two order of magnitude lower than the sustainable value stated in the datasheet). The photon rate implies several limitations on the performances of the photon detection involving event pile-up, electronics dead time and smearing effects on the readout system. A FLUKA[8?] simulation and dedicated studies of the beam halo have been used to evaluate the expected neutron and muon doses on the CEDAR, which are ~ 0.4 Gy/year and ~ 0.3 Gy/year, respectively. A Geant4 MC simulation programme is used to study the optimal configuration for the CEDAR photon detector, which is the one providing a maximum light collection and Kaon ID efficiency as well as a manageable rate for PMTs and readout channels (≤ 5 MHz). The Geant4 simulation allows to perform several studies with the hydrogen-filled CEDAR-West:

(a) evaluate the kaon-pion separation achievable with the counter;
(b) optimize the diaphragm aperture width for kaons;
(c) maximize the kaon ID efficiency;
(d) minimize the pion suppression;
(e) control the number of detected photons per kaon;

The CEDAR-West internal optics is not optimized for operation with the hydrogen gas, as a consequence the Cherenkov photon spectrum produced by kaons peaks at two different radii on the diaphragm plane and the low wavelength part is mostly unusable being in a region not free from pions. Preliminary simulations have showed that the hydrogen-filled CEDAR-West counter can work optimally at diaphragm apertures > 1.5 mm (standard aperture width previously fixed for the nitrogen-filled version). This modification is necessary to compensate the significant photon loss at low wavelengths due to the pion contamination. By requiring at least a 6-fold coincidence among the eight light spots a kaon ID efficiency $> 95\%$ is achievable with a diaphragm aperture width of ~ 3.5 mm. For a single photon time resolution[9] of ~ 300 ps, the mean value of detected photons per kaon provides a kaon time resolution better than 100 ps.

6. CEDAR test beam at CERN

A test beam of a prototype of the CEDAR-West will be performed in October 2011. The validation of the Cherenkov counter assigned for application in NA62 and the test of new PMTs, front-end and readout electronics will be achieved during the test.

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