5.5 Two Very Special K^0 Beams: Discovery of Direct CP Violation

Niels Doble and Lau Gatignon

Technology Meets Research Downloaded from www.worldscientific.com
by GERMAN ELECTRON SYNCHROTRON @ HAMBURG on 05/10/17. For personal use only.

A pair of simultaneous and nearly collinear beams of long- and short-lived neutral kaons, K^0_L and K^0_S, formed an integral part of the NA48 experiment, aimed at studying direct CP-violation [Box 3.4] at the SPS. This study required the four decay rates, $K^0_L \to \pi^0\pi^0$, $K^0_L \to \pi^+\pi^-$, $K^0_S \to \pi^0\pi^0$, $K^0_S \to \pi^+\pi^-$, to be measured with extremely high relative accuracy in a common set of detectors [30], among which a liquid krypton calorimeter [Highlight 5.6] played an essential role. The two beams were obtained by a novel application of a bent silicon crystal.

Design Concept

Key to the success of NA48 was its concept to minimize painstakingly systematic errors in the relative decay rate measurements. The K^0_L and K^0_S beams were therefore designed to enter the same fiducial region simultaneously and along adjacent lines, converging at a small angle towards the NA 48 detectors.

A primary proton beam of high momentum (450 GeV/c) and high flux ($\sim 10^{12}$ protons/s) was required to produce sufficient numbers of the rare, CP-violating $K^0_L \to 2\pi$ decays. A much lower proton flux (by a factor $\sim 10^{-5}$) sufficed to produce comparable numbers of K^0_S decays. The high-intensity K^0_L beam was obtained from a branch of the slow-extracted high-intensity primary proton beam from the SPS. A small fraction of these protons was shaved off using the phenomenon of ‘channelling’ in a bent crystal to derive the proton beam for the K^0_S production [Box 5.3]. The channelling method offered three advantages: the selected protons were reduced in flux, deflected and defined to have a suitable small emittance. Moreover, the relatively low flux of protons could be detected and tagged individually, so as to attribute them to the correct K^0 beam.

Two target stations, one for high-rate K^0_L production, the other one for low-rate K^0_S production were used. They had to be located at quite different distances from the detectors, given the very different decay lengths of K^0_L and K^0_S ($\lambda_L = 3480$ m, $\lambda_S = 6.0$ m, at a mean momentum of 110 GeV/c).

The acceptances for detecting $\pi^0\pi^0$ and $\pi^+\pi^-$ decays were each functions of the kaon momentum (p_K) and longitudinal position of the decay vertex (z). It was therefore important that the momentum spectra of the K^0_L and K^0_S decays were as similar as possible over the useful range of momenta ($70 < p_K < 170$ GeV/c) and of z. To this end, the z-range was chosen taking into account the K^0_S decay length (λ_S) and weighting factors were then applied to equalize the z-distributions and hence the detector acceptances for K^0_S and K^0_L decays.

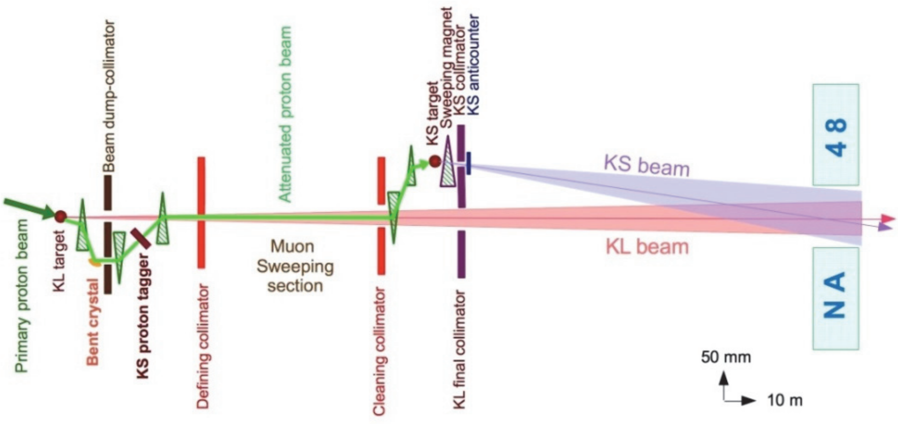

Fig. 5.13. Schematic layout of the K^0 beams.

Layout

The beams were derived from protons striking two separate targets, located at 126 m and 6 m, before the beginning of the decay region, upstream of NA 48. The layout of the beams is shown in Fig. 5.13.

The K^0_L beam

The K^0_L beam (red cone in Fig. 5.13) was produced by the primary beam from the upstream target at a small angle to reduce the neutron flux. The beam, after emerging from the opening in a beam dump-collimator, passed through three successive collimators, designed to maximize the acceptance of the beam and to minimize backgrounds outside the central apertures of the detectors.

A vertically-deflecting dipole magnet after the K^0_L target swept away charged particles, whereby the primary protons, which had not interacted, were deflected downwards to impinge on the channelling crystal, situated below the K^0_L beam axis. The crystal was designed to split off the wanted, small fraction of the protons and to deflect them upward, back to the horizontal. The majority of protons and other particles, which were not deflected by the crystal, were absorbed in the beam dump-collimator.

The K^0_S beam

The low-intensity proton beam required for the K^0_S beam was generated with the channelling crystal (Fig. 5.14) [31]. A silicon mono-crystal was used, cut to dimensions $60 \times 18 \times 1.5$ mm^3, parallel to the 110 plane. It was bent through an angle θ_0 (greater than the required beam deflection angle, $\theta = 9.6$ mrad) over 56 mm of its length, by pressing it with rollers against the cylindrical surface of an aluminium block, precisely machined to have a radius of curvature, $R = 3$ m. The

Technology Meets Research Downloaded from www.worldscientific.com
by GERMAN ELECTRON SYNCHROTRON @ HAMBURG on 05/10/17. For personal use only.

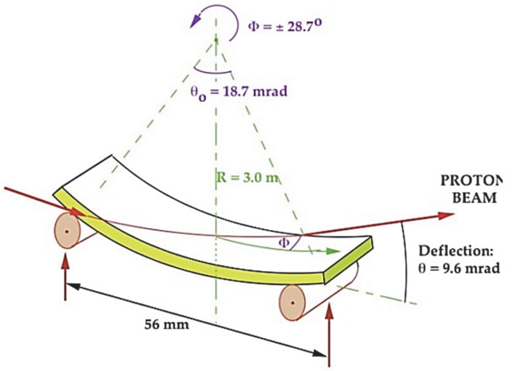

Fig. 5.14. Schematic arrangement of the bent crystal [31].

holder was mounted on a motorized goniometer, which allowed the crystal to be aligned with two transverse displacements and two rotations about axes perpendicular to the incident beam. When the crystal was rotated through an angle Φ about the vertical axis, the beam traversed the crystal from one edge to the other. The effective distance traversed in the crystal, and hence the vertical angle of the beam deflection, was controlled by adjusting Φ. With this set-up the orientation of the crystal could be chosen to adjust the deflection of the beam and its emittance.

The beam dump-collimator following the crystal contained a passage for the channelled protons, below that for the K^0_L beam. The protons (green line in Fig. 5.13) were brought back onto the K^0_L beam axis, passing through a 'tagging station' on the way. With a coincidence measurement between this station and the principal detectors of the experiment, an observed K^0 decay could be attributed or not to the K^0_S beam. The protons were then refocused and steered onto the K^0_S target.

The production angle of the K^0_S beam (blue cone in Fig. 5.13) was chosen to make the ratio of K^0_S and K^0_L decays in the fiducial region as similar as possible over the momentum range used (70 GeV/c–170 GeV/c). After a sweeping magnet and appropriate collimation with passages for the two neutral beams, the K^0_L and K^0_S beams emerged into the common decay volume and converged to the centre of the detectors at a distance of 120 m from the K^0_S target.

To count the $K^0_S \to \pi^+\pi^-$ and $K^0_S \to \pi^0\pi^0$ decays with the same acceptance, the beginning of the decay fiducial region had to be defined precisely. For the charged decay mode, this was done directly using a thin scintillation counter at the exit of the K^0_S collimator to detect the $\pi^+\pi^-$. For the neutral decay mode, the photons from the quasi-instantaneous decay of the π^0's were converted to e^+e^- in a disc of high-Z material placed immediately in front of the counter. The thickness and scattering

Technology Meets Research Downloaded from www.worldscientific.com
by GERMAN ELECTRON SYNCHROTRON @ HAMBURG on 05/10/17. For personal use only.

effect on the beam of this material was minimized by using another, carefully-aligned, crystal (iridium), which coherently enhanced the conversion probability.

This pair of beams served to establish direct CP-violation in the decay of neutral kaons by experiment NA48 from 1997 to 2002 [32]. The line was subsequently transformed to provide another pair of simultaneous beams, this time of oppositely-charged kaons (K^+ and K^-), into the same set of detectors [33].

Technology Meets Research Downloaded from www.worldscientific.com
by GERMAN ELECTRON SYNCHROTRON @ HAMBURG on 05/10/17. For personal use only.

5.6 Liquid Krypton Calorimetry: Elucidating Nature's Subtle Asymmetries

Italo Mannelli

The discovery of the violation of Charge–Parity (CP) symmetry shook the foundations of physics [Box 3.4]. Considerable experimental efforts followed, spanning more than 20 years, seemingly indicating that this effect was confined to K^0 – anti-K^0 mixing. In parallel, however, with the development of the Standard Model incorporating three families of quarks [Box 6.4], the presence of a further mechanism of CP Violation (Direct CP Violation) was predicted in kaon decays. This would manifest itself as a difference in the ratio of K_L decays into charged to neutral pion-pairs relative to this ratio in K_S decays. The effect was predicted to be subtle. Experimental searches turned out to be not sensitive enough, mostly due to the lack of adequate techniques to measure the kaon decays to two neutral pions.

First evidence for Direct CP violation was obtained at the CERN SPS by the NA31 experiment in 1987. An analogous experiment at FNAL did not support the CERN result. The need was recognized by both collaborations for new experiments, taking advantage of novel technical developments, which could achieve an order of magnitude higher statistical and systematic accuracy.

Key to the success was the quality of the measurement of the neutral pion decay into two photons with energies up to 100 GeV. This required the e-m calorimeter to be homogeneously sensitive for best resolution. It also had to locate the position of the photon showers with millimetre accuracy to reconstruct the neutral pions. The newly-formed CERN-based NA48 collaboration bet on an audacious, novel concept: the development of an ionization calorimeter with liquid krypton (LKr) as the active absorber.

Why an ionization calorimeter? Previous incarnations, using liquid argon (LAr), had demonstrated the superior control of systematic effects and long-term stability [Highlight 4.10]. Why LKr? It has three times the absorption power compared to LAr. A 100 GeV photon shower is contained in a length of 125 cm; the transverse shower size is reduced by about a factor two compared to LAr,