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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

The NA48 liquid krypton prototype calorimeter

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The NA48 experiment for a precision measurement of the CP violation parameter ϵ'/ϵ in $K^0 \to 2\pi$ decays will require a fast electromagnetic calorimeter with excellent energy and time resolution. A quasi homogeneous calorimeter using liquid krypton and a fast readout with 40 MHz FADCs is proposed. A prototype with 400 kg of liquid krypton was built and tested in an electron beam. Results for the energy, space and time resolution of this prototype are given.

1. Introduction

1.1. The NA48 experiment

The objective of the NA48 experiment [1] is a precision measurement of the CP violation parameter ϵ'/ϵ in $K^0 \to 2\pi$ decays to an accuracy of 2×10^{-4}. A measure for the CP violation is the double ratio R:

$$R = \frac{\Gamma(K_L \to 2\pi^0)}{\Gamma(K_S \to 2\pi^0)} \Big/ \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} = 1 - 6\,\mathrm{Re}(\epsilon'/\epsilon).$$

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Recent preliminary results for $\mathrm{Re}(\epsilon'/\epsilon)$, presented at the LP-HEP 1991 Conference in Geneva, are

CERN, NA31: $(2.3 \pm 0.7) \times 10^{-3}$ (see ref. [2]),
FNAL, E731: $(0.60 \pm 0.69) \times 10^{-3}$ (see ref. [3]).

NA48 is planned to run with at least ten times the beam intensity and event rates as compared to NA31 to reduce statistical errors. Systematic uncertainties will also be reduced by a factor of three.

The main features of NA48 include the concurrent detection of all four relevant decay modes ($K_L \to \pi^+\pi^-$, $K_L \to 2\pi^0$, $K_S \to \pi^+\pi^-$ and $K_S \to 2\pi^0$), the use of almost collinear K_L and K_S beams distinguished by tagging the K_S producing proton, a magnetic spectrometer to measure the charged decays (π^+, π^-), a fast liquid krypton calorimeter to detect the photons

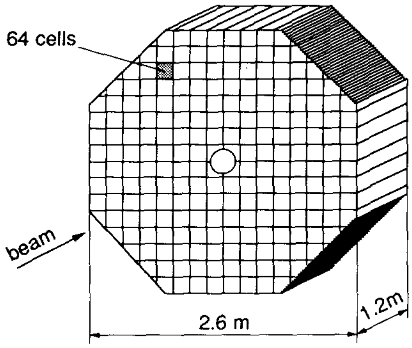

Fig. 1. Proposed cell structure of the octagonal NA48 LKr calorimeter. The central beam hole is to allow undecayed particles to pass through the calorimeter.

from π^0 decays, a 40 MHz flash ADC readout, and a fully pipelined trigger.

1.2. The liquid krypton calorimeter

A fast electromagnetic calorimeter with an excellent energy resolution is required to detect the neutral $K_{L,S} \to 2\pi^0$ decays and to reduce the neutral $K_L \to 3\pi^0$ background (expected single rate is about 1 MHz). The useful photon energy range will be between 2 and 100 GeV with an average of about 25 GeV. The energy resolution aimed for is

$$\frac{\sigma}{E} = \frac{3\%}{\sqrt{E}} \oplus 0.5\% \oplus \frac{0.03}{E},$$

where $\oplus$ denotes addition in quadrature and E is given in GeV.

The time resolution should be better than 1 ns and the space resolution should be better than 1 mm. The two photon separation should be better than 4 cm.

To achieve these design goals a liquid krypton calorimeter is proposed with a 2×2 cm^2 tower readout structure (see fig. 1) with the towers parallel to the beam. Altogether there will be about 13500 towers. This segmentation ensures high rate capability, good space resolution and two photon separation. The use of liquid krypton as converter in a quasi homogeneous active structure (the only other material being thin readout electrodes) ensures low sampling fluctuations as needed for the energy resolution required (see table 1). The total volume of liquid krypton will be about 8 m^3. High speed readout of the detector signals is possible owing to low capacitance detector cells of less than 100 pF. The preamplifiers are placed in the liquid to provide short connections. Initial current readout technique will be used with a pulse shaping of 100 ns FWHM. The total electron-drift time across the one centimetre gap between electrodes is about 2.5 μs.

Table 1
Physical properties of LAr, LKr, and LXe

	LAr	LKr	LXe
Z	18	36	54
A	40.0	83.8	131.3
Density [g/cm^3], at 1 bar	1.39	2.41	3.06
T (boiling point) [K], at 1 bar	87.3	119.8	165.1
T (triple point) [K]	83.8	116.0	161.4
ρ_{liquid}/ρ_{gas} (gas at 15 K, 1 bar)	835	688	550
Dielectric constant ϵ_r	1.5	1.7	2.0
Radiation length X_0 [cm]	14.0	4.76	2.77
Nuclear interaction length [cm]	84	60	55
Molière radius R_M [cm]	7.2	4.7	4.2
Ionisation energy (eV/pair)	23.3	20.5	15.6
e^- drift velocity (mm/μs) [10,11]			
at 1 kV/cm	2	3	2
at 5 kV/cm	3.5	4	2.5
Critical energy E_c [MeV]	41.7	21.5	14.5
Radioactivity [Bq/cm^3]	–	400	–

2. The prototype calorimeter

A prototype liquid krypton calorimeter with a diameter of 39 cm and 140 cm depth corresponding to about 400 kg (170 l) krypton was built for a test in an electron beam, the H4 beamline of the CERN-SPS. The active volume (see fig. 2) is 32 cm in diameter and 120 cm long allowing measurements of electromagnetic showers over three Molière radii from the centre and 26 radiation lengths in depth [4].

2.1. Readout structure

The prototype calorimeter consists of 184 towers oriented parallel to the beam axis. The tower size is 2×2 cm$^2 \times 120$ cm. The readout structure is built of flat Kapton foils of 125 μm thickness. The distance between foils is 1 cm. The foils are streched in the beam direction with a tension of about 2 kg/cm. Copper strips, 18 μm thick, 19 mm wide and separated by

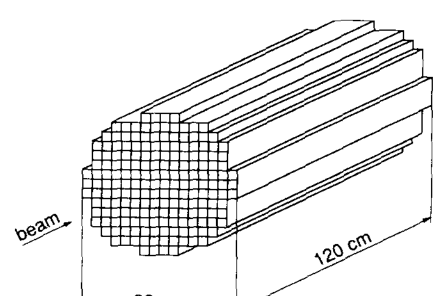

Fig. 2. Sketch of the tower structure of the NA48 prototype calorimeter. There are 184 towers with a size of 2×2 cm$^2 \times 120$ cm.

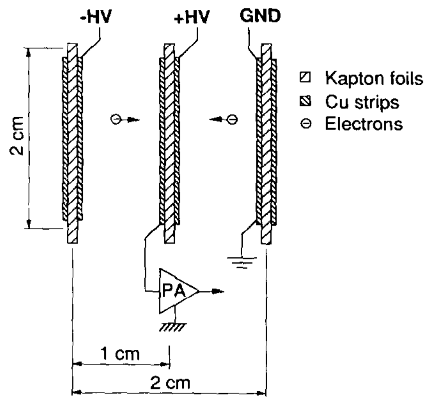

Fig. 3. Scheme of the readout structure of one 2×2 cm^2 cell. A cell is defined by four copper strips placed on three different foils.

1 mm, are glued on each side of the foils. The thickness of the glue is about 20 μm. A tower cell is defined (see fig. 3) by four copper strips placed on three different Kapton foils. An alternating high voltage scheme is used to avoid high voltage coupling capacitors and triple layer boards.

Kapton foil samples were tested with high voltage both in air at room temperature and in liquid argon. The 125 μm foils sustained 10 kV in liquid argon for more than a month without breakdown. Before assembly all foils of the prototype were tested at 10 kV in a nitrogen atmosphere with a relative humidity below 40%. No problems were observed.

2.2. Readout electronics

The amplifier chain of the readout electronics is shown in fig. 4. A current pulse read out from the calorimeter has a fast rising edge of a few nanoseconds, the total pulse length is expected to be about 2.5 μs (see fig. 5a). The detector capacity is about 80 pF per cell, with 30 pF cross capacitance to each neighbouring cell within a gap. The charge sensitive preamplifiers are based on a BNL design (Radeka et al.) for RD3 [5]. They are placed in the liquid to achieve small

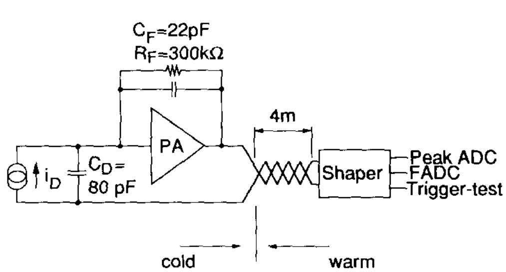

Fig. 4. Readout amplifier chain consisting of the calorimeter cell (C_D), preamplifier (PA), shaping amplifier and three ADCs.

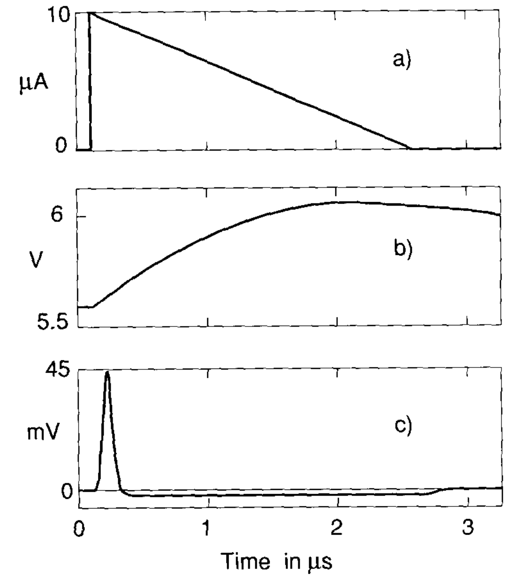

Fig. 5. Typical pulse shape for uniform ionisation across the gap; (a) current pulse into the preamplifier, (b) output signal of the preamplifier, (c) output pulse of the shaper.

inductance leads and therefore fast readout. The design value for the equivalent preamplifier noise is 5 MeV. The transfer time of the charge from the detector to the preamplifier is about 5 ns. The preamplifier has a rise time of about 20 ns and a decay time constant of 6.6 μs. The preamplifier signals (fig. 5b) are fed via four metre long twisted pair cables to the shaper circuits.

The shaper provides two differentiation and four integration stages [6]. The input is ac-coupled. The shaper transformes the preamplified signals to pulses (see fig. 5c) with 100 ns width (at 50%), a rise time (10 to 90%) of 50 ns, a fall time of 80 ns (90 to 10%) and a negative undershoot with an amplitude of 6% of the peak value. The total pulse length is determined by the charge collection time in the detector, i.e. 2.5 μs.

All shapers have three outputs. One was used for LeCroy peak sensing ADCs (LRS 2281, 12 bit resolution), one for nonlinear Struck FADCs (Struck DL350, 8 bit resolution, 10 bit dynamic range, 80 MHz) and one for trigger tests [7], using a linear 8 bit, 200 MHz FADC. The ADCs were read out via CAMAC.

2.3. Calibration system

The schematic of the calibration system is shown in fig. 6. A fast DMOS FET is used to form the fast rising edge of the reference pulses. The decay time constant of about 2 μs was chosen by an appropriate RC-circuit in order to simulate the initial response of a 2.5 μs triangular current signal. A dc calibration voltage de-

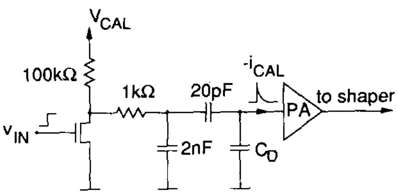

Fig. 6. Schematic of the calibration system. A fast DMOS FET is used to form the fast rising edge of the reference pulse, the decay time constant is 2 μs.

fines the height of the calibration pulses, which are fed to the preamplifier via a calibration capacitance of 20 pF. All capacitances and resistances of the calibration system were measured at room temperature and at liquid nitrogen temperature. They are known to better than 1% [8].

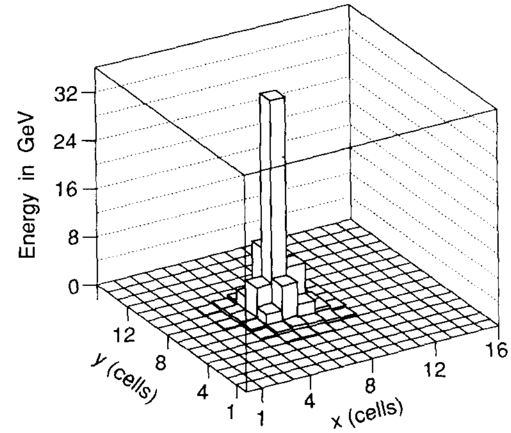

Fig. 7. Average transverse shower profile of 120 GeV electrons. On average, 30% of the total shower energy was deposited in the central cell.

3. The prototype test

3.1. Setup of the prototype test

The prototype calorimeter was exposed to an electron beam (H4 beam at the CERN-SPS) with energies between 15 and 120 GeV. During the data taking the calorimeter was operated at high voltages up to ±2.5 kV. The electron lifetime in liquid krypton, which was measured to be about 70 μs before the filling, deteriorated substantially after filling the calorimeter. It is believed that this defect was due to remnants of the agents used in the final cleaning of the Kapton foils and to other materials.

3.2. Results from the prototype test

The average shower profile of 120 GeV electrons is shown in fig. 7. On average, about 30% of the total shower energy was deposited in the central cell.

3.2.1. Energy resolution

The energy resolution of the prototype calorimeter resulted from data measured with the LeCroy peak sensing ADCs. The calibrated ADC-response was summed over 7 × 7 cells. The energy resolution of the calorimeter as a function of the beam energy is shown in fig. 8. We obtained the following energy resolution [9]:

$$\frac{\sigma}{E} = \frac{4.4\%}{\sqrt{E}} \oplus 0.7\% \oplus \frac{0.21}{E}.$$

The electronic noise of the 49 cells was 210 MeV. This was substantially larger than expected, since the calculated noise figure was 5 MeV per cell. The larger measured noise is partly due to insufficient charge collection as a result of the short electron lifetime. Ground problems also contributed to the noise.

3.2.2. Space resolution

The space resolution was determined with the help of NA48 prototype drift chambers [9] placed upstream of the calorimeter. For this purpose the centre of gravity of the pulse-height distribution in the calorimeter was compared to the track position from the chambers. Resulting distributions show a space resolution of 510 μm for the x-coordinate (perpendicular to the foils) and 760 μm for the y-coordinate (in foil direction) for 120 GeV particles. For 20 GeV beam energy the space resolution was 990 μm for the x-coordinate and 1360 μm for the y-coordinate.

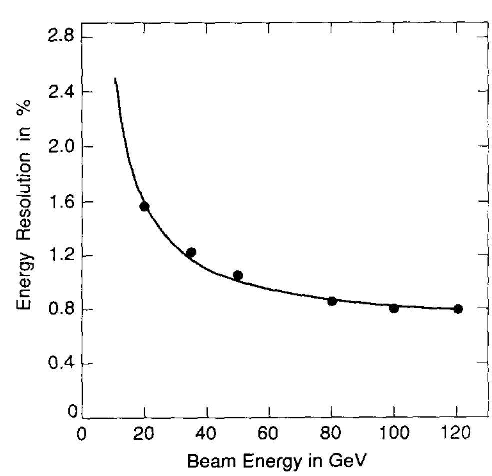

Fig. 8. Energy resolution as a function of beam energy.

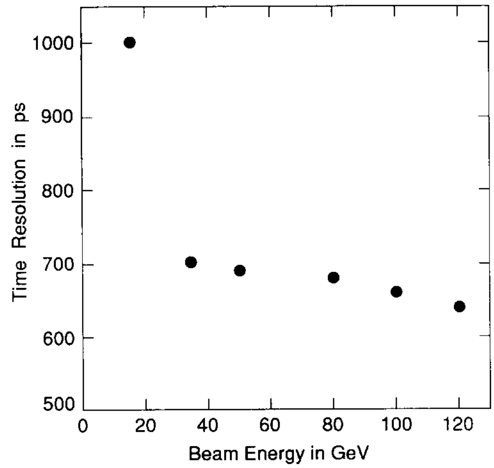

Fig. 9. Time resolution of a single cell as a function of beam energy.

3.2.3. Time resolution

The time resolution of the prototype calorimeter was derived from the Struck FADC-data and combined with precise TDC information (LeCroy 2228, 50 ps time resolution) on the trigger. The TDC measured the phase between the trigger signal and the FADC-clock. Fig. 9 shows the time resolution obtained for a single cell as a function of the energy of the test beam. The time resolution is better than 700 ps for energies above 20 GeV. The difference in propagation delay of different cells was on average about 2 ns.

4. Conclusion

The LKr prototype calorimeter has achieved the expected time and space resolution. We plan to improve the energy resolution during upcoming test runs. We will increase the electrical field to increase the electron drift velocity and to decrease recombination effects. Furthermore, the on-line purification of the liquid krypton will be improved to increase the electron lifetime.

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