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A HIGHLY SEGMENTED NAI(T1) DETECTOR WITH VACUUM PHOTODIODE READOUT FOR
MEASURING ELECTROMAGNETIC SHOWERS AT THE CERN ISR.

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ABSTRACT

In this report we describe construction and performance of two identical units of electromagnetic shower counters which were installed in the Axial-Field-Spectrometer at the CERN-ISR in 1982 to provide improved detection of photons and electrons over a 1.3 steradian solid angle of the AFS calorimeter.

Thallium doped sodium-iodide in the form of small blocks served as an active shower material. Vacuum photodiodes and low-noise charge sensitive electronics were used for the deposited energy measurement and signal amplification.

The stable performance of the detectors over a period of more than 18 months until the closure of the ISR has proven that vacuum photodiodes can reliably be utilized in highly modularized large scale detectors operating in a high magnetic field environment.

1. INTRODUCTION

The Axial-Field-Spectrometer (AFS) at the ISR ^{1,2} (fig.1) was designed to study the structure of those hadronic collisions which are characterized by a very high transverse energy flow in the central region of rapidity.

The fine granularity and the excellent energy resolution for hadronic showers of the AFS calorimeter have been chosen to deal with high particle fluxes as they emerge in the production of hadronic jets at large transverse energies. The cylindrical vertex detector provides the ability of charged particle tracking and momentum reconstruction with good resolution.

A class of events are characterized by the emergence of single photons with large transverse momenta ($p_T > 2 \text{ GeV}/c$) which do not originate from particle decays but are directly produced in parton-parton scattering processes.

A study of these direct photon events requires the suppression of background from particle decays (mostly π^0 and η). This can most efficiently be achieved by the detection and reconstruction of the additional decay photons over a solid angle as large as possible.

The inclusive production of direct photons was first measured at the ISR in pp collisions for transverse momenta between 3 and 12 GeV/c in a series of experiments using liquid Argon calorimeters ³. The study of the associated event structure was rather limited in these experiments.

Since then the AFS has been constructed and the measurement of the associated particle identity and energy flow in the central rapidity range $|Y| < 1$ became feasible.

Direct photons may also be copiously produced at very small transverse momenta $p_T < 100 \text{ MeV}/c$ ⁴. The measurement of such events requires a better resolution than that provided by the AFS hadron calorimeter. Another physics aspect is the measurement of high mass γ - γ events and of prompt electrons over a wide transverse momentum range. This latter topic has attracted much attention recently due to the strongly rising e/π ratio for transverse momenta below 1 GeV/c which has been observed in various experiments ⁵ and which cannot be explained by the known sources of electrons.

In order to extend the capability of the AFS detector for photon and electron detection over a large transverse momentum range we have installed two electromagnetic shower detectors in front of the AFS hadron calorimeter.

In this paper we describe construction and performance of these detectors which have been operated for about 18 months until the shutdown of the ISR.

2. GENERAL DESIGN CONSIDERATIONS

In designing the detectors a number of constraints had to be fulfilled, some of which resulted from the limited space in the AFS left for the installation of additional detectors, and the presence of strong magnetic fields. Others were dictated by the physics program that we wished to carry out. The general requirements of the design were:

- Sufficient granularity and good spatial resolution to allow for an efficient reconstruction of the two decay photons from π^0 's with transverse momenta up to 8 GeV/c;
- Excellent energy and position resolution for electromagnetic showers over a very large energy range;
- The ability to detect electromagnetic showers unambiguously in high multiplicity events (jets);
- Good electron/hadron discrimination;
- Stable operation over long periods in a 3.5 KGauss magnetic field;
- Good calibration and monitoring;
- Ability to provide very selective triggers.

These constraints affected the design of the shower counters strongly. In particular, the limited space of only 30 cm in the longitudinal shower direction and the magnetic field of the Axial-Field-Magnet (AFM) at the position of the detector posed serious constraints on the shower material, the light collection and readout, as well as on the signal amplification.

These considerations led us to the following concept of the two shower counters:

Each of the modules consists of an array of 20 x 30 small blocks of NaI (Tl) 5.3 radiation lengths long, mounted immediately on the front face of the AFS uranium calorimeter and pointing to the interaction region (fig. 1).

The individual blocks are optically isolated from each other. The tower structure of the detectors provides unambiguous recognition of multishower events.

The light produced in the NaI crystals is recorded with vacuum photodiodes (VPD) which are directly glued to the front face of the crystals.

Due to the magnetic environment, the use of standard photomultiplier tubes is excluded. To obtain a good signal to noise ratio the VDP signals are amplified by low-noise charge-sensitive integrating preamplifiers.

3. EXPERIMENTAL SET-UP

Each of the two detector units is composed of 600 identical modules (NaI, VPD, Preamplifier) assembled in a sealed housing, a pulser system for stability checks, a 120 mCi string-like radioactive Cs¹³⁷ source for calibration, and electronics for analog signal processing.

3.1 MECHANICAL DESIGN OF THE DETECTOR CONTAINERS

Since the NaI crystals are hygroscopic it is necessary to maintain them in a dry atmosphere. For this purpose two gastight containers were constructed of the form shown in fig. 2. The choice of material permitted for the construction is dictated by the environment in the ISR where a minimum absorption length alloy is highly desirable, and, since the detector position is close to the central field of the AFM, the material must also be non-magnetic. The containers therefore were made from a half-hard aluminium alloy and their shape was adapted to the acceptance angle of the detector. Dry N₂ gas was circulated through pipes welded to the lower and upper regions of the container. For the electrical and signal cable connections to the preamplifier boards, gastight feedthroughs were made using cast araldite as a means of sealing. The complete container assembly was suspended at three points aligned with the vertical walls thus avoiding undue deformation of the top plate.

3.2 THE NaI-VPD-PREAMPLIFIER MODULES

The 1200 NaI blocks[§] are all of the same dimension in the shape of square pyramids truncated at an angle of 70° with respect to the symmetry axis (fig. 3). As is explained below this angle was essential to achieve stable operation in the magnetic field of the AFS. The average length of the blocks is 13.8 cm and corresponds to 5.3 radiation lengths. The lateral dimensions are 35 x 35 mm² at the front and 40 x 40 mm² at the back side, respectively. After polishing, the crystals were wrapped in 25 µm thick aluminized mylar foil and checked for energy resolution and uniformity using the 667 KeV photopeak of a collimated Cs¹³⁷ source. These measurements were performed with the photodiodes replaced by a photomultiplier. Only crystals with an energy resolution of better than 12% (FWHM) were accepted. In order to compensate for the position dependence of the measured pulseheight, the mylar foil was painted with a 3 to 6 cm wide black strip at the end near the photodiode. Only blocks with $(\text{Ph}_{\text{max}} - \text{Ph}_{\text{min}}) / \langle \text{Ph} \rangle < 0.05$ were accepted for the fiducial region of the detectors. However, blocks with a nonuniformity up to 8% were accepted and used at the edges of the walls which are not used for event reconstruction but as a veto region only.

The VPD were directly glued onto the front face of the NaI blocks. Good optical contact as well as mechanical stability was obtained by using a transparent silicon rubber^{§§} as optical cement. This material provided a rather flexible but still safe interface and allowed for changing of the photodiodes without damaging the crystal surface.

§ The crystals were grown and machined by HIMPROM, USSR.

§§ Silopren C

3.3 DETECTOR ASSEMBLY

In a preparatory step, 10 NaI-VPD modules were put together to form a layer corresponding to half of a horizontal row in the final assembly (fig.4). A minimum of dead space between individual blocks was achieved by using thin double sided scotch tape for sticking the blocks together. Two additional strips at top and bottom provided the necessary rigidity for the individual layers in order to allow a stacking layer by layer. These strips were the only measures taken to prevent the crystals in the upper and lower part of the detector container from sliding forward or backward, respectively.

Two thin strips of printed circuit board attached to both sides of the individual layers provided the support of the preamplifier motherboards. The completely stacked detectors were finally equipped with the preamplifiers.

Due to the conical crystal shape all blocks point approximately to the center of the ISR intersection.

3.4 PERFORMANCE OF THE VACUUM PHOTODIODES

The vacuum photodiodes^S (VPD's) were especially developed for the use in high magnetic fields in cooperation with the manufacturer. The main aspects were high efficiency and stable operation in a magnetic field of approximately 3.5 KGauss. In addition the capacitance must be kept low to limit the electronic noise contribution. To obtain high efficiency for collecting the photoelectrons in the magnetic field, the anode-cathode separation was kept small compared to the diameter of the anode-cathode system. In our case this distance was less than 0.5 mm to be compared to the 19 mm cathode diameter.

The design of the anode was also critical. The best performance was obtained for an anode in the shape of a cup which traps the majority of the photoelectrons. With this design the capacitance of the VPD could be kept as low as 6 pF.

^S Philips AV 29

For an anode-cathode distance below 0.5 mm the operation at moderately high anode-cathode voltages of $V_{ac} = 400$ Volts became unstable. This problem was greatly reduced by placing an electrostatic shield around the outer surface of the VPD and holding it at the same potential as the cathode.

Typical photodiode responses as a function of high voltage and angle between the photodiode axis and magnetic field direction are shown in fig. 5 and fig. 6. A strong decrease of the charge collection efficiency is observed only for angles larger than $\Theta = 75^\circ$. Keeping this angle below 70° and operating the photodiodes at $V_{ac} = 200$ Volts yielded a response of greater than 90% of the response without magnetic field.

In our detector, angles of $65^\circ - 70^\circ$ between the photodiode axes and the magnetic field direction of are realized due to the asymmetric shape given to the NaI blocks.

All 1200 photodiodes have been checked in a special test setup for stable performance in magnetic fields ⁶. Also the long term stability has been checked for a number of randomly selected samples. The typical variation over a period of 100 hours was less than $\pm 0.5\%$ (fig. 7).

3.5 LINEAR ELECTRONICS

The intended application of this calorimeter required the detection of photons with energies down to ~ 15 MeV. It was therefore desirable to limit the internal noise contribution of the electronics to the uncertainty in the energy measurement to a value of ~ 1 MeV for an individual channel.

This was achieved with the preamplifier circuit shown in fig. 8 which yields a theoretical rms value for the white noise contribution of ~ 400 photoelectrons. The measured energy-equivalent was approximately 0.7 MeV with 50% channel to channel variation mainly due to fluctuations in the light transmission of the NaI crystals and to the VPD photocathode sensitivity.

This contribution to the detector noise did not pose a problem because the noise increased as the square root of the number of channels added linearly for trigger purposes. The total detector white noise therefore did not exceed 25 MeV.

Pickup noise was found to be a serious problem. Although the detector casings were designed to yield good electrical shielding, it was not possible to reduce this contribution to energy equivalent values much below 1 MeV per channel under experimental conditions at the ISR. The main source of pickup was found to be the high voltage supply of the uranium calorimeter photomultipliers that fed signals via capacitive coupling into the preamplifier inputs. This coherent noise prevented the linear adding of all detector channels for trigger purposes.

Typical values of the total rms noise level were 1 to 2 MeV per channel. Only in a few percent of all cases did the noise level exceed 4 MeV.

Crosstalk from the preamplifier output stage to the input wires of neighbouring channels was initially found to be a problem. The mechanical design required the preamplifier input leads to cross the preamplifier printed circuit board, thus creating capacitive coupling between adjacent channels. After placing additional copper shielding on the back side of each preamplifier board the crosstalk was reduced to an acceptable level of less than 1%.

The balanced preamplifier output signals were transmitted to the shaping electronics via 100 m long shielded twisted pair cables. The shaping amplifier modules were identical to the ones previously used in the liquid argon calorimeter of ISR experiment R806¹⁰ and they provide semigaussian shaping with an overall widths of 1.5 μ sec.

The gains of the individual shaping amplifier channels were adjusted so to yield the same signal for the same energy deposition in the NaI blocks. In order to minimize the effect of gain variation on the trigger threshold these gains were kept to $\pm 5\%$ of the nominal value.

The shaped analog signals of the individual channels were finally transferred to LeCroy 2282A 12 bit ADC's and read out with a standard CAMAC system under the control of the AFS on-line computer.

4. PERFORMANCE IN THE TEST BEAM

The performance of the shower detectors in conjunction with the AFS calorimeter was investigated in a test beam at the CERN PS with electrons and pions with energy from 250 MeV to 4 GeV.

In these measurements an array of 5 x 5 NaI blocks was placed in front of 3 uranium calorimeter stacks. The beam entered the test setup parallel to the crystal axis. The gains of all channels were equalized using the energy loss of 4 GeV muons in individual blocks.

The energy scale and the weighting factors for the NaI and the uranium calorimeter (front and back) were set with electrons at energies of 1, 1.5, 2, 2.5, 3 and 4 GeV, using the relative weights of front and back section of the uranium calorimeter as obtained in previous test measurements.

The relative energy deposition in the NaI and the uranium calorimeter part was studied in detail using the EGS code for electromagnetic shower simulation⁷.

From these studies it was found that the relative weights are not constant values but depend upon the longitudinal shower development and the position of non active absorption material in the electromagnetic shower. This introduced a nonlinearity in the energy measurement which was corrected for using the EGS result.

4.1 ENERGY RESOLUTION FOR ELECTRONS

The measured energy resolution is depicted in fig. 9 as a function of incident electron energy. The measured points agree well with Monte Carlo simulation using the EGS code. The data are as well reproduced assuming the resolution to be solely determined by the uncertainty of the energy measurement in the uranium part. The measured rms energy resolution of the AFS calorimeter is

$$\frac{\sigma(E)}{E} = \frac{(15.0 \pm 0.4)\%}{\sqrt{E}}$$

In our case, on the average only a fraction $K(E) = E(UCAL)/E(TOT)$ of the total energy is absorbed in the uranium calorimeter. In this case we obtain

$$\frac{\sigma(E)}{E} = \sqrt{K(E)} \frac{(15.0 \pm 0.4)\%}{\sqrt{E}}$$

The hatched band in fig. 9 represents this formula where $K(E)$ was taken from the measurements. It provides a good description of the data. Slight deviations at small electron energies are expected from a deterioration of the calorimeter resolution for very low energy electrons as compared to the above parametrization.

4.2 ELECTRON-PION DISCRIMINATION

Both the longitudinal and transverse segmentation of the setup can be used to differentiate between electrons and hadrons. It turns out, however, that the threefold longitudinal subdivision into two front (electromagnetic) parts (5.3 rad. length NaI, 6 rad length uranium/scintillator) and one back (hadronic) part (3.7 absorption lengths uranium/copper/scintillation) provides the most effective handle for discriminating against hadronic showers.

The different longitudinal development of electromagnetic and hadronic showers yields very different energy depositions in the various calorimeter parts. This is demonstrated in fig. 10-12.

Since the particle momentum was known in the test beam, as it was at the ISR experiment using the AFS, the applied cuts for electron selection were chosen to be momentum dependent, such as to yield momentum independent electron efficiencies. In particular, for a particle to be called an electron, we required a certain minimum fractional energy deposition in the NaI part and in the front part of the uranium calorimeter (EM-UCAL). In addition a minimum energy deposition in the sum $E(\text{NaI}) + E(\text{EM-UCAL})$ was required.

Accepting a 30% loss of electrons the optimum rejection for pions was found by requiring 85% of the electrons to pass the cut on the energy deposited in the NaI part, 95% of the electrons to pass the cut on the energy $E(\text{EM-UCAL})$ in the front part of the uranium calorimeter, and by applying an additional cut on $E(\text{NaI}) + E(\text{EM-UCAL})$ to yield the total electron efficiency of 70%.

The final rejection factor defined as the ratio of pions not satisfying the electron selection cuts to the pions passing them is shown in fig. 13. A rejection factor of approximately 10^3 is obtained at 4 GeV.

5. OPERATION AT THE ISR

5.1 CALIBRATION AND STABILITY MONITORING

Operating detectors with a large number of readout channels over periods of years, as at the ISR, requires a reliable and easily manageable scheme for calibration and monitoring of stability that can be used with the detector in place.

The calibration scheme of the AFS calorimeter has been described elsewhere¹; here we describe only the calibration of the 1200 NaI blocks.

Before the installation of the detectors at the ISR the gains of all channels were equalized using a 1.6 mCi ^{137}Cs -source. Due to the equivalent preamplifier noise level of approximately 0.7 MeV the photopeak was not resolved. Instead we used the average energy deposition at high counting rates which produces a measurable dc-level shift in the preamplifier output stage. This dc-shift rises linearly with the photodiode charge output (it is the product of the photodiode output current and the feedback resistors R_f in the preamplifiers and was measured for all channels with the source attached to the center of the crystal backside, thus providing identical solid angles for all channels.

These measurements yielded a channel to channel intercalibration of $\pm 2\%$.

5.1.1 Minimum Ionizing Calibration

After the detector units had been incorporated in the AFS experiment they had to be recalibrated in order to take into account the influence of the magnetic field on the gain of the vacuum photodiodes.

For this purpose minimum ionizing hadrons passing through single NaI crystals were selected and the pulse height in individual crystals was attributed to the theoretical energy loss of 85 MeV for 2 GeV pions.

To enrich the data sample with events containing minimum ionizing hadrons traversing single sodium iodide blocks, a special single particle trigger was set up. It required large clustered energy deposition in the hadronic floor of the calorimeter behind the respective NaI array and small energy deposition in the electromagnetic floor, this way indicating the passage of a hadron. The threshold in the hadronic floor was set to 1.5 GeV in order to select 'straight-track-particles' which have a high probability for traversing single NaI blocks only.

For calibrating all 1200 channels to an accuracy of $\pm 2\%$ we accumulated $5 \cdot 10^5$ triggers, yielding on the average about 200 minimum ionizing particles per channel. In the offline analysis, the peak in the pulseheight distribution was used for adjusting the gains of the individual channels.

Since the above procedure was quite time consuming (a full calibration of both detectors required 16 hours of data taking) it was carried out only if the detectors had to be removed from the experiment and then reinstalled. This happened twice within the full running period of the experiment.

5.1.2 Source calibration

For a more frequent monitoring of the NaI-VPD-preamplifier system, two 120 mCi Cs^{137} -sources in the forms of 1250 mm long vertical wires were incorporated in the setup. The sources were regularly scanned across the backside of each wall (fig. 14) and the change in the preamplifier dc-output was measured (fig. 15) by means of five digital voltmeters^(§) with 0.2 mV resolution and a maximum conversion time of 40 msec. The DVM's were connected to the 600 preamplifier dc-outputs via five analog multiplexers^(§§) with 128 channels each. The difference between the quiescent dc-level and the maximum response was determined online by a fit and enabled a monitoring of the NaI-VPD-preamplifier performance with an accuracy of better than 1%. For a full calibration five scans per wall were needed. The whole procedure took approximately 20 min for both walls and was regularly performed for every ISR run (typically every 70 - 80 hours).

The average loss in response as a function of time was about 5% over a period of 6 months. A frequent monitoring was therefore extremely important.

This reduction in response may partly be attributed to radiation or hydration damage of the sodium-iodide material and partly to a decrease in VPD-cathode sensitivity. Inspection of the crystals after one year of ISR operation did not show any recognizable change in the appearance of the crystals.

(§) SEN 2DVM 2013

(§§) CERN 182

5.1.3 Pulser Calibration

The stability of the electronics chain (preamplifier, shaping amplifier, ADC) was frequently checked using a precision pulser which generated voltage steps with an accuracy of 0.01%. These were routed through a switching box by means of reed relays to the calibration input of the preamplifier. In order to simulate experimental conditions the pulser output was shaped according to the 220 nsec decay time of the NaI signal. Fifty channels could be calibrated at the same time. The observed instabilities in the electronics chain were typically of the order of 10^{-3} between two pulser calibrations performed one week apart in time.

5.2. THE TRIGGER SYSTEM

High energy photons and electrons deposit only a fraction of the total electromagnetic shower energy in the NaI detector. Selective triggering thus requires to combine the energy deposition in both, the NaI and the front part of the uranium calorimeter.

In order to integrate the NaI trigger into the general AFS trigger logic, it was necessary to provide a fast pretrigger formed by the uranium calorimeter towers directly behind the NaI array and a second level trigger based upon the NaI information.

Fig. 16 shows a schematic diagram of the pretrigger. The PM signals of all uranium towers which are covered by the NaI wall are added, after appropriate weighting for compensation of the ISR center of mass motion. This sum is brought to a set of five discriminators which are latched by a coincidence between a timing signal from the experiment and a circuit which senses the peak of the summed signal. The lowest level discriminator output when combined with the corresponding signal from the other wall (both OR and AND were used) formed the pretrigger.

Fast pretrigger timing is required to be compatible with other AFS pretriggers. The remaining discriminator levels were used to make further restrictions at the first level trigger (150 nsec), which was carried out using the general AFS Very Fast Bus trigger system.⁸

The NaI signal -processing is sketched in fig. 17. First, all shaped signals of the 20 crystals within each row are summed up. The sums of two adjacent rows form 29 two-row sums which are investigated by four sets of discriminators. They are strobed by the pretrigger signal or by any of the various pretriggers of the AFS trigger system. This enabled the utilization of the NaI detector for the full AFS physics program. The outputs of the 4×29 discriminators are used in two ways. First, employing edge counting in a majority logic, the number of vertically by a row of crystals separated clusters is determined. This information is used to check on the energy deposition in the NaI and to limit the number of clusters above a given threshold. This information is used to select - or to suppress π^0 -events at the trigger level. Examples of a one - and a two cluster event are shown in fig. 18. Second, the individual discriminator signals are used to provide an electron trigger. For this trigger also information from the central drift-chamber (DC) located between the vertex and the NaI was used. The trigger was defined by an energy deposit in a NaI two row sum and a track in the drift chamber pointing to it. The logic of the electron trigger is sketched in fig. 19. Signals of a subset of DC-wires are used in a coincidence to detect a spatial match of a shower and a track. A microprocessor (ESOP) is used to find the respective track, to calculate the particle transverse momentum from the sagitta and to select tracks with momenta above a given threshold.⁹

Different types of NaI triggers are used for various subjects:

- For measuring single γ 's and π^0 's at large transverse momentum electromagnetic energy in the calorimeter behind the NaI arrays and at least one pronounced cluster in one of the NaI walls are required.
- In the search for high mass direct photon pairs a coincidence of the two NaI walls is formed. In order to suppress the copious background of π^0 - π^0 events only events with one and only one cluster above a high and a low threshold in each wall are accepted.
- The electron pair trigger is satisfied if at least one match between a shower and a track is confirmed by ESOP in each wall. This trigger was used to measure electron pairs in the mass region of the J/ψ and below.

6. OFFLINE SOFTWARE

In the reconstruction of the electromagnetic showers two parts of the NaI-uranium calorimeter setup with very different granularity and energy resolution have to be combined. The reconstruction starts by searching for peaks in the pulseheight pattern and counting the number of showers in the NaI array. The energy of each shower is determined by summing the energy in the peak block and the eight surrounding blocks. In cases where two showers are close together, the energy in those blocks where the showers overlap is shared and associated with the respective showers consistent with the lateral shower distribution (obtained in test measurements and from Monte Carlo simulation). The uncertainty in the reconstruction of the shower position in the NaI was found in Monte Carlo simulation to be 6 mm. The shower position is then projected onto the uranium calorimeter along a straight line from the center of the ISR intersection through the shower centroid found in the NaI matrix.

The uranium calorimeter is composed of stacks with a front face of $20 \times 120 \text{ cm}^2$ each. The scintillator light from each stack is read out by means of six 20 cm wide wavelength shifter bars attached to each side of the scintillator, this way creating a tower-like structure with a $20 \times 20 \text{ cm}^2$ front face. Due to the coarser structure of the uranium calorimeter individual showers are usually not resolved. Therefore a different strategy is employed to associate the energy in the calorimeter with the respective showers.

The pulseheight pattern in the scintillators produced by electromagnetic showers has been mapped out in measurements¹¹ in an electron test beam at the CERN PS in fine position and angle steps. This information, together with the known projected shower positions is used in a χ^2 -minimization procedure to associate the energy deposition in the calorimeter towers with the individual showers found by the pattern recognition in the NaI.

With a Monte Carlo simulation we have investigated the efficiency for reconstructing single photon showers and two photon showers from π^0 decays. The result is shown in fig. 20. The single photon reconstruction efficiency varies only slightly over a transverse momentum range of 200 MeV/c to 8 GeV/c.

For π^0 events the reconstruction efficiency drops for transverse momenta greater than 4 GeV/c due to the onset of merging between the two showers which eventually are not resolved any more by the reconstruction program.

The quality of the shower reconstruction can be judged from the two photon mass spectrum gained from experimental data. The widths of the π^0 - and η -mass peaks shown in fig. 21 are consistent with Monte Carlo results.

The position of the π^0 - and η peaks in the 2γ -mass distribution were also used as a continuous check on the energy calibration of the complete NaI/Uranium calorimeter over the full data taking period.

SUMMARY

We have reported on the construction, test and performance of two arrays of NaI(Tl) electromagnetic shower detectors equipped with vacuum photodiodes and charge sensitive electronics.

Both detectors have been operated reliably for more than 18 months in the Axial-Field-Spectrometer experiment at the CERN ISR.

Some important parameters of the shower detector and of the experimental setup at the ISR are collected in table I and table II.

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Table 1. Parameters of the detector components

Total number of NaI blocks:	1200
Lateral dimensions - front side:	$35 \times 35 \text{ mm}^2$
back side:	$40 \times 40 \text{ mm}^2$
longitudinal dimensions:	138 mm (5.3 r.l.)
Energy resolution for 667 KeV photons (FWHM) :	<12%
Non-uniformity of light collection in the NaI blocks :	
($\text{Ph}_{\text{max}} - \text{Ph}_{\text{min}}$)/<Ph> :	<5% (fiducial region)
:	< 8% (veto region)
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Vacuum photodiode charge collection efficiency in a magnetic field of 3.5 KGauss:	>90% at $V_{\text{ac}} = 200 \text{ Volts}$
Variation of the photodiode response to an LED with $\lambda=530 \text{ nm}$:	0.5% / 100 hrs
<hr/>	
Preamplifier noise:	$\sim 400 \text{ p.e (rms)}$
Number of photoelectrons/MeV energy loss:	$3 \cdot 10^2 - 10^3$

Table II. Performance of the NaI/Uranium calorimeter

Energy resolution for 1 GeV electrons	9%	
Pion rejection factor:	0.5 GeV	80 ± 30
(70% electron efficiency)	4 GeV	1000 ± 300
Spatial resolution for single electromagnetic showers (from Monte Carlo simulation)		6 mm

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FIGURE CAPTIONS

- Fig. 1 Experimental set-up at the ISR. Shown is only a part of the AFS calorimeter. The experimental arrangement is symmetric with respect to the ISR intersection. The NaI crystals point approximately to the center of the intersection.
- Fig. 2 Mechanical construction of a detector unit. The NaI blocks are aligned to point to the ISR intersection.
- Fig. 3 The NaI blocks before and after wrapping in aluminized mylar foil and with the photodiode glued onto the front face.
- Fig. 4 One layer of 10 sodium iodide blocks, equipped with VPD, motherboards and preamplifiers. The crystals are scotched together to form a rigid unit.
- Fig. 5 Typical performance of the vacuum photodiodes (AV 29) in a 3 KGauss magnetic field. Shown is the ratio of the VPD response with and without magnetic field to a LED as a function of the angle between the VPD axis and the magnetic field direction. For angles of 65° to 70° as realized in the detectors, charge collection efficiencies greater than 90% are obtained for $V_{ac} = 200$ Volts.
- Fig. 6 Charge collection efficiency of the vacuum photodiodes in magnetic field as a function of the anode-cathode voltage for different orientations of the photodiode axis with respect to the magnetic field direction.
- Fig. 7 Pulse height variation of the photodiodes in a 3 KGauss magnetic field versus time. The measurements were performed using the light of a green LED ($\lambda_{max} = 510$ nm).
- Fig. 8 Circuit diagram for the low noise preamplifier with balanced ("push-pull") output.
- Fig. 9 Energy resolution of the NaI-uranium calorimeter for electrons. The hatched band indicates the result assuming $\sigma(E)/E = 0$ for the energy measured in the sodium iodide part and the parametrization $\sigma(E)/E = (0.150 \pm 0.004)/\sqrt{E}$ for the energy measured in the uranium calorimeter.

- Fig. 10 Energy deposited in the uranium calorimeter versus energy deposited in the sodium iodide wall for 3 GeV pions.
- Fig. 11 Same as fig. 10 but for 3 GeV electrons.
- Fig. 12 Measured energy deposition in the sodium iodide and the first 6 rad. length of the uranium calorimeter for 3 GeV π^- and e^- .
- Fig. 13 Pion rejection (number of identified pions/number of pions misidentified as electrons) versus momentum of incident particles.
- Fig. 14 Cs^{137} source calibration scheme.
- Fig. 15 Response of a single NaI-VPD-Preamplifier channel to the moving Cs^{137} string source.
- Fig. 16 Pretrigger electronics.
- Fig. 17 Linear trigger electronics for energy discrimination and cluster counting in the NaI array.
- Fig. 18 Typical NaI energy pattern for events triggered on one and two energy clusters.
- Fig. 19 Setup for electron trigger to combine energy and cluster information in the NaI and the FAST OR information of the drift chamber.
- Fig. 20 Monte Carlo simulation of the single photon and π^0 -reconstruction efficiencies.
- Fig. 21 Measured 2γ -mass spectrum for $2.5 < P_T < 3.5$ GeV/c.

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