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and a Scintillating Tile Hodoscope ***

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MPIH-V16-1995

(A shorter version of this preprint is submitted to Nucl. Instrum. Methods A)

*supported by the German Bundesministerium für Forschung und Technologie, contract # 06 HD524I

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ONLINE DETECTION OF NEUTRONS WITH A LEAD/SCINTILLATING FIBRE CALORIMETER AND A SCINTILLATING TILE HODOSCOPE *

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KEY WORDS: scintillator, WLS fibre, hadronic calorimetry,
Digital Signal Processor (DSP), neutron trigger.

Abstract

We present the set-up and performance of a high energy neutron trigger based on a detector system consisting of a scintillating tile hodoscope and a compensating lead/scintillating fibre calorimeter. A first level trigger signal is generated by a minimum hadronic energy detected in the fiducial volume of the calorimeter. This signature is complemented at a second level trigger stage by the isolation of a shower whose origin cannot be attributed to a charged particle. Such a decision is taken by comparing the hit pattern of the hodoscope with online available calorimeter information. This complex task can be fulfilled in an efficient and flexible way by Digital Signal Processors (DSP). The presented method of online neutron detection was developed in the framework of the hyperon beam experiment WA89 at CERN and yields an average trigger decision time of $\approx 11\mu s$. From an analysis based on $\Sigma^\pm$ decays ($\Sigma^\pm \rightarrow n\pi^\pm$), we find a second level trigger efficiency for neutrons of 70 % at a rejection level of 95 % for hadronic showers originating from charged particles.

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1 Motivation

In hadron spectroscopy, decay channels involving neutrons are usually among the least investigated. Their analysis involves in most cases very good calorimetry for single particle detection and high neutron identification probability to address the physics issues of interest. This applies in particular to high energy fixed-target experiments where the investigation of rare processes such as the production and decay of heavy flavours is very difficult owing to high particle multiplicities in the forward hemisphere and where the signals have to be extracted within enormous background conditions.

The hyperon beam fixed-target experiment WA89 [1] at CERN was designed to investigate charmed baryons, hyperon resonances and exotic particles containing 1 or 2 strange quarks using a 330 GeV/c Σ^- beam. Initially, only those decays could be addressed, for which the final state particles were reconstructed with a magnetic spectrometer and a lead glass calorimeter. In order to investigate also final states with neutrons and charged hyperons $\Sigma^\pm$ ($\Sigma^+ \rightarrow n\pi^+$, BR $\approx$ 48.3 % ; $\Sigma^- \rightarrow n\pi^-$, BR $\approx$ 100 %), the high resolution SPACAL ('SPAggetti CALorimeter') lead/scintillating fibre calorimeter [2] was implemented as a hadron detector into the experiment in 1991. Among the physics issues to be addressed with this detector are studies of charmed baryon decays to $\Sigma^\pm$, the scattering of Σ^- on electrons in the target material and the search for the H-dibaryon (quark content: $udsuds$) for which the decay into $\Sigma^- p$ is a promising final state if its mass is below the $\Lambda^0 \Lambda^0$ -threshold for strong decays.

The analysis of the 1991 data led to a clean reconstruction of $\Sigma^\pm$ particles [3], but indicated also that the total $\Sigma^\pm$ sample was too small to provide significant results on the rare processes described above. The reason for this lies in the trigger scheme which was based on charged particle multiplicities. Taking advantage of the high signal speed and short pulses of the calorimeter as well as of its fine granularity for hadronic showers, we designed a concept for triggering on high energy neutrons additionally using a scintillating tile hodoscope [4] of appropriate geometry to perform the charge identification. Such a trigger was studied in the following data taking in 1993. In this paper, we present the concept and realisation of this neutron trigger. We will demonstrate its performance on a data sample with well identified neutrons from $\Sigma^\pm$ decays.

2 Concept of online neutron detection

Detection of hadronic showers in the WA89 experiment (see figure 1) takes place in the SPACAL calorimeter centred on the beam axis at about 17 m downstream of the superconducting Omega magnet. Neutrons from $\Sigma^\pm$ particles produced in an interaction or a decay upstream of the magnet, are likely to have a high momentum and a small angle (order of several mrad to tens of mrad) w.r.t. the beam axis. MC simulations have shown that the lateral dimensions of the calorimeter ($\approx$ 1 m diameter) are sufficient to reconstruct $\Sigma^\pm$ hyperons with full geometrical acceptance in the interesting momentum range down to momenta of 60 GeV/c (and with p_T values up to 1 GeV/c). In this regime, the momenta of the corresponding decay neutrons are > 30 GeV/c.

The SPACAL calorimeter was developed in the framework of the CERN/LAA project and has subsequently been upgraded for the high intensity environment of the WA89 experiment [5]. The calorimeter consists of a lead structure with interleaved layers of 2.2 m long scintillating fibres in a geometry as shown in figure 2. Particles enter the calorimeter front face (almost) parallel to the fibres and develop a shower inside the 9.5 interaction

lengths deep detector ($\lambda_I \approx 21$ cm). The calorimeter is laterally segmented in 155 hexagonal towers (figure 3). Each tower is defined by a group of 1141 fibres which are coupled to a common photomultiplier (PM) located at the rear of the detector. The diameter of the active calorimeter area is about 0.95 m corresponding to 4.5 interaction lengths. The SPACAL performance as a hadron calorimeter is excellent in both the energy ($\sigma/E = 30\%/\sqrt{E(\text{GeV})} + 2.5\%$) and position resolution ($\sigma = 31.4\text{mm}/\sqrt{E(\text{GeV})} + 2.4\text{ mm}$) [2].

In view of a fast decision on the charge of a particle that initiates a shower in the calorimeter, we have developed a scintillating tile (SCITIL) hodoscope which was placed 15 cm upstream of the SPACAL calorimeter. The hodoscope is made out of 127 hexagonal tiles (figure 4) and has a granularity identical to the one given by the tower structure of the calorimeter. The individual scintillator tiles are read out via wave-length-shifting fibres that are coupled to PM's located outside the active area of the SCITIL/SPACAL detectors (figure 5). The efficiency of the hodoscope for the detection of charged particles was determined to be $\geq 98\%$ [5].

The principle of an online identification of neutral hadronic particles (i.e. neutrons, or K_L^0) in the environment of a high energy interaction is sketched in figure 6. Particles developing electromagnetic showers (π^0 , γ , $e^\pm$) are absorbed in a 23 radiation length thick lead glass calorimeter [6] upstream of the SCITIL/SPACAL detector system. As a consequence, hadron identification is confined to the detection of an energy deposit in the spaghetti calorimeter well above the one caused by minimum ionising muons. This can easily be done at an early trigger stage with a simple energy threshold on the analogue sum of all signals from SPACAL towers inside the fiducial volume (the central 91 towers, shown as dotted area in figure 7). The remaining problem is to determine the charge of the particle that produced the hadronic shower detected in the calorimeter. Our approach consists in computing online the SPACAL tower which contains the (approximatively reconstructed) impact point and looking whether or not a hit was found in the SCITIL hodoscope area facing this tower. Several showers might develop in the calorimeter; a trigger should be generated if at least one of the showers has no correlation with hits in the corresponding hodoscope region.

For reasons that will be outlined in more detail in subsection 4.1, the complexity of the charge decision is such that this task cannot be fulfilled in a satisfactory way by correlating the information from the SPACAL and SCITIL detectors using standard electronics (ALU, MLU, etc.). In addition, such hardware solutions are not always easy to tune and, if assembled to complex systems, not always easy to debug in case of failures. Therefore, we favoured a new approach to second level triggering using Digital Signal Processors, taking advantage of their fast and powerful data management capabilities. They allow a flexible trigger set-up based on an algorithm that can be tuned to the experimental conditions.

3 Trigger scheme

Figure 7 shows schematically the hardware and electronics involved in the set-up of the neutron trigger.

The right part of the diagram depicts the various conditions contributing to a first level trigger signal indicating the observation of a hadronic shower in the SPACAL calorimeter. First information of a potentially interesting event in the hadron calorimeter has to be present already at an early stage (≈ 320 ns after the passage of the beam particle) in order to activate the readout electronics of the detectors. For this purpose, the SPACAL PM signals are split into 2 branches. One of them is coupled to an ADC system (LRS 1885F, Le Croy)

for offline energy determination. The second branch passes through a fan-out and summation unit (Electronics workshop, MPI Heidelberg) that adds the analogue signals of the central 91 towers. A threshold is applied to the sum signal, corresponding to a total energy release of about 30 GeV in the fiducial detector volume. This minimum energy deposit in the calorimeter has to be in coincidence with a valid beam particle and a subsequent interaction defined by a minimum hit multiplicity ≥ 2 in the vertex region. In addition, a minimum charged particle multiplicity ≥ 2 is required in a hodoscope (H1) downstream of the Omega magnet. The two multiplicity conditions are essential, as they reject the 6×10^5 non-interacting beam particles (the target thickness is about 5 % of an interaction length) that are deflected onto a certain area of the calorimeter where they develop 330 GeV hadronic showers. At this stage, the trigger is not yet sufficiently selective to be compatible with the rates of other existing triggers and the event recording capabilities of the data acquisition system.

Some degree of selectivity for neutron detection can already be implemented into the first level trigger decision (≈ 600 ns after the passage of the beam particle) by using refined criteria on the event topologies. They should, in particular, lead to a higher offline reconstruction efficiency for $\Sigma^+ \rightarrow n\pi^+$ decays. By vetoing charged particles going through the central part of the spectrometer (*H1 central*), one can discard already part of the showers generated by high energy charged particles and reduce pile-up effects where a neutron shower is superimposed on other hadronic shower profiles. Such pile-up effects might also be caused by other particles not necessarily correlated to the actual event. Considering the high beam rate of 6×10^5 per spill (≈ 2 sec), a potential neutron trigger is vetoed (*2nd beam particle*) whenever another beam particle is registered within a time interval of ± 150 ns corresponding to the ADC integration time. In addition, care has to be taken to avoid an overlap of the minimum energy trigger with the on-spill flash lamp monitor (*flash lamp*) which generates flash pulses of several μ s duration at a rate of a few Hz. Finally, one can avoid those cases, where the 30 GeV energy release is made up of several low energy showers distributed all over the fiducial volume. This can be done by requiring at least 1 SPACAL tower with an energy deposit above 10 GeV. Such a condition also provides a reasonable data volume as input for the subsequent trigger processors.

The final selectivity can be achieved with the second level trigger performing a decision on the charge of the particle initiating the shower. The corresponding scheme is shown on the left part of the diagram in figure 7. It can be noticed that the SPACAL calorimeter and the SCITIL hodoscope are read out in a very similar way. The fan-out analogue signals from the 127 inner calorimeter towers are individually discriminated with a threshold corresponding to about 10 GeV. Towers with signals above this threshold will be referred to as SPACAL ‘hits’ in the following. The 127 signals from the hodoscope modules are also discriminated, with a detection efficiency for minimum ionising particles of ≥ 98 % [5]. The SPACAL and SCITIL hits are stored in two separate PCOS III (Le Croy) systems, from where they are written to a 10 MHz data bus connected to the DSP units for second level processing. In addition, these hits are read out for offline analysis.

4 Online identification of neutral hadronic showers

The aim of this section is to present in more detail the principle of the charge decision on which the second level trigger stage is based. Its technical realisation with the help of the DSP’s will be addressed in section 5.

4.1 Experimental requirements

For reasons which will be described below, the decision on the charge of a particle developing a hadronic shower in the calorimeter cannot be made by a simple correlation of the hit pattern of the calorimeter and the hodoscope.

First of all, several showers can occur in the calorimeter, and a minimum of clustering work has to be done in order to recognise if one of the showers has been caused by a neutral hadronic particle. More stringent, however, are the restrictions imposed by the albedo from the calorimeter i.e. charged shower particles that are backscattered and eventually escape from the calorimeter through its front face. They will produce hits in the hodoscope tiles and possibly generate a wrong charge decision for neutrons. Hence, each hodoscope module examined for a hit will contribute to a trigger inefficiency of the order of several % [5] for neutrons near the energy threshold of 30 GeV, the effect increasing linearly with energy. For this reason, one has to keep the tested hodoscope region minimal. This is achieved in a first step by reducing the SPACAL 'hit' pattern to a set of single towers, each containing the cluster centre of a detected shower

In the ideal case, the charge decision would focus only on a potential hit in the hodoscope modules facing the particle impact points (given by the barycentre of the shower energy deposits) on the calorimeter. This picture, however, is too simplifying.

Several effects can cause charged particles to fake neutral ones and by that contaminate the trigger. Imperfections in the relative alignment of the SPACAL and SCITIL detectors, lateral asymmetries in the development of a hadronic shower, particle impacts on the calorimeter under non zero angle of incidence - all these circumstances might lead to the reconstruction of a shower barycentre which is not located in the tower facing the hodoscope module passed by the particle (see sketch of the upper shower in figure 6). The same effect can also originate from the inaccuracy in the online computation of the impact point, which is only an approximation to the correct barycentre calculation (see subsection 4.2). Thus, one should consider a larger region around the module facing the SPACAL impact tower when checking for hits on the hodoscope.

A similar conclusion is valid for neutrons that preshower in the upstream lead glass array ($\approx 1.2 \lambda_I$ thick). The larger the tested region on the tile hodoscope, the higher the probability that one of the charged preshower particles will be detected. In the present case, however, this is of benefit as it allows us to exclude preshowered neutrons whose energy in the SPACAL calorimeter would only be determined with large uncertainties. The same reasoning applies to neutrons which are accompanied by event-correlated leakage of electromagnetic shower energy from the back of the lead glass array.

Another, although minor issue affecting the performance of the neutron trigger arises from the hodoscope inefficiency of $\approx 2\%$ resulting mainly from the dead areas around each tile [5]. The consequence is a contamination of the neutron trigger with charged particles whose passage through the SCITIL detector will not be registered as a hit in any tile.

In summary, we are faced to contradicting requirements concerning the size of the SCITIL hodoscope area to be probed for a potential hit in relation with a hadronic shower in the SPACAL calorimeter. Thus, the identification of neutral hadronic showers is subjected to optimisation.

4.2 Online charge identification

The first step in the charge identification procedure is the online computation of the impact points of particles having developed a shower in the calorimeter.

The impact point is normally defined as the reconstructed barycentre of the shower, projected onto the front face ($y-z$ plane) of the calorimeter:

$$y_{\text{impact}} = \frac{\sum_{i=1,n} E_i^\alpha y_i}{\sum_{i=1,n} E_i^\alpha} \quad z_{\text{impact}} = \frac{\sum_{i=1,n} E_i^\alpha z_i}{\sum_{i=1,n} E_i^\alpha} \quad (1)$$

Parameters to be optimised are the number of towers n participating in the weighted average ($n=19$ in our case) and the exponent α of the energy weights E_i (α is either < 1 or, as in our case, $\alpha = 1$ and complemented with a correction function to y_{impact} , z_{impact}).

A fast computation of the impact point using the DSP's can be achieved at the expense of simplifying formula (1) to some extent and using only integer values as input. First, we restrict the coefficients E_i to be either zero or unity. This corresponds exactly to the digital information as it is given by the SPACAL 'hit' distribution. The coordinates y_i , z_i of the centre of the towers can also be chosen to be integer numbers, if we use an appropriate coordinate system, shown in figure 8a). The DSP will be programmed to group the SPACAL 'hits' in form of clusters of size N and apply for each cluster the simplified formula:

$$y_{\text{impact}} = \frac{\sum_{i=1,N} y_i}{N} \quad z_{\text{impact}} = \frac{\sum_{i=1,N} z_i}{N} \quad (2)$$

We define the tower, into which the impact point is reconstructed online, as the cluster centre tower. Its coordinates (y_c , z_c) can easily be determined, thanks to the chosen coordinate system, by rounding off the values found in equation (2). Strictly seen, there are misassignments possible, but we will see later that the charge identification will not be affected. The tower numbers corresponding to the integer coordinates (y_c , z_c) will then be associated by means of a look-up table stored within the DSP. For ease of later comparison, the numbering system of the hodoscope modules is identical to the one of the calorimeter towers.

The next step in the charge identification procedure is to work out an optimum size of the hodoscope area to be tested for potential hits. From subsection 4.1 it became clear that in general, checking only the 1 tile facing the SPACAL cluster centre is obviously not sufficient, whereas checking in addition 6 surrounding tiles reduces significantly the neutron efficiency mainly due to albedo hits.

It is possible to extract additional information on the position of the online reconstructed impact point within the cluster centre tower, by further exploiting the values found in equation (2). A useful and very simple quantity turns out to be the difference between the coordinates of the online reconstructed impact point and the coordinates of the cluster centre tower:

$$y_{\text{diff}} = y_{\text{impact}} - y_c \quad z_{\text{diff}} = z_{\text{impact}} - z_c \quad (3)$$

This information is used to localise the impact point to be in one of 6 sectors (see figure 8b)) of a tower by checking for one of the exclusive conditions listed in table 1.

At last, one checks for hits in the module facing the cluster centre tower and the two modules adjacent to the determined sector (see the two bottom pictures in figure 8c)). Thus, at maximum 3 tiles have to be considered in the most general case, independent of the original SPACAL cluster size. This method also guarantees that in the case of the rare

sector	sign y_{diff}	sign z_{diff}	relation y_{diff}, z_{diff}
1	+	+	$y_{diff} > z_{diff}$
2	+	+	$y_{diff} < z_{diff}$
3	+	-	none
4	-	-	$y_{diff} < z_{diff}$
5	-	-	$y_{diff} > z_{diff}$
6	-	+	none

Table 1

misassignments of cluster centres to SPACAL towers, the same 3 tiles are selected as for the correct assignment. The situation even simplifies to the test of 2 or only 1 hodoscope tile in special cases in which the reconstructed impact point falls exactly in between two towers or in the tower centre. Situations like this, sketched in the two upper pictures of figure 8c), appear quite frequently according to the SPACAL multiplicity distribution shown in figure 9.

Due to the simplifications leading to equation (2), the online reconstructed impact point ('cluster centre') will obviously be different from the offline reconstructed barycentre. The distribution of their displacement is plotted in figure 10 for different cluster sizes. We find that the algorithm (see below) developed for online reconstruction and executed by the DSP's is sufficiently accurate for our purposes: in ≥ 95 % of the cases for SPACAL 'hit' multiplicity 1 and in ≥ 99 % of the cases with a SPACAL multiplicity ≥ 2 , the selected SCITIL modules to be checked for hits are the same as if derived from precise offline barycentre computation

5 Technical realisation with Digital Signal Processors

The formation of clusters and the charge identification are processes which use initially independent information of the calorimeter and the hodoscope. Thus, a certain parallelism is possible at the second trigger level and separate PCOS readout systems and DSP's are therefore used for the two detectors (figure 7). Only at a later stage, when the positions of the cluster centres on the calorimeter are available and charge tests can be done with the hodoscope data, a communication between the two DSP's is necessary.

5.1 Description of the Digital Signal Processors

For our application we used the DSP module STR370 (Dr. B. Struck). This FASTBUS module consists of four DSP units STR371, each one being equipped with its own processor, memory and input data bus. Two of these processors are connected to the PCOS readout systems of the calorimeter and the hodoscope, respectively, whereas the other two are used for code development and time performance studies.

The 1 kByte deep input first-in/first-outs (FIFO's) are more than sufficient to receive and store the maximum of 127 data words from each of the two detectors. The time needed to register an input word is 50 ns; thus, the FIFO's are sufficiently performing to cope with the data transfer rates on the 10 MHz bus. Each DSP contains also two independent

128 kByte program and data memories, the latter one being used extensively for storage of look-up tables (LUT's). Information that has been processed in one DSP unit can be transferred to another one via intercommunication FIFO's. The outcome of decisions can be transmitted to the outside world with the help of three output registers. The start and control of the program execution is done via two interrupt inputs. A special clear feature can be used to produce a fast reset of the input FIFO's.

The processors themselves are of the type DSP96002 (Motorola), clocked at 40 MHz. These processors have the advantage to dispose of a large instruction set and of two separate data buses which can be used simultaneously.

The program development was done on RISC machines with the help of a PC emulator, as the 96002 Assembler was only available in a PC compatible form. The executable programs as well as all the necessary look-up tables were loaded into the DSP units via FASTBUS.

5.2 Trigger algorithm

In section 4, we presented the basic ideas that allow a fast and efficient recognition of the charges of particles initiating hadronic showers. The trigger decision time can of course also be optimised at the level of the algorithm itself which is implemented and executed inside the DSP's. We present here only the main structure of this algorithm; details can be found in [7].

The DSP's start their operation via an interrupt which is generated if all conditions for the neutron trigger at the first trigger level are fulfilled. The programs in both processors start to read the data from their input FIFO's, while the PCOS systems keep transmitting further data via the 10 MHz bus. The data are decoded and the hits from both detectors stored in an appropriate way for later processing. As the SPACAL 'hit' multiplicity is normally much smaller than the SCITIL multiplicity (figure 9), the DSP handling the calorimeter information is very likely performing already clusterisation operations, while the hodoscope DSP still accepts and decodes data from the corresponding PCOS readout (figure 11).

The *calorimeter DSP unit* is charged almost exclusively with the clusterisation task, which is the most extensive section of the whole charge decision procedure and thus the most time-critical part of the algorithm to be optimised. A fast clusterisation is achieved by setting up in total 3 lists, each with a length given by the SPACAL 'hit' multiplicity.

The first list is used to store the incoming SPACAL 'hits' (i.e. tower numbers). The second list, the so called successor list, is used to store for each tower number a pointer to the next SPACAL 'hit' that belongs to the same cluster. A predecessor list stores the pointer to the previous SPACAL 'hit' and is needed to insert or link 'hits' or cluster fragments during the clusterisation. The filling of the latter two lists is based on a two dimensional LUT, where the existence of a neighbouring relationship is examined for all pairs of hits, avoiding however double checks. If they are neighbours, the entries in the successor and predecessor list are set correspondingly.

Once those lists are filled, the calculation of equation (2) will be performed in the following way. Every SPACAL 'hit' that has no predecessor indicates the start of a cluster. The cluster size N is initialised with 1 and the y_i - and z_i -summations are started with the coordinates of the current 'hit'. With the help of the successor entry, the next 'hit' belonging to the same cluster can now be processed. If an entry exists, the cluster size N is incremented and the coordinates of this 'hit' are added to the sums. Otherwise, the cluster

end has been found. The current y_i - and z_i -coordinate sums, the cluster size N as well as a separation word indicating if data of further clusters are to be expected for this event, will then be transmitted via the intercommunication FIFO to the second DSP unit. In case of further ‘hits’ to be processed, the calorimeter DSP continues with the next cluster.

The *hodoscope DSP unit* stores the zero-suppressed hodoscope hit information, transmitted previously to its input FIFO, in form of a 127 Byte long LUT. This is most convenient for a later test of hits in a limited number of hodoscope modules (≤ 3 per shower). After the LUT has been installed, the processor waits for the first cluster information to be transmitted from the calorimeter DSP unit.

The sum of the y_i - and z_i -coordinates (=denominator in equation (2)) and the number N of towers in a cluster (=numerator in equation (2)) are used to complete the cluster centre calculations and to compute the differences y_{diff} , z_{diff} according to equation (2) and (3), respectively. Then, the tower and the hexagon sector containing the cluster centre as well as the two towers adjacent to the hexagon sector are determined. Finally, the corresponding hodoscope area is probed for hits of a charged particle by looking up the corresponding entries in the hodoscope LUT. As soon as at least one cluster is found which is not accompanied by a hit in any of the (maximum) 3 hodoscope modules tested, a second level trigger is generated initiating a readout of the current event.

Figure 12 shows the time performance of the neutron trigger. The plot reproduces basically the SPACAL multiplicity distribution (upper abscissa) of figure 9. It contains in addition, on the lower abscissa, the corresponding information on the maximum time needed by the DSP to take the final charge decision i.e. to generate either a trigger or a clear signal. The mean decision time is of the order of $11 \mu s$. In 95 % of the cases, the decision is taken earlier than $30 \mu s$ which corresponds to about 6 % of the mean readout time. In the remaining cases, the readout system is activated after $30 \mu s$ without waiting for a final answer; the DSP operations are then interrupted and the units reset. The implementation of the neutron trigger in the WA89 trigger system increases the dead time of the experiment only marginally (by $\approx 4 \%$).

6 Performance of the neutron trigger

Quantitative studies of the neutron trigger require an offline signature of neutrons with sufficiently high purity. In a first step one may require a hadronic shower in the calorimeter which does not match to the extrapolation of any track reconstructed in the spectrometer region. Cleaner conditions, however, can be obtained by the use of the invariant mass constraint from $\Sigma^\pm$ decays which provide a pure neutron sample within the limits given by the signal-to-background ratio in the region of the mass peak.

6.1 Reconstruction of $\Sigma^\pm \rightarrow n\pi^\pm$ decays

For the purpose of the present paper, it is sufficient to visualise and describe the reconstruction of $\Sigma^\pm$ decays by means of an offline event display, shown in figure 13 and 14. (Details on the full reconstruction procedure can be found in [8]).

Tracks originating from the target region are reconstructed with high precision in a silicon vertex detector which is followed by proportional and drift chamber systems in a ~ 10 m long decay zone upstream of the superconducting Omega magnet (figure 13). The momentum of particles is determined through the bending in the magnetic field and subsequent tracking in downstream large area drift chambers. The SPACAL calorimeter detects a high

energy shower which is assumed to be caused by a neutron, as the reconstructed barycentre does not match to any observable track in the spectrometer (figure 13 and 14 b)). A negatively charged track can be traced back to the ‘decay’-chambers upstream of the magnet. This track forms a decay vertex in both projections with a track segment which is only seen in the vertex detector and the M1-chambers and which is attributed to a Σ^- path (figure 14 a)).

$\Sigma^\pm$ are reconstructed and identified by their invariant mass from the momentum of the pion track and the neutron 4-momentum. The latter information is deduced from the shower energy measurement and the coordinates of the decay vertex and the neutron impact point on the calorimeter. Figure 15 shows such an invariant mass spectrum for data recorded with charged particle triggers in 1991, where no neutron trigger was available yet. Strong cuts on the vertex quality and decay topology were applied, leading finally to rather clean signals for $\Sigma^\pm$ (Σ^+ are less abundant in the WA89 data).

6.2 Trigger performance

Except for the minimum hadronic energy condition and its straightforward impact on the acceptance of neutrons and $\Sigma^\pm$ decays (see also section 2), a more detailed determination of the efficiency of the first level trigger with all its selective conditions needs very thorough MC and beam studies. For the second level, however, the performance can be studied from data using a sample taken with the first level trigger conditions, only, and having the DSP decision recorded as a flag.

Two quantities characterise the performance of the DSP’s: the rejection power for charged particles and the detection efficiency for neutrons.

The first quantity can easily be determined by using offline reconstructed tracks that match barycentres of hadronic showers in the calorimeter. 95 % of these tracks are correctly identified as charged particles by the DSP algorithm. Of the remaining sample, 2 % are known to be misidentified due to geometrical hodoscope inefficiency. The 5 % overall charge identification inefficiency can be regarded as a good estimate of the maximum contamination of the neutron trigger with charged particles developing hadronic showers. This is based on the qualitative observation that - due to the high bending power of the Omega magnet - the number of charged hadrons impinging on the central area covered by the SCITIL/SPACAL detectors is eventually of the same order of magnitude as the one of neutral hadrons.

The detection efficiency for neutrons is determined using a sample of hadronic showers that do not match any offline reconstructed track and that produce, combined with a negatively charged particle track, an invariant mass close to the Σ^- mass. From the mass spectrum, one computes the background-subtracted signal with and without the second trigger stage requirement. Using the DSP decision, we find that 70 % of the original Σ^- signal contains an identified neutron, independent of the specific setting of the cuts leading to the invariant mass reconstruction. The detection inefficiency can partially be explained by a remnant of the albedo effect, expected to be of order 10-20 % in the worst case for a tested hodoscope area consisting of 3 tiles. This estimation is based on data from [5] and assumes 50 GeV as a realistic mean shower energy in the WA89 data. Another contribution to the trigger inefficiency comes from preshowering neutrons in the lead glass, expected to occur with a probability of almost 70 %. It should be noted that a fraction of those will only have a small energy loss in the lead glass so that they appear in the offline reconstructed neutron sample, but would probably be rejected by the DSP in the second trigger stage. Due to such biases in the offline data sample, the 30 % DSP *misidentification* cannot be

compared directly with the quoted albedo and particularly the preshower probabilities.

We now want to give an overall characterisation of the two-stage neutron trigger on the reconstruction probability for $\Sigma^\pm$. A comparison of the yields in neutron trigger events to charged particle trigger events will allow to specify the enrichment of the data sample with final states containing reconstructable $\Sigma^\pm$. This is done in figure 16 which shows the reconstruction probability for $\Sigma^\pm$ under different trigger conditions. The entries in this invariant mass plot are normalised to the total number of triggers analysed in each of the three cases.

The lower curve shows the invariant mass plot as it is obtained with a WA89 physics trigger sample without the neutron trigger connected. If harder cuts were applied, the signal-to-noise ratio would become comparable to the situation in figure 15 for the data of 1991. The central curve demonstrates the impact of the first level neutron trigger stage i.e. basically the requirement of a high energy hadronic shower in the fiducial volume of the SPACAL calorimeter. The number of $\Sigma^\pm$ (signal minus background) increases by about a factor of 3 but is accompanied by a large absolute increase of the background. The signal over background ratio is mainly dominated by the low energy part of the hadronic shower spectrum (roughly a $1/E$ spectrum starting around 30 GeV) and improves significantly for higher energies. The upper curve includes also the second level neutron trigger decision. It shows the benefit and power of the DSP decision as it doubles the signal in the invariant mass peak whereas the corresponding background remains roughly the same.

7 Summary and outlook

We presented the first application of a hadronic lead/scintillating fibre calorimeter in a high energy physics experiment. Together with a newly developed scintillating tile hodoscope of similar transverse geometry and granularity, online information of the two detectors was exploited to generate a second level neutron trigger using Digital Signal Processors.

The neutron trigger operates with a mean decision time of 11 μ s and in 95 % of the cases, a decision is available earlier than 30 μ s. The selectivity of the trigger allows its implementation into the general trigger system without any prescaling and any significant increase of the experiment deadtime. Studies of the second level trigger performance i.e. the online charge identification using DSP's, were done offline on a data sample requiring only the first level trigger condition, namely a clean hadronic shower with at least 30 GeV energy deposit in the calorimeter. Out of this sample, $\Sigma^\pm \rightarrow n\pi^\pm$ decays were reconstructed by means of the invariant mass constraint from neutron and $\pi^\pm$ candidates. We determine the second level trigger efficiency for neutrons to be ≈ 70 % at a rejection efficiency of 95 % for charged particles initiating hadronic showers in the same energy range.

Due to the neutron trigger, a total yield of about 10^6 $\Sigma^\pm$ decays were reconstructed offline in the '93 data. This sample is sufficient to extract physics signals with a statistical significance of common occurrence in the field of charmed baryon decays. A more refined analysis will eventually be possible when also the neutron trigger data taken in the 1994 run will be available, adding a factor 3-4 in statistics to the '93 data sample.

8 Acknowledgement

We are grateful to the experienced technical support and advice which we received from J. Zimmer, G. Sannier and in particular from R. De Salvo during the upgrade of the SPACAL

prototype calorimeter, originally developed in a R&D effort (project leader: R. Wigmans) within the CERN/LAA project (project leader: A. Zichichi). The study of the trigger performance is relying on high quality data involving the complete WA89 spectrometer and by that the common effort of the whole collaboration. We also acknowledge the contribution of C. Scheel in the offline studies of the calorimeter performance in the '91 data.

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Figure Captions

- Fig. 1 Layout of the WA89 experiment at the CERN Omega spectrometer.
- Fig. 2 Layout of the SPACAL lead/scintillating fibre matrix. The hexagonal tower structure is obtained by coupling 1141 fibres to a common photomultiplier.
- Fig. 3 Photograph of the rear of the SPACAL calorimeter (155 towers) before the mounting of photomultipliers to the supports of the polished fibre bundles.
- Fig. 4 Layout of a scintillator tile. The light produced by a particle traversing the scintillator is absorbed by 5 wave-length-shifting fibres and guided to the photomultiplier.
- Fig. 5 Photograph of the SCITIL hodoscope built of 127 hexagonal tiles. The hodoscope modules map the inner 127 towers of the SPACAL calorimeter, located 15 cm behind.
- Fig. 6 Scheme for identifying neutral hadrons. (See text for explanations.)
- Fig. 7 Schematic drawing of the trigger and readout electronics for the detection of high energy neutrons.
- Fig. 8 a) Coordinate system in which all SPACAL tower centres have integer coordinates. b) Subdivision of a hexagonal tower into 6 sectors. c) Hodoscope area (dotted) which is tested for a hit, shown for different SPACAL impact point topologies.
- Fig. 9 Multiplicity distributions of hodoscope hits (passage of an ionising particle through a module) and of calorimeter 'hits' (hadronic energy deposit > 10 GeV in a tower).
- Fig. 10 Displacement of the impact points computed online by the DSP's with respect to the barycentres reconstructed offline.
- Fig. 11 Time flow diagram of the DSP operations performing the charge decision at the second level trigger stage.
- Fig. 12 Distribution of the SPACAL 'hit' multiplicity in bins of the maximum second level trigger decision time.
- Fig. 13 Graphic display of an interaction event in the WA89 experiment.
- Fig. 14 Zoom of the same event as in fig. 13. a) Vertex region. b) Display of the SPACAL calorimeter front face.
- Fig. 15 Invariant mass plot for $\Sigma^+ \rightarrow n\pi^+$ decays, as obtained in the 1991 data after applying hard cuts (no neutron trigger available yet).
- Fig. 16 Σ^- invariant mass distributions specifying the reconstruction probabilities for different trigger conditions in the 1993 data. The entries are normalised to the number of analysed events in each case.

WA89

Hyperon beam
1993 layout

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16