Detection of charged pions and protons in the segmented electromagnetic calorimeter TAPS

A. Marín\textsuperscript{a,1}, J. Díaz\textsuperscript{a,*}, R. Averbeck\textsuperscript{b}, A. Döppenschmidt\textsuperscript{c}, S. Hlaváč\textsuperscript{b,2}, R. Holzmann\textsuperscript{b}, F. Lefèvre\textsuperscript{b}, A. Schubert\textsuperscript{b}, R.S. Simon\textsuperscript{b}, Y. Charbonnier\textsuperscript{d}, G. Martínez\textsuperscript{d}, Y. Schutz\textsuperscript{d}, F.M. Marqués\textsuperscript{e}, M. Appenheimer\textsuperscript{f}, F.D. Berg\textsuperscript{f}, V. Metag\textsuperscript{b,f}, R. Novotny\textsuperscript{f}, H. Ströher\textsuperscript{f}, J. Weiβ\textsuperscript{f}, A.R. Wolf\textsuperscript{f}, M. Wolf\textsuperscript{f}, H. Löhner\textsuperscript{g}, R.W. Ostendorf\textsuperscript{g}, P. Vogt\textsuperscript{g}, H.W. Wilschut\textsuperscript{g}, A. Kugler\textsuperscript{h}, R. Pleskač\textsuperscript{h}, P. Tlustý\textsuperscript{h}, V. Wagner\textsuperscript{h}

\textsuperscript{a}IFIC, Centro Mixto Universidad de Valencia-CSIC, 46100 Burjassot, Spain
\textsuperscript{b}Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany
\textsuperscript{c}Institut für Kernphysik, Universität Frankfurt, D-60486 Frankfurt am Main, Germany
\textsuperscript{d}Grand Accélérateur National d’Ions Lourds, 14076 Caen Cedex, France
\textsuperscript{e}Laboratoire de Physique Corpusculaire, 14050 Caen Cedex, France
\textsuperscript{f}II. Physikalisches Institut, Universität Gießen, D-35392 Gießen, Germany
\textsuperscript{g}Kernfysisch Versneller Instituut, 9747 AA Groningen, Netherlands
\textsuperscript{h}Nuclear Physics Institute, 250 68 Řež, Czech Republic

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Abstract

We present the characteristics of the segmented BaF$_2$ calorimeter TAPS for the measurement of charged pions and protons. The method of particle identification exploits the relation between the kinetic energy of a particle, its mass and the time-of-flight required to reach the detector. The detection efficiency is calculated using GEANT-GCALOR simulations. The analysis method is applied in the reaction $^{40}$Ar + $^{nat}$Ca at 0.84 GeV. The simultaneous detection of charged pions and protons can be used to search for correlated pairs signalling the de-excitation of the L(1232) resonance.

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Keywords: Charged pion detection; Proton detection; BaF$_2$ scintillators; L(1232) resonance detection

\textsuperscript{*}Corresponding author. Fax: + 34 96 3864583; e-mail: diaz@evalvx.ific.uv.es.
\textsuperscript{1}Present address: Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany.
\textsuperscript{2}Permanent address: Institute of Physics, Slovak Academy of Sciences, SK-842 28 Bratislava, Slovak Republic.
The study of meson production in relativistic heavy-ion collisions is a powerful tool to extract information on the hot and dense nuclear matter formed during the collision. For example, by measuring \( \pi^0 \) and \( \eta \) meson production simultaneously, the baryonic composition of nuclear matter during the high density stage of the collision can be derived. For this purpose, the segmented Two Arm Photon Spectrometer TAPS [1,2] was designed primarily to measure photons in the energy range from 1 MeV to 10 GeV. Details of the TAPS arrangement and block structure are discussed in Refs. [1,3]. The response of TAPS to photons was studied in Refs. [4,5]. Neutral mesons are identified in the two-photon invariant-mass spectrum constructed from all photon pairs detected simultaneously in TAPS.

Although population and properties of baryonic resonances can be indirectly inferred from the observation of their decay mesons, direct information on the dynamics of baryonic resonances in the nuclear medium can only be obtained by analyzing the correlation of both decay products, i.e., nucleon and meson [6]. For example, the strength distribution of the \( \Delta(1232) \) resonance can be measured in the invariant-mass spectrum of correlated \( \pi \) mesons and nucleons.

In this paper we report on the capability of TAPS to identify and measure charged pions and protons with kinetic energies up to \( \sim 200 \) and \( \sim 370 \) MeV, respectively. The identification method is based on the relation between the kinetic energy of a particle, its mass and the time-of-flight required to reach the detector. The method is applied to events detected from the reaction \(^{40}\text{Ar} + \text{nat}\text{Ca} \rightarrow \) at 0.84 GeV. The beam was provided by the SIS accelerator of GSI Darmstadt.

2. TAPS set-up at GSI

The TAPS calorimeter consists of 384 BaF\(_2\) detectors of hexagonal shape. The length of the BaF\(_2\) crystals is 25 cm and the radius of the inscribed circle is 59 mm. A plastic scintillator (5 mm thick, NE102A) is placed in front of each BaF\(_2\) crystal to tag charged particles. In the present experiment, the crystals were arranged into rectangular blocks of \( 8 \times 8 \) detectors. The 6 blocks were mounted in two towers of three blocks each. The towers were placed at polar angles of \( \theta = \pm 57^\circ \) with respect to the beam axis. The central block of each tower was located in the horizontal plane including the beam axis, while the other two blocks formed angles of \( \phi = \pm 22^\circ \) with this horizontal plane. The distance between the target and the front face of the blocks was 138 cm. In this configuration a solid angle of 4.8\% of 4\( \pi \) was covered. However, the effective solid angle was 3.2\% of 4\( \pi \) since for a better shower containment only the inner 42 out of 64 detectors per block were included in the experimental trigger.

This condition eliminated detectors with less than 5 neighboring detectors. A natural calcium target of 390 mg/cm\(^2\) thickness was used. The incident \(^{40}\text{Ar} \) beam of \( 3.5 \times 10^7 \) particles/s of intensity and 0.84 GeV of energy was monitored by a segmented detector which provided the reaction trigger, delivered the time-zero signal of the reaction, and served to determine the centrality of the collision. This start detector [7] consisted of 32 plastic scintillators mounted in two rings around the beam pipe covering polar angles from 15\(^\circ\) to 30\(^\circ\) and placed at 10 cm distance from the target. The efficiency to detect a reaction was 64\% averaged over all impact parameters. This value was determined from a Monte Carlo simulation performed with the GEANT [8] code using the IQMD [9] model as event generator. Fragment formation was taken into account by using the minimum-spanning-tree procedure [10]. As the main purpose of this set-up was to measure \( \pi^0 \) and \( \eta \) mesons produced at mid-rapidity and identified by their decay into two photons [11,12], the experiment was performed under special triggers to enhance the meson content of the data. For \( \pi^0 \) mesons, the trigger was derived from two neutral particle hits in individual detector modules belonging to different TAPS blocks with an energy deposit larger than 15 MeV. For \( \eta \) mesons, the trigger was derived from two particle hits with an energy deposit larger than 90 MeV, also in individual detector modules belonging to different TAPS blocks. The fact that the 2 \( \times 90 \) MeV trigger also accepted charged particles.
made the present analysis of charged pions and protons possible.

3. Energy and time calibration

3.1. Energy calibration

The energy calibration of the BaF$_2$ detectors was achieved using cosmic rays [13]. The cosmic ray spectrum in a TAPS crystal appears as a peak due to the mainly vertically incident minimum-ionizing muons, on top of a background which is partly due to cosmic rays coming from other directions and which is also due to other components of the cosmic radiation. The average energy deposited by minimum-ionizing muons in BaF$_2$ is 6.6 MeV/cm [4,5]. In the present geometry where the BaF$_2$ modules were laying on their edges, the average energy deposited by minimum-ionizing muons corresponds to 37.7 MeV for the horizontal detectors and 38.3 MeV for the inclined detectors, as estimated from GEANT simulations. The first channel with signal in the cosmic-ray spectra was taken as 0 MeV, because the detection threshold was set just above the noise. A linear dependence between channel and energy was assumed. The cosmic energy calibration was also applied to the charged pions because of the similar ionization density of pions and muons. For protons and deuterons a reduction of scintillation light to an average value of $0.85 \pm 0.05$ of the minimum ionizing muon value was assumed. The influence of the reduced light output known as quenching [14] was corrected for.

3.2. Time-of-flight calibration

The time-zero signal of the reaction was delivered by the start detector. In order to know which of the 32 modules produced the start, the time signals of the 32 start detector modules were staggered in time with a delay of 1 ns between consecutive ones [7]. Therefore, for each BaF$_2$ detector 32 time-of-flight spectra corresponding to the events triggered by one of the 32 start detectors were obtained. These spectra were aligned by positioning the maximum of the photon peak at 4.6 ns, which corresponds to the photon time-of-flight to cover the distance between the target and the front face of the detector.

Crosstalk effects in the 8-fold CFD and TDC modules of TAPS were accounted for by measuring the shift of the time peak for the case in which two channels fired in the same module with respect to the position in which only one channel fired. If more than two channels fired, we assumed an additive correction for the channels involved in accordance with previous findings [13]. This correction is more important for a photon analysis than for the analysis of charged particles, because the module occupancy in the former case will be larger due to the fact that electromagnetic showers are on the average larger than hadronic ones and because neighbouring detectors in the same block column used the same electronic modules. Also an energy dependent walk effect exists. The time walk in TAPS was corrected by sorting the energy signals into nine different bins and calibrating the prompt peak for each energy bin. During the experiment, the prompt time peaks of the individual BaF$_2$ detectors were continuously monitored and stabilized at the nominal value of 4.6 ns. After correcting for these three effects, the total width of the prompt peak was 0.980 ns (FWHM). This accounts for both the intrinsic BaF$_2$ and start detector time resolutions (Fig. 1, inset).

![Fig. 1. Time-of-flight spectrum corrected for crosstalk, walk and time shifts for the 2 x 90 MeV hardware trigger as observed in the reaction Ar + Ca at 0.84 GeV. In the inset, the time-of-flight is plotted for the additional analysis conditions: no plastic scintillator fired, pulse shape of photons and an energy deposit larger than 5 MeV. The time resolution is 0.980 ns (FWHM).](image)
4. Standard identification of charged particles in TAPS

Combining the information given by charged particle tagging, time-of-flight (TOF) and pulse-shape analysis (PSA) γ rays and hadrons can be discriminated in TAPS.

4.1. Charged particle tagging

The plastic scintillators placed in front of each BaF$_2$ crystal provide a tag for charged particles. When a charged particle penetrates the plastic detector depositing an energy larger than a given threshold, the BaF$_2$ signal is marked with a bit. This bit can be used in the later analysis to show if the hit was produced by a charged particle or by a neutral one. The deposited energy in the plastic ΔE-detector decreases as the energy of the incident particle increases. Therefore, to ensure identification even of minimum-ionizing charged particles, which deposit 1 MeV in the detector, all plastic detector thresholds were adjusted to 0.5 MeV. First, by means of $^{90}$Sr and $^{60}$Co radioactive sources a linear energy response of the plastic detectors was established. Then, the Compton edge of the $^{60}$Co spectrum in the CPV detectors was used to set the threshold in each module. The detection efficiency is close to 100% [15, 16]. By using tapered light guides which are coupled to the full length of the edge of the ΔE-detector, a very uniform light output was achieved. Within $\pm$ 10% the pulse was independent of the position of the penetrating particle.

4.2. Time-of-flight discrimination

Relativistic ($\gamma$ and $e^-$) and non-relativistic particles (nucleons and nuclear fragments) appear as two well separated peaks in the TOF spectrum (Fig. 1). Charged pions are found in the intermediate region between the two time peaks. Therefore, the selection of charged pions using only the time-of-flight information presents two problems. Firstly, charged pions with energies $E_k > 200$ MeV will not be resolved from the $\gamma$ peak. Secondly, fast protons and slow charged pions overlap in the time spectrum.

4.3. Pulse-shape discrimination

The fact that the intensity of the two different components in the scintillation light produced by BaF$_2$ depends on the ionization density and therefore on the type of the particle can be exploited to provide additional discrimination of particles. With minimum electronic effort pulse-shape discrimination is performed by integrating the anode charge of the BaF$_2$ photomultiplier during two different time gates within 25 ns and 2 $\mu$s resulting in the measured energies $E_n$ and $E_w$, respectively. In a two-dimensional representation of $E_n$ versus $E_w$ two main branches appear, as shown in Fig. 2a. The upper branch corresponds to photons and electrons and the lower branch to non-relativistic charged particles. Neutrons may show up in the upper branch if they lose energy by capture processes, or in the lower one, if they give rise to nuclear reactions that result in proton emission. In between, an additional branch produced by charged pions can also be observed. The charged-pion line can be well seen as a peak between the peaks corresponding to nucleons and to photons in the one-dimensional projection ($E_n/E_w$) of the diagram (Fig. 2b). PSA discrimination is able to...
discriminate photons from hadrons. To this effect, one usually determines a line [13] which separates the upper and lower branches in the $E_n$ versus $E_w$ plot. The calculation of a similar separation line between charged pions and protons, however, is very difficult if not impossible because these two peaks are very close to each other, and they may even overlap. Moreover, an additional separation line between protons and heavier nuclear fragments (mainly deuterons, tritons and alphas) would be needed to isolate protons from heavier fragments. In summary, PSA is applicable for $\gamma$ against particle selection but not for the identification of $\pi^\pm$ and protons. Consequently, in Section 5 an alternative method for charged-particle identification will be presented.

5. Identification of charged particles

It is well known that the processes involved in the stopping of hadronic particles are completely different from those involved in the energy loss of photons and electrons. While high-energy photons in BaF$_2$ produce a shower that may spread over several neighboring detectors, the main characteristic of hadronic particles is that they lead to clusters which predominantly involve only one detector ($s = 1$). A hadronic cluster is defined by a detector with a deposited energy larger than 5 MeV accompanied by a signal in the corresponding plastic detector and all the neighboring detectors in which the energy deposited is larger than 1 MeV. Hadronic clusters covering 2 or 3 detectors ($s = 2$ or $s = 3$) correspond mainly to particles impinging with a non-normal direction onto the detector and with sufficiently high energy for traversing obliquely several BaF$_2$ crystals. Also, reactions of incoming particles in the detector can lead to this pattern and to even larger clusters. The kinetic energy $E_k$ of the hadronic particles can be obtained by adding the deposited energy in all the detectors of the cluster. Candidates of charged particles were defined as clusters of detectors that fulfilled the following three conditions: (i) exactly one plastic detector fired, (ii) the BaF$_2$ module with the highest energy deposit does not have a photon-like signal [11]; and (iii) the cluster size is limited to a maximum of 3 detectors ($s \leq 3$).

5.1. Mass of charged particles from the measurement of kinetic energy and TOF

The relation between the kinetic energy $E_k$ of a particle with mass $m$ and the time $t$ needed to travel a given distance $L$ is

$$E_k = m\left(\frac{1}{\sqrt{1 - \beta^2}} - 1\right) = m(\gamma - 1),$$  \hspace{1cm} (1)

where $\gamma = 1/\sqrt{(1 - \beta^2)}$ and $\beta = L/(ct)$. If we measure the kinetic energy and the time-of-flight and $L$ is known, the mass of the particle can be determined [11,17]. In the two-dimensional plot, $E_k$ versus $t$ (Fig. 3), the experimental correlation of these two kinematical variables is shown for charged particles selected under the experimental conditions previously described. The theoretical relationship (Eq. (1)) is represented by the full lines indicating the position for charged pions, protons and deuterons. For simplicity, the time is taken as the time-of-flight between the target and the front face of the detector. Due to the limited time and energy resolution and to the finite size of the
detectors the lines are spread out into bands. The method employed in the present work to select charged pions and protons is to define two-dimensional cuts around the theoretical curve for each particle species (Fig. 3). This method was found to be more appropriate than the procedure of pulse-shape discrimination: it presents the advantage of separating charged pions, protons and heavier nuclear fragments (mainly deuterons, tritons and alphas), simultaneously.

Charged pions, protons and deuterons are well identified in the mass spectrum (Fig. 4) obtained from Eq. (1) for clusters with $s \leq 3$. However, the peak structure in the mass spectrum corresponding to these three different particles is lost for clusters with $s > 3$. The three conditions required to select charged particles are satisfied by more than 80% and 92% of the showers in the charged pion and proton mass windows, respectively.

The mass identification of charged particles based on Eq. (1) has been applied to the data. A high energy detection limit is imposed by the length of the BaF$_2$ crystals which is $\sim 200$ MeV for charged pions and $\sim 370$ MeV for protons. Above these incident energies charged pions and protons punch through the BaF$_2$ crystals. On the other hand, at low energies, corrections due to energy losses in the passive parts of the detector and target region must be considered.

6. Response of the TAPS spectrometer to charged particles

6.1. Charged pions

Charged pions interact via several different kinds of processes which also depend on the isospin of the pion. The first process to be considered for both types of pions is the decay in flight into a muon and a neutrino with a lifetime of 26 ns. The muon disintegrates with a lifetime of 2.2 $\mu$s into an electron and two neutrinos. If the muon reaches TAPS, it will be indistinguishable from a pion. Concerning the decay in flight, both types of charged pions behave in the same way. With the present TAPS geometry, 10% of the charged pions with a kinetic energy of 100 MeV have decayed before reaching the TAPS blocks.

While charged pions are slowing down inside the detector, they can suffer absorption by the Ba and F nuclei of the scintillator material. In this process, they interact with a number of nucleons [18]. The interaction with only one bound nucleon has a very small probability due to the little phase space available [19], whereas the interaction with two correlated nucleons is the most probable process. In fact, the proportion of pions absorbed by a nucleon pair is 85% for pions with an energy of 100 MeV and still 60% for pions with an energy of 170 MeV [20].

The different possible channels are

\[ \begin{align*} 
\pi^- + (pp)_c &\rightarrow p + n, \\
\pi^- + (pn)_c &\rightarrow n + n, \\
\pi^+ + (pn)_c &\rightarrow p + p, \\
\pi^+ + (nn)_c &\rightarrow p + n, 
\end{align*} \tag{2} \]

where the subscript $c$ indicates that the nucleons are correlated. In case of $\pi^-$ ($\pi^+$) the excitation of 2n (2p) in the final state is the favoured channel being 5 times [19] more probable than the pn channel. In all these cases, part of the actual kinetic energy and of the pion mass is transformed into kinetic energy of the nucleon pair. The remaining energy is dissipated by evaporating nucleons and by producing low-energy photons [21]. When there are neutrons in the final state, only part of this additional energy will be finally deposited in the detector due to the poor response function of TAPS.

Fig. 4. Mass spectrum of charged particles calculated from Eq. (1), for cluster sizes $s \leq 3$ (full line) and $s > 3$ (dashed line). The nominal masses of $\pi^\pm$, proton and deuteron are indicated by vertical arrows. The mass windows used to select charged pions and protons are indicated by the horizontal arrows.
to neutrons [22]. Charge exchange of $\pi^+ (\pi^-)$ producing $\pi^0 + p(n)$ represents around 20% of the total reaction cross section in the energy range considered here. All these processes will lead to clusters of larger size and they will be suppressed by the analysis conditions.

Once charged pions come to rest, the measurement of the kinetic energy is completed for both kinds of mesons. However, from there on, their behaviour is completely different. Positive pions decay into a positive muon and a neutrino. The muon kinetic energy was also measured in the detector because the integration gate was larger than 26 ns. Then, the muon disintegrates into an electron and two neutrinos. However, the electron energy was not always integrated because we required in the electronics to have a signal during the first 300 ns in order to activate the energy integration. Then, integration would mainly happen for those detectors where both impact and disintegration occurred.

On the other hand, all negative pions at rest will form pionic atoms. Then, negative pions come close to nuclei where they are absorbed mainly by a pair of correlated nucleons as in the previous case (Eq. (2)). Part of the mass of the negative pion is transformed into kinetic energy of nucleons (mainly neutrons). Apart from the emission of the two correlated nucleons there is also emission of photons and evaporation of neutrons and protons having very small kinetic energy [21]. As the energy deposited by neutrons in TAPS and the detection efficiency are small [22], the pion mass contributes very little to the deposited energy and therefore the average difference in deposited energy between $\pi^+$ and $\pi^-$ would be small. However, due to the emission of photons and evaporation of protons, negative pions produce preferentially clusters which comprise several detectors. We employ this sensitivity to the size of the cluster to enhance the amount of undistorted charged pions in our analysis.

GEANT [8] simulations were performed in order to understand the detection process of charged pions with the TAPS detector. The description of charged-pion interactions in the standard GEANT package is only reliable for kinetic energies larger than 2.5 GeV. As the energy range of our interest was 0–300 MeV, the specific program GCALOR in the form of a GEANT-CALOR interface was applied [23], where the significant processes undergone by charged pions were considered.

The response of TAPS to monoenergetic charged pions in the kinetic energy range from 0 to 350 MeV emitted isotropically in the laboratory frame was studied for the set-up described in Section 2. The different cluster size distribution obtained for the two kinds of charged pions (Fig. 5) is a clear signature of their specific interaction mechanisms in our detector. For example, it can be observed that the relative amount of $\pi^+$ with cluster size $s = 1$ is two times larger compared to $\pi^-$. The number of $\pi^+$ with cluster size $s = 2$ becomes comparable in intensity. On the other hand, the number of $\pi^-$ with cluster size $s = 1$ does not dominate even at low energies and the cluster size is larger on average compared to $\pi^+$. In the following, only clusters with size $s = 1$ will be considered because we are interested in the most clean and undistorted signal of charged pions, i.e., when absorption is not the dominant process. The response function of TAPS to monoenergetic charged pions as obtained from the simulations shows two components: a sharp peak reflecting the initial energy and a background that corresponds to the case where additional processes have taken place. Furthermore, four different peaks were found for the same

![Fig. 5. Relative number of $\pi^+$ (a) and $\pi^-$ (b) as a function of the cluster size ($s$) for three different kinetic energies as obtained from the simulations.](image)
Fig. 6. Initial $\pi^+$ kinetic energy as a function of the position of the sharp energy peak observed for the central columns of the $8 \times 8$ BaF$_2$ block and for the columns at the edges which differ by the amount of absorbing material due to the light guides of the $\Delta E$-detectors. The condition $s = 1$ has been applied in the analysis. Pions that punch through the detector ($E_k > 200$ MeV) are also shown.

initial energy corresponding to the four different thicknesses of material in front of the BaF$_2$ module, represented by the plastic $\Delta E$-detector only or by the $\Delta E$-detector plus one, two or three light guides. In Fig. 6, the initial kinetic energy is shown as a function of the position of the sharp energy peak observed for initial pion energies from 50 MeV up to 350 MeV. The difference between the initial energy of the emitted pion and the energy deposited in the BaF$_2$ module increases as the deposited energy decreases due to the increasing energy loss in the plastic $\Delta E$-detector and the light guides. For kinetic energies smaller than 30 MeV pions are stopped before entering the BaF$_2$. For energies larger than 200 MeV, pions punch through the detector and deposit less energy in the BaF$_2$ module. The response function of TAPS to monoenergetic $\pi^\pm$ after correcting for energy losses is shown in Fig. 7, where $I_0$ is the number of emitted pions and $I$ reflects the number of pions detected at a given energy. The bottom frame of the figure (250 MeV initial energy) shows that the response of TAPS to $\pi^+$ and $\pi^-$ that punch through the detector is identical.

The efficiency for detecting charged pions, which is specific for the current setup (Section 2) can be extracted from the same figure. We have considered the detection efficiency given by the fraction of particles recorded in the whole energy spectrum, and the full peak efficiency given by the fraction of incident particles contributing to the full-energy peak. The detection efficiency is needed in order to calculate the production cross section of charged pions. In Fig. 8 both quantities are plotted for the two kinds of charged pions. It can be observed that the detection efficiency for $\pi^+$ is about 2 times larger than for $\pi^-$ mesons. Under the current analysis conditions, the charged pion spectra will contain $\sim 66\%$ of $\pi^+$ and $34\%$ of $\pi^-$. If, in addition to this, we consider the isospin factor of the $^{40}\text{Ar} + ^{48}\text{Ca}$ system, 62% of the spectrum will correspond to $\pi^+$ and 38% to $\pi^-$. The first test of the validity of the GEANT-GCALOR simulation is the comparison of the relative number of pions as a function of the cluster size in the simulation with the experimental one. As
input to the simulation a thermal and isotropic source of $\pi^\pm$ mesons in the nucleon–nucleon center-of-mass frame was used with the experimentally measured inverse slope parameter of $T = (55.5 \pm 1.5)$ MeV [12]. For the comparison events under the pion peak in the mass spectrum and with a kinetic energy between 20 and 200 MeV were considered. The contribution from other particles, i.e. mostly protons, has been subtracted (see Section 6.3). The experimental data and simulated results are shown in Fig. 9. In the same figure, the individual distributions assuming only a source of $\pi^+$ or $\pi^-$ are also shown. The fair agreement between data and simulations should be noted, which can only be achieved when both kinds of charged pions are included. The same simulation was used to calculate the meson acceptance that will be used to correct meson spectra.

The important conclusion of these simulations is that by selecting clusters of size $s = 1$, we enhance considerably the number of charged pions where the energy is not distorted by interaction processes in the detector. We also demonstrate that the GCALOR package is able to reproduce the distribution in $s$, the size of the clusters, which is a clear signature of the different processes undergone by charged pions.

6.2. Protons

The response of monoenergetic protons emitted isotropically in the laboratory frame was studied in the kinetic energy range from 0 to 600 MeV. The energy spectra show a sharp peak corresponding to the initial energy with a tail expanding to lower energies that is due to reactions of protons in the BaF$_2$. As already seen for charged pions, four different peaks were found for the same initial energy reflecting the four different thicknesses of material in front of the BaF$_2$ module, represented by the plastic $\Delta E$-detector only or by the $\Delta E$-detector plus one, two or three light guides. In Fig. 10 the initial kinetic energy is shown as a function of the position of the sharp energy peak observed for proton energies up to 600 MeV. The difference between the initial energy of the emitted proton and the energy deposited in the BaF$_2$ increases as the deposited energy decreases due to the increasing energy losses in the plastic $\Delta E$-detector and the light guides. For kinetic energies smaller than 50 MeV, protons are
Fig. 10. Initial proton kinetic energy as a function of the position of the sharp energy peak observed for the central columns of the $8 \times 8$ BaF$_2$ block and for the columns at the edges which differ by the amount of absorbing material due to the light guides of the $\Delta E$-detectors. The condition $s = 1$ has been applied in the analysis. Protons that punch through the detector ($E_k > 370$ MeV) are also shown.

Fig. 11. Response of TAPS to monoenergetic protons under the condition $s = 1$. The energy of the protons has been corrected for energy losses in the passive part of the detector using the dependence shown in Fig. 10. See text for the definition of $I/I_0$.

Fig. 12. Detection efficiency for monoenergetic protons calculated with the total amount of counts in the energy spectra (closed symbols) and full-peak efficiency using only the counts in the peak (open symbols).

already stopped before entering the BaF$_2$. For energies larger than 370 MeV, protons punch through the detector and they deposit less energy in the BaF$_2$ module. Therefore, they will produce a tail towards the pion mass region that will be analysed in Section 6.3. The kinetic energy spectrum for monoenergetic protons after correcting for energy losses is shown in Fig. 11, where $I_0$ is the number of monoenergetic emitted protons and $I$ reflects the number of detected protons at a given energy. As in the case of pions we have calculated the detection and full-peak efficiencies for protons. In Fig. 12 both efficiencies are plotted. Proton spectra also need to be corrected for the proton acceptance. Simulations assuming an isotropic thermal source at rest in the nucleon–nucleon center-of-mass frame were used. An inverse slope parameter of $T = 75$ MeV was chosen consistently with the existing systematics [24,25].

6.3. Simulation of the present setup

The influence of the experimental trigger selection on the charged-particle detection with TAPS needs to be studied. Events generated by the IQMD model (Section 2) were used as input to the GEANT-GCALOR simulation in order to work with all particles produced in a typical heavy-ion reaction. The output of the simulation was
analysed under the experimental conditions and showed that the electronics trigger reduces the efficiency to detect single charged particles by a factor 12.5 because of the requirement of two hits in two different TAPS blocks with an energy deposit larger than 90 MeV (Section 2). The good agreement for charged pions and protons between the experimental spectra and the IQMD simulation (Fig. 13) supports the use of this factor to correct the experimental results. A similar simulation was also performed excluding the pions from the input source in order to estimate the contamination in the pion mass region from particles that lost energy in the passive parts of the detector or punched through the detector. The expected contribution of these sources between 0 and 200 MeV is (17 ± 3)%.

The width of the mass peak, after correction for energy loss in passive materials of the detector, can be estimated from the energy and time resolutions as

\[
\frac{\delta m}{m} = \sqrt{\left(\frac{\delta E_k}{E_k}\right)^2 + \gamma^2(\gamma + 1)^2\left(\frac{\delta t}{t}\right)^2}. \quad (3)
\]

In Fig. 13 values of \(\frac{\delta m}{m}\) of 64% and 28% for pions and protons, respectively, are observed. These values are consistent with an average kinetic energy of ~80 MeV for charged pions and ~160 MeV for protons, calculated using the energy resolution which is 10% FWHM [5] and the time-of-flight resolution of 0.98 ns.

7. Energy spectra of charged particles

7.1. Charged pions

Charged pions were selected by choosing events in the mass spectrum from 30 to 300 MeV/c^2. The kinetic energy distribution in the nucleon–nucleon center-of-mass system was measured in the interval 74° < θ_cm < 106° and corrected for the acceptance \(\varepsilon(E_{cm}, \theta_{cm})\). The spectrum after efficiency and acceptance correction and background subtraction is shown in Fig. 14 extrapolated to 4\(\pi\). The spectrum is described within the limited energy range of the present analysis with a Boltzmann distribution with an inverse-slope parameter of \(T = (59 ± 6)\) MeV.

The inclusive reaction cross section obtained for charged pions is \(\sigma^{\pi^+ + \pi^-} = (2.4 ± 0.3)\) barns which agrees with the result for \(\pi^-\) measured simultaneously, \(\sigma^{\pi^-} = (1.18 ± 0.17)\) barns [12] and with the result for the system Ar + KCl at the same incident energy of \(\sigma^{\pi^+ + \pi^-} = (2.4 ± 0.5)\) barns [24].

Fig. 13. Experimental mass spectrum corrected for energy losses for clusters of \(s = 1\) (full line) compared with the one obtained from the simulation of the experimental trigger with IQMD (dashed line). An IQMD simulation excluding pions shows the contamination from other particles (mainly protons) in the pion region (dotted line). The arrows indicate the widths of the pion and proton peaks.

Fig. 14. Kinetic energy spectra in the nucleon–nucleon center-of-mass for charged pions (\(\pi^+ + \pi^-\)) (closed symbols) measured in the interval 74° < θ_cm < 106° and extrapolated to 4\(\pi\). The continuous line corresponds to a fit with a Boltzmann distribution. For comparison the corresponding spectrum for \(\pi^-\) scaled by the isospin factor and also extrapolated to 4\(\pi\) is plotted (open symbols, dotted line).
7.2. Protons

Protons were selected by choosing events in the mass spectrum from 600 to 1300 MeV/c². The kinetic energy in the nucleon–nucleon center-of-mass system was measured in the interval $10^4 < \theta_{cm} < 120^\circ$ and corrected for the acceptance $\varepsilon(E_{cm}, \theta_e)$. The spectrum after efficiency and acceptance correction is shown in Fig. 15 extrapolated to $4\pi$. The spectrum is described within the limited kinetic energy range imposed by our detector with a Boltzmann distribution with an inverse-slope parameter of $(69 \pm 5)\text{MeV}$. The inclusive reaction cross section obtained for protons is $\sigma = (12.7 \pm 1.9)\text{b}$ which agrees with the results for the system Ar + KCl at the same incident energy of $\sigma = (14 \pm 3)\text{b}$ [24].

8. Conclusion

We have shown that the electromagnetic calorimeter TAPS can be used to identify and measure charged pions and protons produced in heavy-ion collisions at relativistic energies. The method is based on the direct mass determination of these particles using their deposited energy in the detector and their time-of-flight needed to reach the detector. We have also shown that the GCalor Monte Carlo program is able to describe the charged-pion identification with TAPS. The selection of clusters with size $s = 1$ has been established as the most convenient condition to obtain charged pions undisturbed by interaction processes in the detector. Furthermore, cross sections and energy distributions of charged pions and protons are in agreement with the existing systematics. The good agreement between data and simulation allows to estimate the individual contributions of $\pi^+$ and $\pi^-$ to the spectra. Under the current setup and analysis conditions the amount of $\pi^+$ in the spectra is 62% whereas the amount of $\pi^-$ represents 38%. These features of TAPS can be exploited to search for the $\Delta$ resonance $\pi^+p$ correlations.

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References