NEUTRAL PIONS PRODUCED IN 60*A* MeV Ar+C, Ni, Ag, Au REACTIONS*

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The neutral pion production was studied in subthreshold 60A MeV Ar+C, Ni, Ag, Au reactions. A kinematical fit procedure was applied for a reliable reconstruction of neutral pion kinematics. The transverse momentum spectra are very similar for all studied systems and they are reasonably described by Boltzmann distributions. The temperature parameter does not depend on the total energy available in the system. Perpendicular to backward emission of neutral pions is well described by a simple geometrical model of pion reabsorption.

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1. Motivation

The main goal of this work is to study the mechanisms of production and absorption of π^0 mesons in nuclear matter. Particularly, we want to analyze the physical characteristics of neutral pions produced inside the collision region of two nuclei at 60A MeV beam energy, that is at energy per nucleon well below the threshold in elementary nucleon–nucleon collisions. The colliding systems were chosen in such a way that they cover a wide range of masses.

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Short-lived neutral pions are usually detected through their two-photon decay (BR ≈ 98.8%) [1]. Subthreshold π^0 mesons produced in heavy-ion reactions were first measured, in $\gamma\gamma$ invariant mass analysis, by lead-glass Cerenkov detectors in the eighties [2] and more recently by BaF_2 spectrometers [3] of much better invariant mass resolution (from 40% down to 10%, FWHM).

2. Experiment

The experiment was carried out at the KVI facility in Groningen, the Netherlands. The experimental setup consisted of TAPS spectrometer [4] and the Forward Wall detector [5, 6]. The TAPS consisted of 6 blocks of 64 BaF_2 modules, covering 17% of the full solid angle. The $60A$ MeV ^{36}Ar beam was delivered by the superconducting AGOR cyclotron with a bunch rate of 37.1 MHz and with intensities of 3.0–12.5 nA. The projectile ions were directed on ^{12}C, $^{\rm nat}$Ni, $^{\rm nat}$Ag and ^{197}Au targets.

The rejection of charged particle hits was done with the help of a thin plastic scintillator counter placed in front of each TAPS module. The data presented here were obtained with the trigger condition that at least two BaF_2 modules in separate blocks registered neutral hits above 10 MeV energy.

3. Analysis

The raw experimental data were calibrated using the FOSTER [7] package following the analysis prescriptions described in ref [8]. The identification of π^0 mesons is based on invariant mass analysis of coincident pairs of energetic photons. The raw data of those pairs is shown in Fig. 1. The invariant mass spectrum is broadly spread around the π^0 mass peak ($m_{\pi^0} \approx 134.98 \mathrm{MeV}/c^2$).

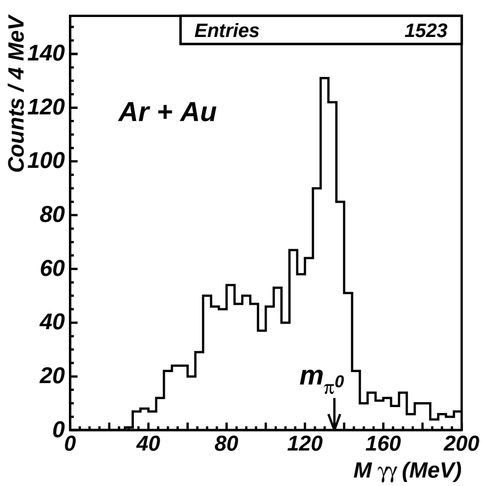

Fig. 1. Raw invariant mass spectrum of photon pairs measured in Ar+Au collisions.

The neutral pion candidates are presented in a two-dimensional plot in Fig. 2 as a function of invariant mass and opening angle of two photons. They can be grouped in two separate regions. One, located at low opening angles, can be attributed to background events of uncorrelated photons.

Since neutral pions from subthreshold reactions are produced with low kinetic energies, the opening angle between the decay photons, $\theta_{\gamma\gamma}$, is rather large. Therefore, only events with 2 photons having large opening angles are attributed to π^0 decays.

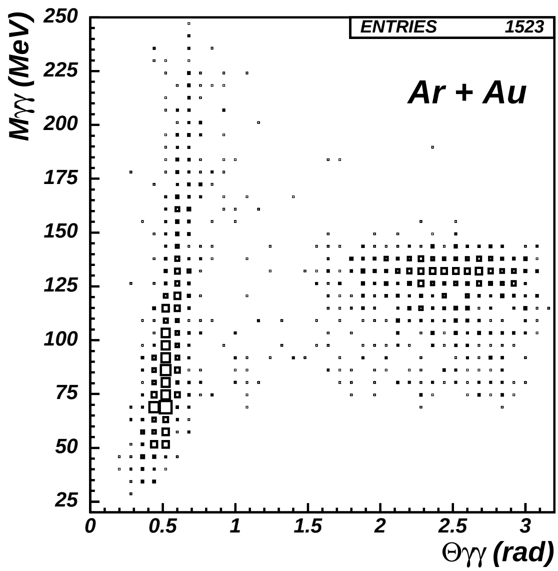

Fig. 2. Invariant mass vs opening angle for the photon pairs detected in Ar+Au collisions.

The kinematical properties of neutral pions were reconstructed from the measured pion momenta using the kinematical fit procedure, described in Ref. [9]. This analysis is based on the event by event χ^2 minimization of the photon momenta with respect to the experimental values, requiring the invariant mass of two photons to be exactly equal to the mass of a neutral pion. The method serves as an acceptance criterion and filters out events on the selected confidence level (90%). The application of the kinematical fit procedures requires that the distortion of the measurements are of statistical nature, so the χ^2 analysis can be quantitative. This condition narrows the invariant mass window for $\gamma\gamma$-events down to 112–155 MeV/c^2 range. Subsequently the data were corrected for the acceptance, using the TAPS simulation code KANE [10].

4. Results

The transverse momentum spectra of neutral pions measured in the four systems studied here have a very similar shape (Fig. 3). Assuming a thermodynamically equilibrated source of pions, the transverse momentum distribution can be described by the formula

$$\frac{dN}{dp_{\mathrm{T}}} = A\, p_{\mathrm{T}}\, m_{\mathrm{T}}\, \exp\left(-\frac{m_{\mathrm{T}}}{T}\right) , \tag{1}$$

where $m_{\mathrm{T}} = \sqrt{p_{\mathrm{T}}^2 + m_\pi^2}$ is the transverse mass, p_{T} is the transverse momentum, A is a normalization coefficient and T is an apparent temperature.

Fitting Eq. (1) to the experimental spectrum, the temperature parameter can be extracted. The spectra are well reproduced in terms of χ^2 analysis, however some discrepancy pointing to a non-thermal behavior can be observed. More detailed discussion on this point would require better statistics of the measured spectrum. The good description of the spectrum by Eq. (1) does not imply that the source is thermodynamically equilibrated. The temperature just serves as a parameter describing the spectrum.

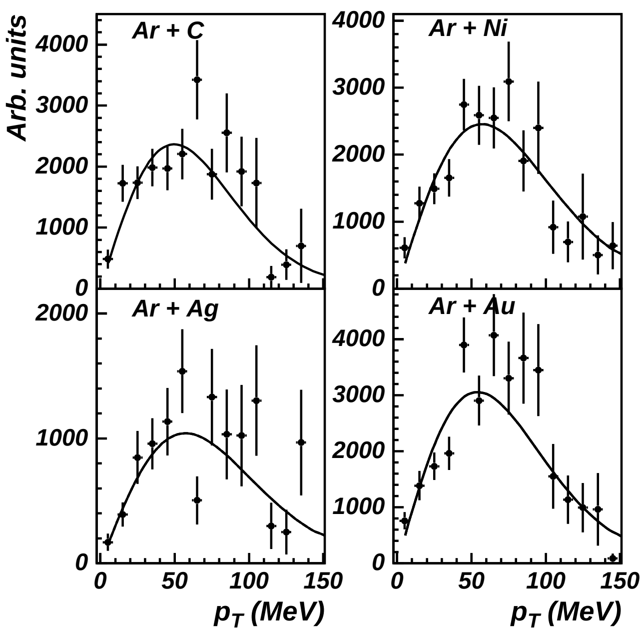

Fig. 3. Transverse momentum spectra of neutral pions measured in four colliding systems (Ar+C, Ni, Ag, Au). The lines represent Boltzmann distributions fitted to the data.

The temperature parameters obtained for all four studied systems and for the Kr+Ni reaction at $60A$ MeV [11] are very close to each other. The average temperature parameter equals to $T = 15.6 \pm 0.8$ MeV. We do not observe any change of the temperature parameter as a function of the total energy available in the nucleus–nucleus (AA) collisions (Fig. 4). This observation is consistent with the assumption that subthreshold pions are produced in the first stage of the collision and gather energy necessary for their production from the coupling of the beam momentum with the internal Fermi momentum of the nucleons.

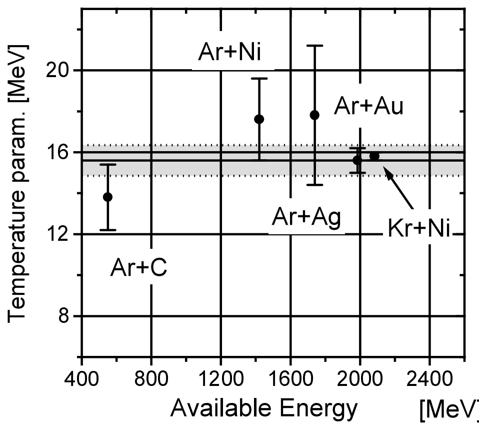

Fig. 4. Temperature parameter as a function of the available energy in AA center-of-mass, fitted to $p_{\rm T}$ spectra for different colliding systems at 60 A MeV.

The reabsorption of pions can be compared by looking at their emission patterns. Pions emitted parallel to the beam axis undergo stronger absorption than those emitted perpendicularly. This is caused by different paths neutral pions have to pass through the nuclear matter for those two cases.

The rapidity spectra in the range of the detector acceptance $-1.0 < y < 0.5$ are shown in Fig. 5. The forward emitted pions do not fall within the acceptance window. In this situation, the effects of pion reabsorption can be studied by the comparison of the number of pions emitted perpendicularly ($\mathrm{p}_{\perp} > |\mathrm{p}_{||}|$) to those backward emitted.

The ratio of those two numbers (Fig. 6) shows a weak dependence on the target mass. The same ratio was calculated within a geometrical model of pion reabsorption [12]. Assuming a fixed pion absorption length, λ, the model fails to reproduce the light target results. However, introduction of a momentum-dependent absorption length, $\lambda(p)$ decreasing at very low momenta [13], describes the data very well. A very strong effect is predicted for very low mass targets. However, the model fails to reproduce the angular

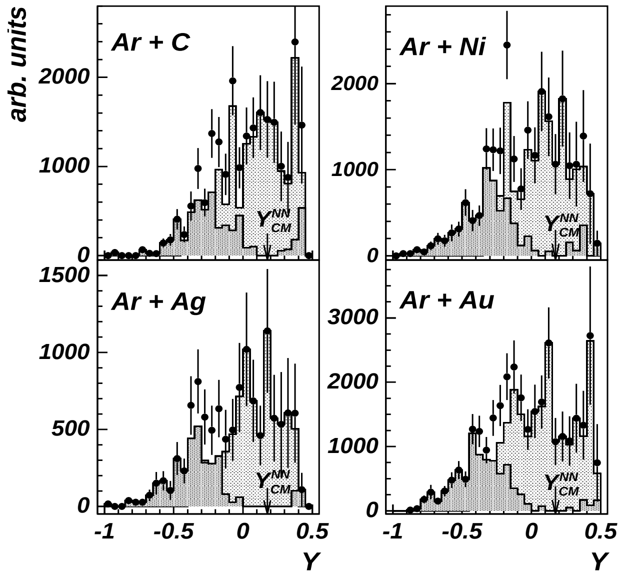

Fig. 5. Rapidity distributions of π^0 mesons, obtained for four types of colliding systems. Dark-shaded spectra represent the backward emission ($p_\perp < |p_{||}|$) while light-shaded ones represent the perpendicular emission ($p_\perp > |p_{||}|$).

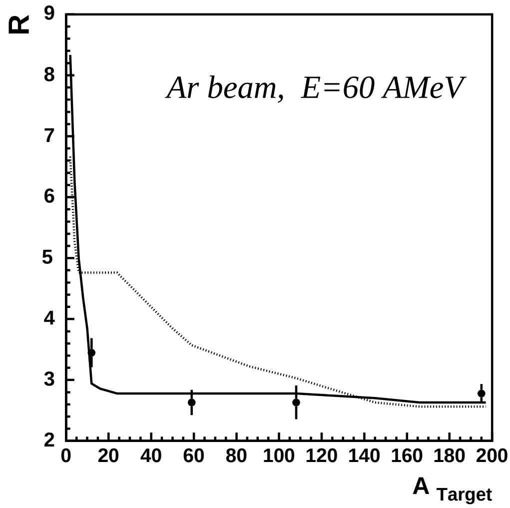

Fig. 6. Ratio of neutral pions emitted backward to the ones emitted perpendicularly (up to the acceptance limit) as a function of target mass. Results derived from the geometrical absorption model [12] are plotted with dotted line (when $\lambda = \text{const.}(p)$) and solid line (when $\lambda = f(p)$).

distribution of backward emitted neutral pions in ^{12}C+^{7}Li reaction [12]. Therefore, the applicability of the model to low-mass systems may not be appropriate, although it works well for α+Mg system.

5. Conclusions and perspectives

The analysis of neutral pions produced in 60A MeV Ar-induced reactions on C, Ni, Ar and Au targets confirms the idea that subthreshold pion production takes place in the first stages of the collision. The temperature parameters of the spectra do not depend on the total energy available in the system.

The study of the rapidity spectra within a simple geometrical model permits us to describe quantitatively the reabsorption of the pions using a momentum dependent absorption length.

The analysis of neutral pions produced in 95A MeV Ar-induced reactions on ^{12}C, $^{\rm nat}$Ar, $^{\rm nat}$Ni, $^{\rm nat}$Ag and ^{197}Au is in progress.

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