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ABSORPTION OF NEUTRAL PIONS PRODUCED IN SUBTHRESHOLD NUCLEUS–NUCLEUS COLLISIONS*

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Neutral pions produced in Ar-induced reactions at $95A$ MeV on C, Al, Ag and Au targets were identified through their $\gamma\gamma$ decay photons, measured with TAPS spectrometer installed at GANIL Caen. Angular distributions of neutral pions are reasonably well described within a phenomenological model of pion reabsorption, taking into account momentum-dependent absorption length. The angular distribution of primary neutral pions (before absorption) seems to be independent of the beam energy and mass numbers of colliding nuclei. This distribution is described by the formula: $1 + A_2 P_2(\cos\vartheta)$ with $A_2 = 0.33 \pm 0.05$, determined from the comparison to all available angular distributions of neutral pions. The transverse momentum spectra of neutral pions can be fitted within the thermal model only for momenta above 60 MeV/c. Assuming, that the model of pion reabsorption is correct, the transverse momentum spectra of primary pions were reconstructed. These spectra are surprisingly well described by the thermal model with temperatures about 22 MeV.

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1. Introduction

Subthreshold particle production (*i.e.* production of particles at beam energy per nucleon below the free nucleon–nucleon threshold energy) is an

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extensively used method of studying nuclear matter properties in the initial phase of the collision [1]. Particularly, the production of energetic photons is a process of significant importance, as photons are not subject of strong final state interaction. However, their observation is linked to (and disturbed by) the creation of neutral pions, produced in similar conditions and decaying predominantly (98.8%) in two-photon channel. Understanding and proper description of the neutral pion energy and angular distributions is not only important for the studies of the initial phase of nucleus–nucleus collision, but also for the appropriate evaluation of the photon flux stemming from neutral pion decays. In this contribution, we present neutral pion spectra from 95A MeV Ar-induced collisions. The spectra are interpreted within a phenomenological pion absorption model.

2. Experiment and data analysis

The 95 AMeV Ar beam was delivered by the GANIL accelerator facility. Four targets were used: C, Al, Ag, Au. Photons from neutral pion decay were measured in the TAPS spectrometer [2]. During this installation at GANIL, TAPS was arranged in 6 rectangular blocks of 64 modules each, located in one plane around the target and covering approximately 20% of the full solid angle. One TAPS module is composed of a hexagonal BaF_2 scintillating crystal and a thin hexagonal plastic scintillator (*veto*), placed on the front face of the BaF_2 crystal and read by a separate photomultiplier. BaF_2 crystal has 25 cm length (12 radiation lengths) and inscribed diameter of 6.1 cm.

In the off-line analysis, photon-induced hits in TAPS were selected through 3 conditions: *(i)* time-of-flight (TOF) signal within the prompt peak (FWHM $\approx$ 700 ps), *(ii)* pulse-shape analysis (PSA) of the ratio of the fast to the slow scintillation light component from BaF_2, and *(iii)* lack of signal in the plastic veto counter. As the electromagnetic cascade induced by energetic photon might spread over several neighbouring TAPS modules, photon energy and direction were reconstructed through the appropriate cluster analysis [3]. Neutral pion decays were observed as a clear peak around $M_{\gamma\gamma} = M_{\pi^0}$ in the invariant mass spectrum of coincident photon pairs detected in separate TAPS blocks. The kinematical fit procedure [4] was then applied to reconstruct the vector of pion momentum. The efficiency of the experimental set-up was obtained through the Monte-Carlo simulation, using the GEANT-based code KANE [5]. Additional correction was introduced, accounting for the presence of contaminated clusters, *i.e.* composed of modules with pure photon-like signal and modules (usually a single one) reporting photon-like TOF and, simultaneously, hadronic PSA [6]. The angular distribution of the contaminated clusters peaks at forward angles, so the abovementioned correction is relevant mainly for the angular distribution of neutral pions emitted at low scattering angles. The angular distribution of neutral pions emitted from Ar+Au collisions agrees well with the results of the previous measurements [7].

3. Results

The angular distributions of neutral pions were interpreted within a simple, phenomenological model of meson absorption [8]. This geometrical model takes into account the impact-parameter effects and generates mesons within the overlap zone of two spherical nuclei. Neutral mesons are sampled in energy according to the Boltzmann distribution and in emission angle within the angular distribution

$$\frac{dN}{d\Omega} = K\left(1 + A_2 P_2(\cos\vartheta)\right) , \tag{1}$$

where K is the normalization constant. The parameter A_2 was varied in order to obtain the best description of the experimental data. The probability for the generated pion to escape out of the collision zone was calculated as $e^{-d/\lambda}$, where d denotes the path from the creation point to the surface and λ is the momentum-dependent absorption length, taken from Ref. [9]. The model allows to describe the observed shape of pion angular distribution in a reasonable way (see Fig. 1), not only for the results obtained here, but also for other data taken from the literature (for the details, see [6]). The value of A_2, averaged over available experimental data, equals to 0.33 ± 0.05. This result enables to make reasonable prediction of the photon yield due to the decays of neutral pions produced in subthreshold nucleus–nucleus collisions.

It has been observed in other experiments [10], that the shape of the transverse momentum spectrum can not be reasonably well described by the Boltzmann thermal distribution. Namely, when the high-momentum slope is well described, the experimental yield of particles is well below the Boltzmann distribution at low momenta. The same effect is observed in the pion spectrum from 95A MeV Ar+Au reactions (Fig. 2), where the temperature parameter T was found to be equal to 13.6 ± 0.1 MeV for events above 60 MeV/c.

The energy spectrum of neutral pions from ^{36}Ar+^{197}Au rection at 95 AMeV measured with the TAPS spectrometer during the previous experiment at GANIL was reasonably described [7,11] within a model of reabsorption of pions in the nuclear medium. The initial pion spectrum, exhibiting a thermal behaviour with the temperature parameter equal to 26 MeV, was subsequently modified in order to account for the destruction processes. As a result, a very good description of the experimental data was obtained.

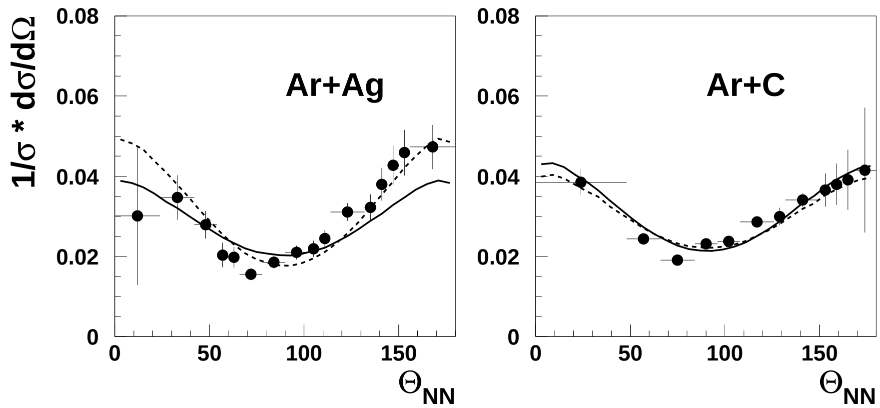

Fig. 1. Angular distributions of neutral pions emitted from Ar+Ag and Ar+C reactions at 95 AMeV beam energy. The lines indicate the results of pion absorption model calculations with $A_2 = 0.33$ (solid line) as the global average value and with A_2 obtained from the best fit to the experimental values (dashed line).

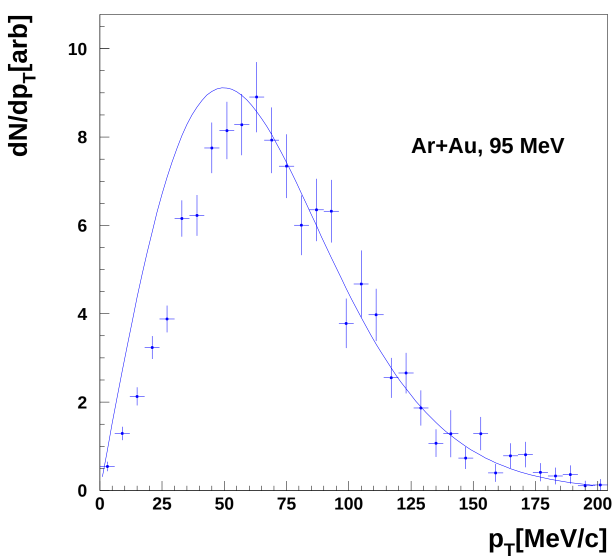

Fig. 2. Transverse momentum distributions of neutral pions from Ar+Au collisions at 95 AMeV corrected for detector acceptance. The line indicates the results of a fit of the Boltzmann distribution for momenta above 60 MeV$/c$.

The reasonable results of describing the neutral pion angular distributions within the phenomenological absorption model for several projectile-target combinations at different beam energies, encourage an attempt to correct for absorption also the experimental transverse momentum spectra.

While in Ref. [7,11] the initial pion spectrum was modified by the absorption processes, we have attempted to obtain the spectrum of primordial pions as a result of the division of the experimental transverse momentum spectrum by the pion transmission probability, evaluated within the phenomenological absorption model discussed above for a given projectile-target combination. This spectrum (Fig. 3) can be very well described by the thermal distribution with the temperature parameter $T = 22.9 \pm 0.4$ MeV. Similar results as shown in Fig. 3 were obtained from the analysis of data measured in this experiment for other targets [6]. The subthreshold particle production process occurs, as we understand it now, predominantly in first-chance nucleon–nucleon interactions, very far from thermal equilibrium. Therefore, it is hard to expect the thermal behaviour of these particles. The excellent agreement of the observed spectrum with the thermal distribution is certainly surprising, however the pion spectra evaluated within the BUU transport calculations were reported [7] to exhibit the thermal shape. Further work is needed in order to analyze other experimental data. Model calculations, more fundamental than the phenomenological model applied in this work, would be very helpful.

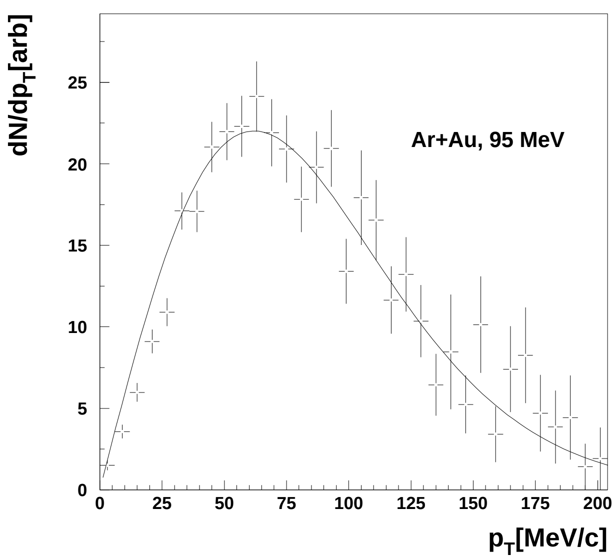

Fig. 3. Transverse momentum distributions of neutral pions from Ar+Au collisions at 95 *A*MeV corrected for pion absorption in nuclear matter. The line indicates the result of a fit of the Boltzmann distribution. The errors are statistical only.

4. Conclusions

Neutral pions, produced in subthreshold 95 *A*MeV Ar-induced reactions on C, Al, Ag and Au targets, were measured via their 2-photon decay registered in the TAPS spectrometer. The angular distributions of neutral pions are reasonably well described within a phenomenological model of pion absorption in the nuclear matter, in which they were produced. Assuming that the absorption effects are correctly accounted for by the model, the transverse momentum spectrum of primordial neutral pions was determined. This spectrum can be very well described by a Boltzmann thermal distribution.

The results presented here are based on an experiment performed by the TAPS Collaboration: Y. Schutz, D. Baiborodin, H. Delagrange, D. d'Enterria, J. Dìaz, F. Fernández, H. Löhner, G. Martínez, T. Matulewicz, M.J. Mora, R. Ortega, R.W. Ostendorf, S. Schadmand, P. Tlusty, R. Turrisi, V. Wagner, H.W. Wilschut, N. Yahlali. Financial support at the early stage of this research was provided through the Polish State Committee for Scientific Research (KBN) grant 2P03B 01314. One of us (KT) acknowledges the support of GSI Darmstadt, where part of the analysis was done. The support of the IN2P3/Poland collaboration is gratefully acknowledged (TM).

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