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for the TAPS collaboration

Talk presented at the XXI. International Workshop on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria, January 18 - 22, 1993.

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Neutral Pion Production in Heavy Ion Collisions at SIS-energies *

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Abstract

The production of π^0 mesons has been studied in the reactions ^{40}Ar+Ca and ^{197}Au+Au at 1.0 GeV/u. While the pion transverse momentum spectrum from the reaction Ar+Ca is consistent with a simple thermal exponential slope a second component is seen for the system Au+Au. Both neutral pions, neutrons and charged particles exhibit an anisotropy in the reaction plane azimuth. At midrapidity the emission of pions perpendicular to the reaction plane increases with their energy.

1 Introduction

The modification of the nucleon-nucleon interaction in the dense nuclear medium can be studied with heavy ion reactions at sufficiently high energy. Central collisions of symmetric heavy ion systems at 1 GeV per nucleon incident energy are likely to yield about 3 times normal nuclear density. The complexity of the multi-nucleon dynamics requires exclusive experiments so that correlations among different observables reveal sufficient sensitivity to the various physical aspects of such a collision. Of special interest is the production of energetic particles near midrapidity. Such particles when emitted out of the reaction plane can provide an undistorted view of the hot and dense nuclear matter.

2 The experiment

The Two Arm Photon Spectrometer (TAPS) [1, 2, 3] was designed to identify neutral mesons by their 2-photon decay. During its operation at the heavy ion synchrotron SIS in 1990-91 the detector system consisted of 256 telescopes of plastic scintillator charged-particle-veto (CPV) detectors and BaF_2 crystals (hexagonal: face-to-face 59mm, depth 12 radiation lengths) arranged in 2 towers with 2 blocks each. The 2 towers were positioned at angles of $\theta=\pm52^0$ with respect to the beam direction and the blocks, mounted at 1.20 m (Ar+Ca) and 2.0 m (Au+Au) from the target, were tilted by $\Phi = \pm12^0$ (Ar+Ca) and $\Phi = \pm7.3^0$ and $\pm23^0$ (Au+Au) relative to the horizontal plane. The main trigger required two coincident neutral hits in TAPS (for Ar+Ca in two different blocks) and a signal from the in-beam start foil. For each event the BaF_2 time-of-flight, short gated (50ns width) and long-gated (2 μs width) pulse heights, together with the CPV signal were recorded.

For event characterization the Forward Wall (FW) of the FOPI-collaboration was employed. The hardware-derived charged particle multiplicity signal recorded in eight separate segments of the outer part of the FW covering laboratory angles between 7^0 and 30^0 has been used for the determination of the reaction plane and for impact parameter selection.

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3 Data Analysis

Here we give only a brief account of the various subsequent steps in the data analysis. For more details see [2, 3]. First, neutral (charged particles) are separated by requiring an anticoincidence (coincidence) with the respective CPV in front of the BaF_2-module. In a second step, the time-of-flight information and the analysis of the BaF_2 pulse shape are used to separate photon candidates from neutrons. The response of the BaF_2-blocks to photons with energies from 50 to 750 MeV has been studied in a dedicated calibration experiment at the tagged photon beam facility at MAMI-B (Mainz) [4] and compared to Monte Carlo calculations using the code GEANT3 [5]. Invariant mass spectra have been calculated from pairs of photons using the expression

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - cos\Theta_{12})} \quad (1)$$

Here, E_1, E_2 are the energies of the reconstructed photon clusters and Θ_{12} is the relative angle between the cluster centers. The π^0 mass resolution of 11% FWHM has been achieved.

Though the TAPS angular position has been optimized to measure π^0 mesons at 90^0 in the center-of-mass system (i.e. at midrapidity) its arrangement in 4 blocks together with the 2-photon decay kinematics makes the geometrical acceptance a complicated function of the pion momentum. Hence, GEANT simulations have to be performed. The resulting π^0 efficiency is displayed in fig 1.

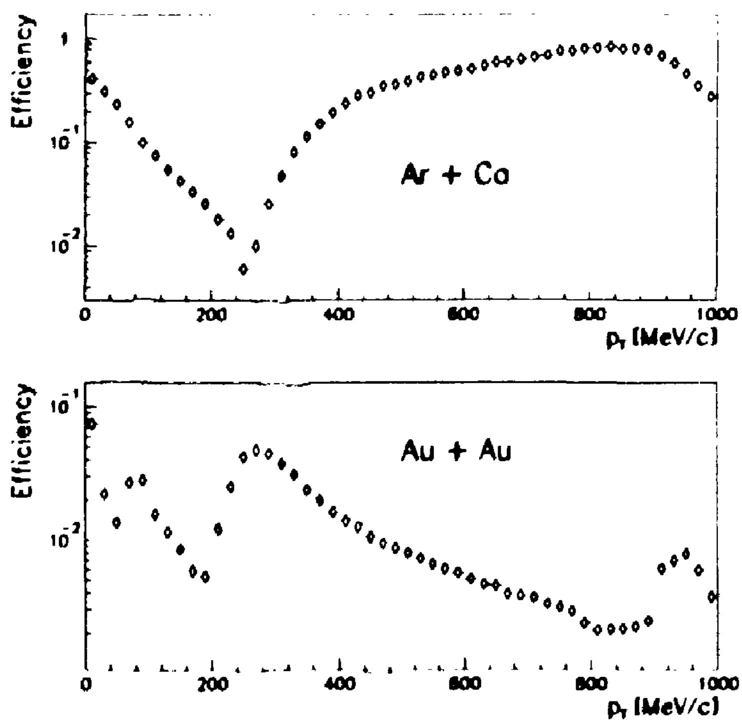

Figure 1: π^0 meson acceptance including the photon detection efficiency. The results were obtained in a Monte Carlo simulation for the TAPS geometry of the Ar+Ca (upper picture) and Au+Au (lower) run. The calculation assumes isotropic pion emission from the nucleon-nucleon center-of-mass system. A minimum energy of 20 MeV and at least 3 neighbouring detectors were required to surround the centroid of a photon cluster.

4 Experimental Results and Discussion

Efficiency corrected transverse momentum (p_T) distributions of π^0 mesons at midrapidity are shown in fig.2. A noticeable feature of the spectra is their large extension – up to $p_T \approx$1000 MeV/c (Ar+Ca) and $\approx$1400 MeV/c (Au+Au), i.e. far beyond the free nucleon–nucleon kinematical limit (p_T^{max}=380 MeV/c at 1GeV/u). A fit to the p_T–spectrum in a narrow window at midrapidity with a thermal distribution

$$\frac{1}{p_T} \cdot \frac{d\sigma}{dp_T} \sim m_T \cdot e^{-\frac{m_T}{T}} \quad \text{with} \quad m_T = \sqrt{m_\pi^2 + p_T^2} \tag{2}$$

yields a value for the "temperature" parameter T = 66 ± 2 MeV (Ar+Ca) and T = 62 ± 2 MeV (Au+Au). While in the case of Ar+Ca the fit reproduces the full experimental spectrum up to the high momentum tail a significant departure from a one–temperature distribution is seen in the case of the heavier Au+Au system. In this case the spectrum is quantitatively described by a two-slope fit, formed as the sum of two thermal distributions (2) with temperatures T_1 = 53 ± 5 MeV and T_2 = 95 ± 5 MeV. For Au+Au T_1 and T_2 are within the errors the same for both semi-central and central FW-multiplicity-selected events. But with decreasing impact parameter the contribution of the second component seems to increase.

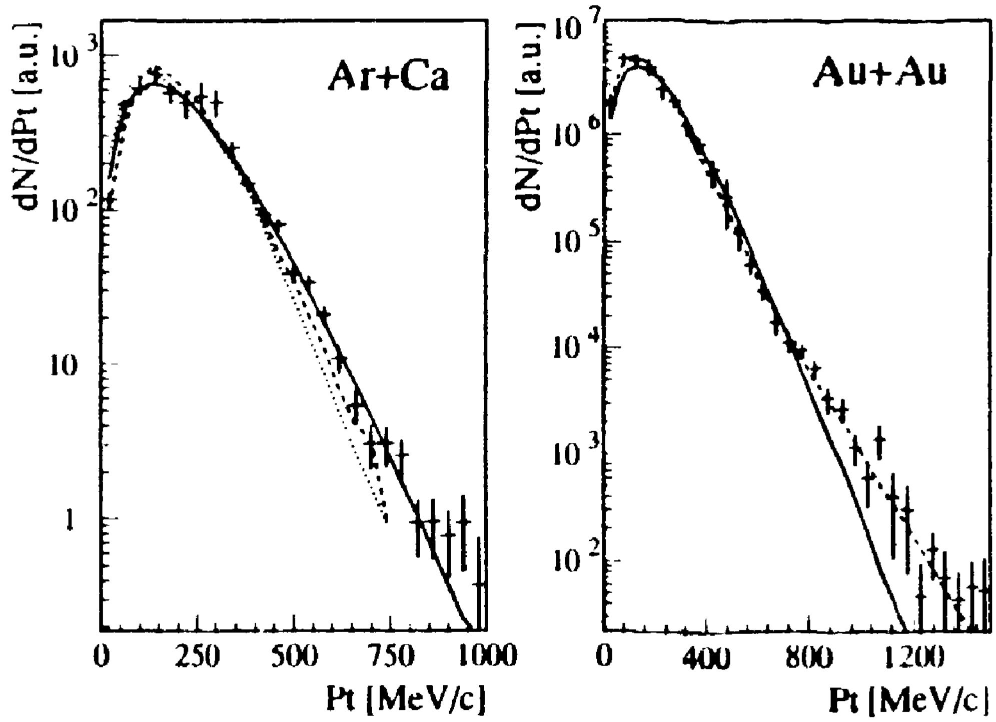

Figure 2: p_T–spectra of π^0 mesons from Ar+Ca in the rapidity window $|y - y_{c.m.}| \leq 0.2$ and from Au+Au collisions at 1GeV/u in the rapidity range $|y - y_{c.m.}| \leq 0.15$. Full line – a single–slope thermal fit. For Au+Au the dashed-line is a two–slope thermal fit. For Ar+Ca: RQMD – dashed line, QGSM – dotted line.

Let us note that indication of the second component was first observed for π^-–mesons at the BEVALAC [6, 7] and then confirmed also for π^0 [8] and π^+-mesons at SIS [9]. For the lighter and/or non-equal mass reaction systems the two-temperature shape of CMS energy spectra of π^--mesons has been reported for data from the Dubna Synchrophasotron [10, 11].

At energies around 1GeV/u the presence of two slopes T_1 and T_2 is explained as resulting either from two mechanisms of pion production: direct (T_2) and via Δ resonance decay (T_1) [6] or from a different contributions of Δ's produced at early and late stages of the reaction [12]. At Dubna energies (3.5 GeV/u) calculations performed in the framework of the intranuclear cascade model [13] were shown to reproduce the two-temperature shape of spectra qualitatively [11]. A quantitative discrepancy between experimental data and the model predictions was ascribed to uncertainties in the resonance–nucleon cross section.

Comparison of our experimental p_T-spectra with predictions of microscopic models (QGSM [13] and RQMD [14]) has shown that up to $p_T \approx 600$MeV/c they both qualitatively describe the data. In both models production of the baryon and meson resonances as well as their subsequent interactions have been implemented. This plays a vital role in the description of subthreshold particle production [8]. However, the description of the high-momentum part of the spectra is, besides being very CPU intensive also quite sensitive to the proper parameterization of the tail of the distribution functions describing different elementary processes.

A phenomenological approach to the subthreshold particle production based on the self-similarity hypothesis has been recently developed in [15]. It assumes that the invariant cross section of the inclusive nucleus-nucleus reaction:

$$A_1 + A_2 \to C + \ldots + X \tag{3}$$

has a scale-invariant dependence on the incoming and outcoming particle 4-momenta. Hence, only dimensionless Lorentz-invariant combinations are allowed. Quite generally, the threshold for production of particle C with a given 4-momentum p_C in reaction (3) can be related to the fractions x_1 and x_2 of the target and the projectile nucleus 4-momenta p_1 and p_2. This is expressed by the condition that the invariant mass squared

$$s = (x_1 p_1 + x_2 p_2)^2 \tag{4}$$

should be minimal. Its minimum value s_{min} and the fractions x_1, x_2 can be determined from the 4-momentum conservation law and the condition of minimum

$$(x_1 p_1 + x_2 p_2 - p_C)^2 = m_X^2, \qquad \frac{ds}{dx_{1,2}} = 0 \tag{5}$$

If x_1 and x_2 are expressed in units of the nucleon mass

$$\xi_i = \frac{x_i m_i}{m_N}, \; i = 1,2 \tag{6}$$

the new variables, when $\xi_1 > 1$ or $\xi_2 > 1$, formally define the subthreshold production. Using the dimensionless quantity $\Pi = \sqrt{s_{min}}/2m_N$ the invariant cross section has the form [15]:

$$E\frac{d^3\sigma}{d^3p} \sim A_1^{\alpha_1(\xi_1)} A_2^{\alpha_2(\xi_2)} f(\Pi) \quad \text{where} \quad \alpha_i = \frac{2}{3} + \frac{\xi_i}{3}, \; i = 1,2 \tag{7}$$

Experimentally $f(\Pi) \sim exp(-\Pi/\Pi_0)$ with $\Pi_0 = 0.13$ for nucleus nucleus subthreshold production in the projectile/target fragmentation region [15] and $\Pi_0 = 0.16$ for pp-data [16].

Let us now consider particle production at $\Theta_{CMS} = 90^0$. From symmetry it follows that $\xi_1 = \xi_2$ and the solution of the equation (5) is

$$\Pi = \xi\gamma \qquad \text{with} \quad \xi = \frac{E_C}{2m_N(\gamma - \gamma^{-1})}\left[1 + \sqrt{1 - \frac{m_C^2}{E_C^2}(1 - \gamma^{-2})}\right] \tag{8}$$
$$\text{where} \quad \gamma = \sqrt{(T_{lab} + 2m_N)/2m_N}$$

and T_{lab} is the projectile kinetic energy per nucleon. Using (7) we can relate the slope parameter T of the invariant cross section at midrapidity to the slope Π_0 of the universal function $f(\Pi)$:

$$T = \frac{T_{lab}}{T_{lab} + 2m_N} \cdot \frac{m_N}{\Pi_0^{-1} - \frac{ln(A_1 A_2)}{37}} \tag{9}$$

The slope T is now dependent both on the incoming energy as well as on the masses of colliding nuclei (see fig.3). The value of Π_0 from pp-data was used. Moreover from $T_{lab} \approx$ 200GeV the "temperature" T is quite close to its limiting value $T_o = \Pi_o m_N$.

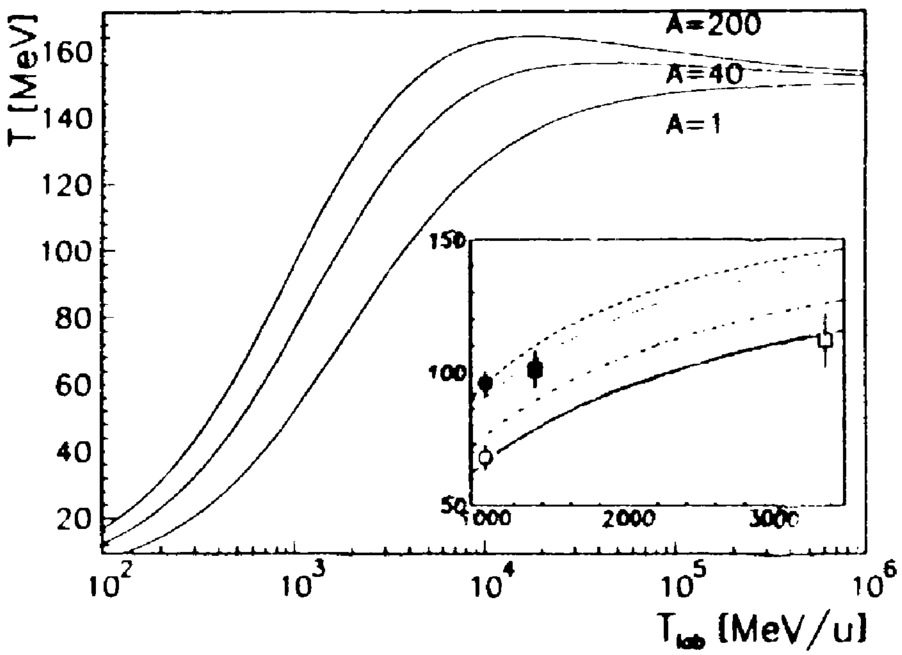

Figure 3: Energy dependence of the slope parameter T for symmetric systems. The inset shows a comparison with experimental data on T_2 at midrapidity. Dashed line and full circle - Au+Au (present experiment), dotted line and full square - La+La [7], dash-dotted line and empty circle - Ar+Ca (present experiment), full line and empty square - C+C [11]

Additional information on the collision dynamics can be obtained when studying particle emission with respect to the reaction plane. The azimuthal angular distributions of π^0 mesons for four p_T-bins (step 200MeV/c) are shown in fig.4. While for p_T <200MeV/c the distribution is approximately isotropic at higher p_T it peaks around 90^0 and 270^0. Moreover this anisotropy increases with pion energy. In the same picture the azimuthal distributions of neutrons and charged particles measured within the angular range $46^0 < \Theta_{lab} < 60^0$ are shown. Now the binning is in the particle velocity $\beta = v/c$ from $\beta = 0.5$ to $\beta = 0.8$ in steps of roughly 0.05. The corresponding rapidity interval is $0.42 < y_{c.m.} - y < 0.06$. In the target fragmentation region the the opposite-side emission of particles with respect to the projectile fragments can be observed. At midrapidity both the neutrons and the charged particles seem to be "squeezed-out" perpendicularly to the reaction plane [17] similarly to the pion case. More quantitative results can be extracted from the fits to the azimuthal distributions of particles with a function $f(\phi) = N_0(A\cos(\phi) + B\cos(2\phi) + 1)$. Values of the fit parameters A and B which measure the flow and squeeze-out, respectively, are summarized in table 1.

Table 1: Strength parameters for the distribution of emission angles with respect to the reaction plane for charged particles, neutrons and π^0.

β	charged part.		neutrons		p_T	π^0	
	A	B	A	B	(MeV/c)	A	B
0.49 – 0.53	-0.40	-0.04	-0.16	-0.03	0- 200	0.00	-0.03
0.53 – 0.58	-0.38	-0.05	-0.16	-0.07	200- 400	0.06	-0.37
0.58 – 0.63	-0.35	-0.07	-0.19	-0.03	400- 600	0.04	-0.66
0.63 – 0.69	-0.30	-0.09	-0.20	-0.08	600- 800	0.22	-0.72
0.69 – 0.78	-0.23	-0.10	-0.18	-0.07			
0.78 – 0.88	-0.11	-0.11	-0.10	-0.11			

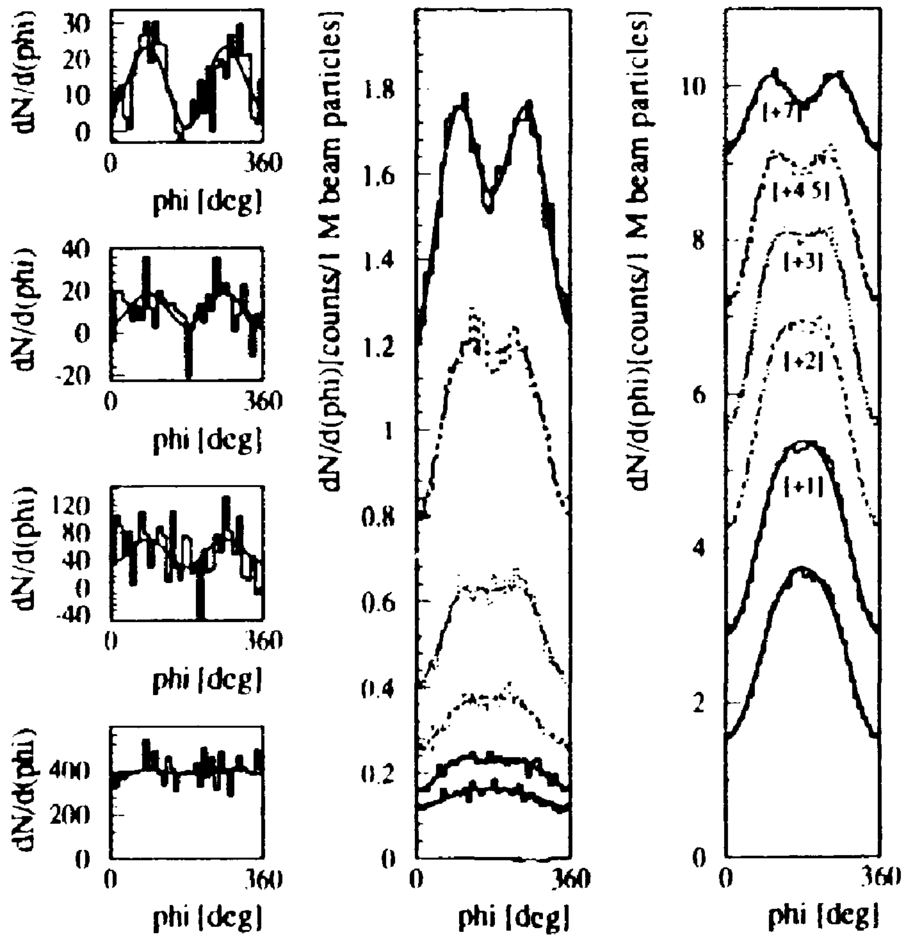

Figure 4: Azimuthal angle (ϕ) distributions of π^0 (left column), neutrons (middle) and charged particles (right) from Au+Au collisions at 1GeV/u as a function of increasing (from bottom to top) particle momentum/velocity. The results of fit $f(\phi) = N_0(A\cos(\phi) + B\cos(2\phi) + 1)$ are also shown.

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