Transverse Momentum Distributions of η Mesons in Near-Threshold Relativistic Heavy Ion Reactions

F.-D. Berg,[1] M. Pfeiffer,[1] O. Schwalb,[1] M. Franke,[1] W. Kühn,[1] H. Löhner,[2] V. Metag,[1] M. Notheisen,[1] R. Novotny,[1] A. E. Raschke,[2] J. Ritman,[1] M. Röbig–Landau,[1] R. S. Simon,[3] M. Šumbera,[2] L. Venema,[2] and H. Wilschut [2]

[1] *II. Physikalisches Institut, D-35392 Universität Giessen, Germany*

[2] *Kernfysisch Versneller Institut, NL-9747 AA Groningen, The Netherlands*

[3] *Gesellschaft für Schwerionenforschung, D-64220 Darmstadt, Germany*

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Transverse momentum spectra of η mesons have been measured near the free nucleon-nucleon production threshold in the heavy ion reactions ^{40}Ar+^{nat}Ca, ^{86}Kr+^{nat}Zr, and ^{197}Au+^{197}Au at 1.0A GeV and also in ^{40}Ar+^{nat}Ca at 1.5A GeV. The measured transverse momentum distributions are compared to model calculations. The relative abundance of $\Delta(1232)$ and $N(1535)$ resonances excited in the collision is deduced. A comparison to pion data reveals scaling with the transverse mass of the emitted meson.

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Relativistic heavy ion collisions are a unique tool to study highly excited and compressed nuclear matter. According to various theoretical predictions [1–3] baryon densities up to 3 times normal nuclear matter density ρ_0 are reached in the reaction volume. Furthermore, at bombarding energies of 1–2A GeV a gradual transition to *resonance matter* seems to occur, i.e., strongly interacting hadronic matter with about 30% of the baryons excited to Δ and N resonances corresponding to a density $\rho_\Delta \approx \rho_0$ [4–6]. To learn more about the properties of this form of matter it is important to determine its baryonic composition, i.e., the abundance of nucleons, Δ, and N resonances. Since these resonances decay by π and η emission a promising approach to investigate the population of excited baryonic states in the collision of two heavy nuclei is to measure meson yields. The rate of pions is in first approximation related to the excitation of the Δ resonance which decays into the π channel by 99%. η mesons almost exclusively originate from the decay of the $N(1535)$ resonance and are thus a very selective probe for the excitation of this resonance.

Although π^0 and η production in the 1A GeV energy regime proceeds through the excitation of different baryon resonances it is of interest to check to which extent η-production cross sections and transverse momentum spectra are governed by phase space and the average energy available per nucleon-nucleon collision. General scaling laws have been established for meson production in the 10A MeV to 14.0A GeV bombarding energy range [5,7,8]. At very high bombarding energies a scaling of meson abundancies with the transverse mass (m_t scaling) has been observed [9]. It is of importance to clarify whether such universal features of transverse momentum distributions also hold at bombarding energies as low as 1A GeV and whether there is a common underlying mechanism for the buildup of transverse mass.

Furthermore, the knowledge of η-meson production cross sections in heavy ion reactions is essential for the understanding of dilepton experiments [10], since the η Dalitz decay contributes substantially to the dilepton invariant mass spectra below masses of 500 MeV.

Meson production in heavy ion collisions has been extensively studied at the LBL Bevalac [11]. While these experiments concentrated on charged mesons a program studying neutral mesons has been initiated [12] at the heavy ion synchrotron SIS at GSI Darmstadt. In this Letter we report for the first time on transverse momentum spectra of η mesons produced in collision systems of different mass at energies below and above the threshold for η production in free nucleon-nucleon collisions.

We have investigated η production in the systems ^{40}Ar+^{nat}Ca at 1.0 and 1.5A GeV as well as in the systems ^{86}Kr+^{nat}Zr and ^{197}Au+^{197}Au at 1.0A GeV. Beams of up to 10^6 particles per spill provided by the heavy ion synchrotron SIS impinged on targets of ^{nat}Ca (1.02 g/cm^2), ^{nat}Zr (0.13 g/cm^2), and ^{197}Au (0.188 g/cm^2) corresponding to 1% (Ca) and 0.1% (Kr, Au) nuclear interaction length, respectively. The π^0 and η mesons have been measured via their two-photon decay channel (branching ratios: π^0, 98.8%; η, 38.9% [13]) using the Two Arm Photon Spectrometer (TAPS) [14]. This detector system consisted of 256 BaF_2 scintillators of hexagonal shape arranged in 4 blocks of 64 modules with individual charged particle veto detectors in front of each module. The geometry of the detector setups is summarized in Table I. The block configurations allowed the simultaneous measurement of pions and η's in a small window at midrapidity ($| y - y_{c.m.} | \leq 0.1 - 0.2$) independent of the meson transverse momentum.

An array of 16 plastic scintillation detectors covering a solid angle of 5% of 4π in the range $32° \leq \theta \leq 55°$ was mounted around the beam pipe at 6 cm distance from the beam axis to serve as a reaction trigger. In Kr+Zr and Ar+Ca at 1.5A GeV this device was used also as a time-zero detector whereas an in-beam start detector was available in the other experiments. For event characteri-

TABLE I. Geometrical setups of the TAPS detector system in the different experiments. In the Au+Au and 1.5A GeV Ar+Ca experiments two and three different detector setups have been used, respectively, in order to cover a larger kinematical range. Θ denotes the angle of a TAPS tower with respect to the beam direction and Φ the tilt angle of the block with respect to the horizontal plane containing the beam. d is the distance between the block front sides and the target.

Experiment	d (cm)	Θ (deg)	Φ (deg)
^{40}Ar+^{nat}Ca	120	± 52.5	± 12.1
^{86}Kr+^{nat}Zr	160	± 52.2	$\pm 16/\pm 9.5$
^{197}Au+^{197}Au	200	± 52	$\pm 7.3/\pm 23$
^{40}Ar+^{nat}Ca	220	± 47.5	$\pm 7/\pm 15/\pm 23$

zation the charged particle multiplicity was measured in the forward wall of the FOPI detector [15], comprising 512 plastic strips at laboratory angles between 7° and 30°. The main trigger required a signal in the time-zero detector together with two neutral hits in TAPS, which introduces no significant bias for π^0 and η detection. In addition, a signal was required in the forward wall in the case of Au+Au.

Photon-particle discrimination and η-meson identification via invariant mass analysis have been performed as described in [12]. η transverse momentum spectra have been derived by selecting events in the η mass region and by subtracting the combinatorial background deduced by event mixing. These spectra are corrected for the detector acceptance which has been obtained from Monte Carlo simulations with the GEANT3 [16] package.

Figure 1(a) presents the invariant mass distributions for all four experiments together with the combinatorial background which fits the spectra over the full mass range except for the π^0 and η signals. The mass range near the η meson is shown separately in Fig. 1(b) where a structure of FWHM $\approx$ 50 MeV can be identified at a peak/background level of (10–20)%. In the case of Kr+Zr and Au+Au a cut on the forward wall charged particle multiplicity M_{ch} of less than 85% and 60% of the maximum value has been applied, respectively, to reduce the combinatorial background due to the larger photon multiplicity in the heavier systems.

Combining the present results with π^0 data [17], η/π^0 ratios are deduced which are listed in Table II after correction for π^0 and η detection efficiencies. The η/π^0 ratio is found to vary by less than 40% as a function of M_{ch} in all collision systems. η/π^0 ratios obtained in the heavy systems for cuts in M_{ch} can thus be considered inclusive values within the errors quoted. The simultaneous measurement of both mesons reduces systematic errors in the η/π^0 ratio. These measured quantities are extrapolated to the full solid angle assuming a thermal and isotropic source in the nucleon-nucleon c.m. system as suggested by earlier π^- data [18]. The fraction of mesons observed in a given rapidity range depends on the temperature of

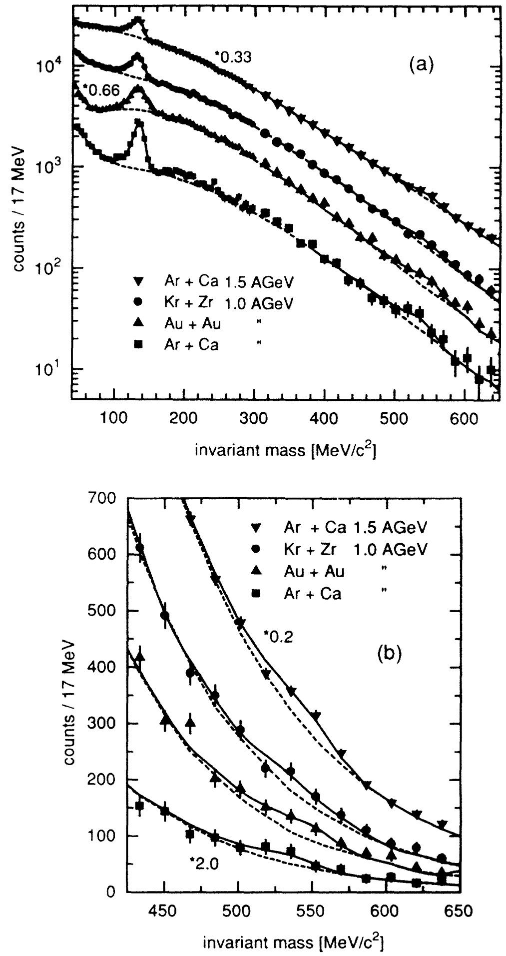

FIG. 1. (a) Invariant mass spectra for the systems Ar+Ca at 1.5A GeV, Kr+Zr, Au+Au, and Ar+Ca at 1.0A GeV (top to bottom) together with the mixed event background. Part (b) shows the same spectra in the η region. The spectra for the two heavier systems are accumulated under the condition of a forward wall charged particle multiplicity of less than 85% (Kr+Zr) and 60% (Au+Au) of the maximum value, respectively.

the source. Consequently, the uncertainty in the slope of the transverse momentum distribution in the case of Ar+Ca at 1.0A GeV gives rise to relatively large total errors. The high η/π^0 value of 1.9% for Ar+Ca at 1.0A GeV reduces to 1.3% assuming a slope parameter of only 64 MeV for the transverse momentum distribution which has been measured for pions in this reaction [17] and fits well into the systematics of the other systems. With this assumption a slight increase of the η/π^0 ratio with energy is found.

Table II lists the results of recent Boltzmann-Uehling-Uhlenbeck (BUU) calculations for the experimental rapidity range [19]. Using the code and parameters of [20], these microscopic transport-model calculations [2,6,20] describe heavy ion reactions as a sequence of nucleon-

TABLE II. Summary of experimental results: The rapidity range (Δy) and the quantities measured within this interval are listed together with BUU results for this y range. In the case of Ar+Ca at 1.0A GeV the η/π^0 ratio and cross section are also listed for a temperature of 64 MeV which has been measured for pions. The last three columns show an extrapolation of the measured values to the full solid angle assuming a thermal and isotropic source in the c.m. system together with results from QGSM calculations [22].

	Expt. parameters			In rapidity range Δy				Extrapolation to full solid angle		
System	E_{beam}/A (GeV)	Δy	$y_{beam}/2$	T_η (MeV)	η/π^0 (%)	$\sigma_\eta^{\Delta y}$ (mb)	$(\eta/\pi^0)_{BUU}$ (%)	$\sigma_\eta^{4\pi}$ (mb)	η/π^0 (%)	$(\sigma_\eta^{4\pi})_{QGSM}$ (mb)
Ar+Ca	1.0	0.48 – 0.88	0.68	100^{+40}_{-20}	2.6 ± 1.6	11 ± 7		29 ± 18	1.9 ± 1.2	
				64 ± 1	2.1 ± 1.3	9 ± 6	2.3	19 ± 12	1.3 ± 0.8	12
Kr+Zr	1.0	0.52 – 0.84	0.68	70 ± 11	2.1 ± 0.9	50 ± 22	2.3	140 ± 60	1.3 ± 0.6	
Au+Au	1.0	0.52 – 0.84	0.68	63 ± 8	2.4 ± 0.9	150 ± 90	2.3	420 ± 250	1.4 ± 0.6	
Ar+Ca	1.5	0.68 – 0.84	0.80	79^{+11}_{-8}	4.0 ± 0.8	14 ± 3	5.6	72 ± 14	2.2 ± 0.4	44

nucleon collisions, taking mean field effects into account. They reproduce the η/π^0 ratios for all systems at 1A GeV within the errors of both experiment and simulation. At 1.5A GeV Ar+Ca the theoretical prediction is slightly too high. The total η cross sections are also in reasonable agreement with quark-gluon-string-model (QGSM) calculations [21,22] also listed in Table II.

From the η/π^0 ratio the relative abundance of the $\Delta(1232)$ and $N(1535)$ resonances at the respective freeze-out can be estimated, which can be related to the baryonic composition in the collision zone provided absorption is similar for both mesons [20]. Taking only the dominant $\Delta \rightarrow N\pi$ decay into account and applying the appropriate isospin factors together with a branching ratio

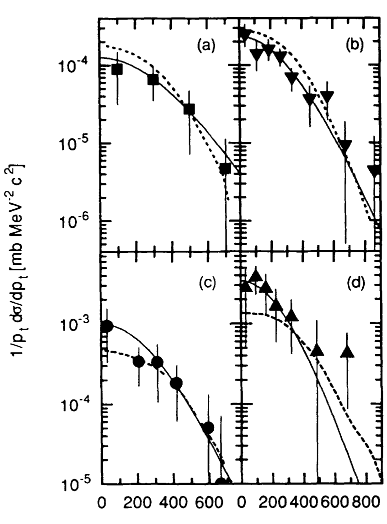

FIG. 2. Transverse momentum distributions at midrapidity for the systems Ar+Ca at 1.0 (a) and 1.5A GeV (b), Kr+Zr (c), and Au+Au (d) at 1.0A GeV. The solid curves represent fits with a thermal, isotropic source at midrapidity while the dashed curves show the BUU calculations by Ehehalt and Mosel [19]. The fit results and the rapidity range covered by TAPS are listed in Table II.

of 40% for the $N(1535)$ into the η channel [13], one gets a $N(1535)/\Delta(1232)$ ratio of $(1.1 \pm 0.6)\%$ and $(1.8 \pm 0.3)\%$ at 1.0 and 1.5A GeV, respectively. This result is similar to recent BUU simulations [6], which predict an excitation of the lowest lying nucleon resonances Δ, $N(1440)$, and $N(1535)$ with a fraction of 30%, 4%, and 1% of all baryons in the reaction volume at 2A GeV, respectively.

The transverse momentum distributions for η mesons are shown in Fig. 2 together with a fit with the expression $(1/p_t)d\sigma/dp_t \sim m_t e^{-m_t/T}$ with $m_t = \sqrt{p_t^2 + m_\eta^2}$, which corresponds to a thermal and isotropic η source observed in a small interval at midrapidity. At 1A GeV the temperatures obtained by this fit do not vary with the mass of the system within the errors, except for the Ar+Ca data which has poor statistics. Only a slight increase with the beam energy is observed. Figure 2 also shows BUU calculations [19], again based on the work of [20], which are in reasonable agreement with the experimental data. These calculations, however, do not yet use as input the recently measured elementary η-production cross sections [23,24].

More striking is the fact that the η transverse momenta show quantitatively the same behavior as the π^0 spectra. This is demonstrated in Fig. 3 where the transverse mass distribution $(1/m_t^2)d\sigma/dm_t \sim e^{-m_t/T}$ is plotted for the two Ar+Ca runs in the respective rapidity intervals. In this graph π^0- and η-meson data roughly fall on one line for $m_t \geq 550$ MeV, indicating that the energy required to produce a given transverse mass m_t is the important parameter determining the relative abundance of the two meson species. Hence, these spectra resemble the so-called m_t-scaling hypotheses [9] well known in high energy physics. There, however, the η/π^0 ratio asymptotically approaches ≈ 0.5 for high p_t, while in the SIS energy regime this ratio is closer to 1.0. This observation is nevertheless remarkable as in the energy regime of 1A GeV π^0 and η production proceeds through the excitation of different baryon resonances while other production mechanisms on the parton level prevail at higher energies. Transport model calculations address-

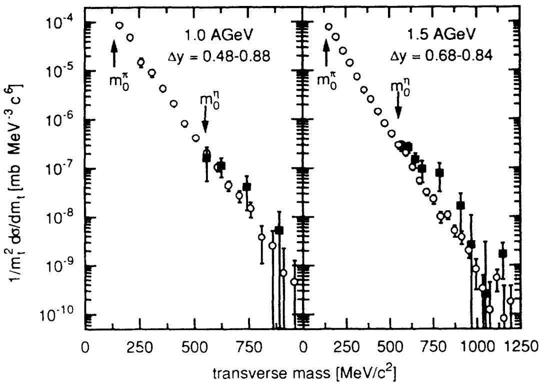

FIG. 3. Comparison of the transverse mass distributions of π^0 and η mesons in Ar+Ca at 1.0 and 1.5A GeV.

ing this universal feature of transverse mass production are highly needed.

In conclusion, η-meson production near the production threshold in free nucleon-nucleon collisions has been studied in heavy ion reactions in a first round of experiments with TAPS at the new heavy ion accelerator facility SIS at GSI. The measured η cross sections provide information on the baryonic composition of the resonance enriched matter formed in the collision zone. The experimental results are in resonable agreement with BUU and QGSM calculations. The transverse momentum spectra of pions and η's scale with the transverse mass.

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[1] J. Aichelin, Phys. Rep. **202**, 233 (1991).
[2] W. Cassing *et al.*, Phys. Rep. **188**, 363 (1990).
[3] H. Stöcker and W. Greiner, Phys. Rep. **137**, 277 (1986).
[4] U. Mosel and V. Metag, Phys. Bl. **5**, 426 (1993).
[5] V. Metag, Prog. Part. Nucl. Phys. **30**, 75 (1993).
[6] W. Ehehalt *et al.*, Phys. Rev. C **47**, 2467 (1993).
[7] A. Shor, Phys. Lett. B **274**, 11 (1992).
[8] A. A. Baldin, JINR Rapid Commun. **3**, 54 (1992).
[9] M. Bourquin and J. M. Gaillard, Nucl. Phys. **B114**, 334 (1976).
[10] G. Roche *et al.*, Phys. Lett. B **226**, 228 (1989).
[11] R. Stock, Phys. Rep. **135**, 259 (1986).
[12] F.-D. Berg *et al.*, Z. Phys. A **340**, 297 (1991).
[13] Particle Data Group, K. Hikasa *et al.*, Phys. Rev. D **45**, S1 (1992).
[14] R. Novotny, IEEE Trans. Nucl. Sci. **38**, 379 (1991).
[15] A. Gobbi *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **324**, 156 (1993).
[16] R. Brun *et al.*, GEANT3 User's Guide, Report No. CERN-DD/EE/84-1, 1986 (unpublished).
[17] O. Schwalb *et al.*, Phys. Lett. B (to be published).
[18] R. Brockmann *et al.*, Phys. Rev. Lett. **53**, 2012 (1984).
[19] W. Ehehalt and U. Mosel (private communications).
[20] Gy. Wolf, Prog. Part. Nucl. Phys. **30**, 273 (1993).
[21] N. S. Amelin *et al.*, Yad. Fiz. **51**, 512 (1990) [Sov. J. Nucl. Phys. **51**, 327 (1990)].
[22] V. D. Toneev, in Proceedings of the 2nd TAPS Workshop (World Scientific, Singapore, to be published).
[23] A. M. Bergdolt *et al.*, Phys. Rev. D **48**, R2969 (1993).
[24] E. Chiavassa *et al.*, Nucl. Phys. **A519**, 413 (1990).