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η-MESON PRODUCTION AND Δ-RESONANCE EXCITATION IN HEAVY-ION COLLISIONS BELOW THE PION THRESHOLD *

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We measured η and π^0 meson production in nucleus–nucleus reaction at beam energy below the free nucleon–nucleon pion creation threshold. Preliminary resuts indicate that the scaling on the transverse mass between π's and η's is still valid at very low energies. Meson cross sections can be understood in terms of thermal population of the baryonic resonances $\Delta(1232)$ and $N^{\star}(1535)$. Also, we observe a statistically-significant correlation for proton-π^0 coincidencies, which we assign to the strength distribution of the Δ baryonic resonance. The same analysis shows no correlation in the case of deuteron-π^0 coincidencies.

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1. Introduction and motivation

Understanding the properties of hadronic matter at high densities and temperatures is an intensively studied goal of nuclear physics research. Such matter is created in heavy-ion collisions in a wide range of beam energies per nucleon from several tens MeV up to several GeV. Energetic particles, produced in such collisions, effectively probe the small space–time extent of the hot and dense phase in the reaction. This is due to the fact that they were not initially present in the nuclear system and their production is strongly suppressed in the subsequent expansion phase. Microscopic transport models, like BUU, QMD, Dubna Cascade model *etc.*, describe quite sucessfully

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the production of particles at beam energies per nucleon around the free nucleon–nucleon (NN) production threshold [1]. In these models the in-medium propagation of nucleons is governed by an effective one-body field with direct two-body NN collision term. Due to these collisions new particles might be directly produced, or nucleons might be excited to baryonic resonances. The created resonances propagate in their own mean field, collide with other nucleons or resonances, or decay through particle (mainly meson) emission. The last process is responsible for the bulk of meson production at beam energies around the NN threshold. Energetic elementary collisions involving already produced resonances can subsequently excite higher lying ones, the decay of which produces more massive mesons, rarely produced if only NN collisions are considered. In this way baryonic resonances act also as an intermediate energy storage, influencing the thermal equilibration of nuclear matter. Among the resonances, the $\Delta(1232)$ isobar through its contribution to the (direct and indirect) production of mesons is of primary importance. Also, the $N^{\star}(1535)$ resonance attracts much attention, as its population can be studied through the dominant decay with the emission of η-meson.

2. Experimental setup

The experiment has been performed using the 180A MeV Ar beam from the heavy-ion synchrotron SIS at GSI Darmstadt. The beam intensity was 5×10^8 particles in a spill of about 9 s. The Ca target corresponded to 1% interaction probability. The photon pairs needed for the neutral meson identification were detected in the TAPS electromagnetic calorimeter composed of 384 BaF_2 scintillation modules arranged in 6 blocks of 64 modules each. The blocks were placed in two towers positionned symmetrically with respect to the beam line at a distance of 80 cm from the target. The position of the towers was optimized for detection of particles emitted from a midrapidity source. The method of reconstruction of photon-induced showers and invariant mass analysis is described in Ref. [2]. Identification of protons in TAPS is reported in Ref. [3].

3. η-meson production

The measured invariant mass distribution of photon pairs indicates a prominent peak at the neutral pion rest mass ($m_{\pi^0} = 135$ MeV). The mass resolution is 11% FWHM. Around the η rest mass ($m_\eta = 547.2$ MeV) we observe a significant excess of counts on top of the background calculated by the event mixing technique. We attribute these events to the η-meson decays. The measured ratio of η to π is $N_\eta/N_{\pi^0} = (5 \pm 2)10^{-6}$. This is far below the value of 10^{-4} expected from the systematics of dependence of meson production probability on the beam energy in units of free production threshold.

The scaling of meson abundances with transverse mass ($m_t = \sqrt{p_t^2 + m^2}$, where p_t is the transverse momentum), known as m_t *scaling*, is also valid at relativistic energies, $1A$ GeV and $1.5A$ GeV [4], for η and π mesons. Our results (Fig. 1) indicate that the m_t scaling appears to be still valid at beam energies per nucleon below free pion production threshold. This observation is rather striking as the mechanism involved at ultrarelativistic energies are expected to be much different to those producing mesons near the absolute threshold. From the fit of thermal distribution to the neutral pion data we obtain $T = 26 \pm 2$ MeV.

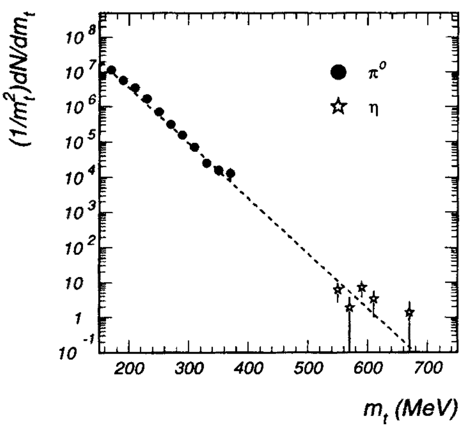

Fig. 1. Transverse mass distribution of π^0 and η mesons measured for the system Ar+Ca at 180A MeV, in the rapidity domain 0.18 to 0.48.

The m_t scaling is reminiscent of a thermal behaviour in the meson production. Consequently, the production might be considered as originating from equilibrated nuclear matter. In such a situation, the population of a resonance R is proportional to $\exp[-(m_R - m_N)/T]$, where m_N is the nucleon mass, m_R the resonance mass and T the temperature. In particular, the ratio of the $N^*(1535)$ to the $\Delta(1232)$ yield will be given by $\sigma_{N^*}/\sigma_\Delta = \exp(-(m_{N^*} - m_\Delta)/T)$ The experimental ratios of $\sigma_{N^*}/\sigma_\Delta$ were obtained from measured N_η/N_{π^0} after corrections for the branching ratios and 3 isospin pion projections. Experimental temperature is deduced from the fit to the pion transverse momentum distribution. An excellent although surprising agreement is obtained, which indicates that π and η mesons seem to be emitted from thermally equilibrated nuclear matter. Thus, their relative production depends mainly on the value of the temperature of the emitting source [5].

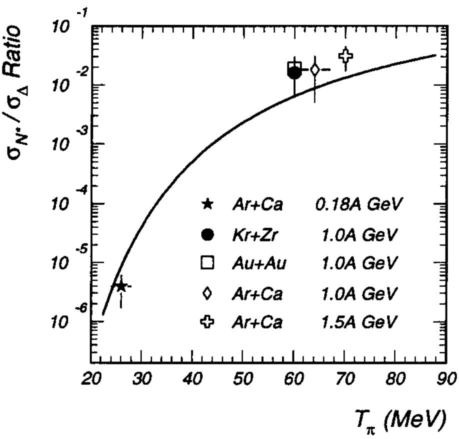

Fig. 2. Measured ratio of the $N^*(1535)$ to the $\Delta(1232)$ population versus the temperature deduced from the momentum distributions of neutral pion. The solid line represents a thermal population of the baryonic resonances.

A phenomenological model can be proposed for the η production from deep-subthreshold energies up to ultrarelativistic energies. Assuming the thermal emission of η's and π's, we can calculate the η probability per number of participants as:

$$P_\eta^{\mathrm{part}} = 1.2 \times P_{\pi^\circ}^{\mathrm{part}} \times \exp\left[\frac{m_{N^\star} - m_\Delta}{T_\pi}\right], \tag{1}$$

where $P_{\pi^\circ}^{\mathrm{part}}$ is a well known quantity over a large span of beam energies. The pionic temperature is equally well established. A good agreement is obtained with the measured η probability at relativistic energies [4] and with our experimental value at deep-subthreshold energy [5]. This calculation differs notably at the lowest energies from the empirical behaviour deduced from pion data mainly. It is explained by the fact that the measured η production is not an independent variable as it depends strongly on the pionic temperature. This tells us that the production of π and η mesons are intimately linked together.

4. π°-proton correlation

From the π°-proton events the invariant mass was evaluated according to the formula

$$M_{p\pi}^{\mathrm{inv}} = \sqrt{m_p^2 + m_\pi^2 + 2E_pE_\pi(1 - \beta_p\beta_\pi\cos\theta_{p\pi})}\,, \tag{2}$$

where m, E, β denote mass, total energy and velocity, respectively, and $\theta_{p\pi}$ the opening angle between proton and pion. In order to search for a

Δ-resonance signal the precise knowledge of the shape of the background is necessary. The background spectrum was obtained by the technique of event mixing. Special care was taken that an event constructed from a proton and a pion (originating from different events) fulfill the trigger conditions and is detectable (no overlapping showers). Then, the correlation function $C_{p\pi}$ was constructed as the ratio of coincident $Y_{p\pi}$ to the mixed $Y_p \otimes Y_\pi$ invariant mass spectrum. The correlation function was normalized to unity in the region of low invariant mass, where it stays constant (Fig. 3a). With increasing invariant mass, approaching the Δ-resonance mass, the π°-proton correlation function systematically raises reaching values around 1.15. We interpret this correlation signal as the signature of the excitation of the Δ-resonance.

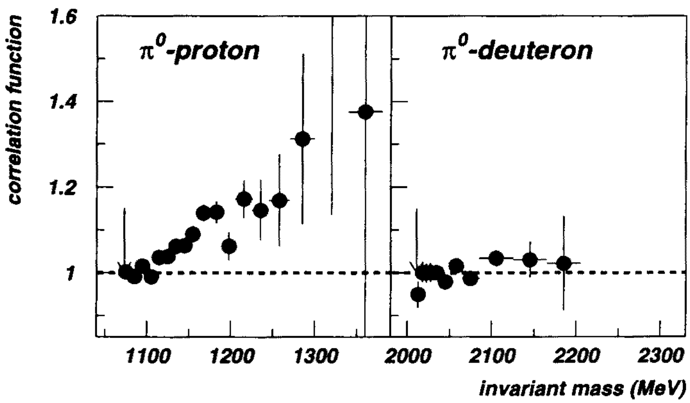

Fig. 3. Correlation function as a function of the invariant mass for the π°-proton and the π°-deuteron events. The arrows indicate sum of rest masses.

To verify the validity of the correlation signal we have applied a similar analysis to a system where no resonance is expected. We have selected the π°-deuteron system, where no baryonic resonance exists. The whole procedure applied to protons has been repeated for deuterons and the π°-deuteron correlation function has been obtained (Fig. 3b). This correlation function shows no resonance signal. This result ensures that the signal observed in π°-proton system is really due to the Δ-resonance and not an artifact of the analysis [6].

5. Summary

Preliminary results have been presented from the analysis of the reaction Ar+Ca studied by TAPS at SIS/GSI at the beam energy of 180A MeV. The measured η probability is 20 times lower than expected from the systematics. The transverse mass scaling, established at ultrarelativistic energies well beyond the threshold in a free NN collision, is still observed at such a low energy. Therefore, the m_t scaling appears as a universal feature at all bombarding energies. The production of mesons from thermalized nuclear matter satisfactorily explains the ratio of π to η meson production. We developed a phenomenological model which describes the η production as governed by the pion production and the pionic temperature.

Statistically-significant correlation of proton-π^0 events was observed, which we assign to the strength distribution of the $\Delta(1232)$ baryonic resonance. The same analysis shows no correlation signal in the case of deuteron-π^0 coincidencies. Work is in progress to correct the data for population probability and experimental acceptance to extract the Δ-resonance parameters.

The data presented here are a result of a common effort of the TAPS collaboration: L. Aphecetche, M. Appenheimer, R. Averbeck, Y. Charbonnier, H. Delagrange, J. Díaz, A. Döppenschmidt, A. Gabler, M.J. van Goethem, S. Hlavac, M. Hoefman, R. Holzmann, A. Kugler, F. Lefèvre, H. Löhner, A. Marín, F.M. Marqués, G. Martínez, V. Metag, W. Niebur, R. Novotny, R.W. Ostendorf, Y. Schutz, R.H. Siemssen, R.S. Simon, R. Stratmann, H. Ströher, P. Tlusty, P.H. Vogt, V. Wagner, H.W. Wilschut, F. Wissmann, M. Wolf. The main load of the data reduction was carried out by the GANIL fraction of TAPS: L. Aphecetche, Y. Charbonnier, H. Delagrange, F.M. Marqués, G. Martínez and Y. Schutz. The calculations with the Dubna Cascade model have been performed by V.D. Toneev. The author acknowledges the support of the GSI Darmstadt enabling his participation in the experiment and the warm hospitality extended to him at GANIL Caen.

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