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Observation of $\Delta^+ \rightarrow p\pi^0$ decay in heavy-ion collisions

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Abstract. Proton-π^0 coincidences have been measured at the beam energy of 180A MeV in the reaction Ar+Ca studied by TAPS at SIS/GSI. In the proton-π^0 invariant mass spectrum we observe a significant excess of strength above the background obtained by event mixing. We attribute this signal to the strength distribution N_{Δ^+} of the Δ^+ baryonic resonance. No correlation is observed in the case of deuteron-π^0 coincidences. Assuming isotropic emission of π^0 and Δ^+ from a midrapidity thermal source and isospin symmetry, we determined the global N_Δ/N_π ratio of 0.79 ±0.30(stat) ±0.2(syst). This value indicates that most pions produced at subthreshold energy in heavy-ion reaction are mediated by the Δ-resonance.

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Baryonic resonances, like the Δ-resonance, play a role of increasing importance in the dynamics of heavy-ion collisions from intermediate energies below the π production threshold $E^{\pi}_{\rm th}$ to higher energies well above it [1,2]. Nucleon resonances are excited in two-body nucleon-nucleon (NN) collisions and subsequently propagate through nuclear matter, collide with other nucleons or resonances, or decay through mainly meson emission. The latter process is believed responsible for the bulk of meson production at beam energies close to the free NN threshold. However, experimental evidence for that is still scarce. Energetic elementary collisions involving already produced resonances can subsequently excite heavier ones, whose decay produces more massive mesons, rarely produced by NN collisions. Baryonic resonances act as an intermediate energy storage, influencing the equilibration of nuclear matter. Compared to reactions at and above $E^{\pi}_{\rm th}$ (280 MeV for π^0), production of pions at *subthreshold* energies (*i.e.*, energy per nucleon below the threshold in free NN collision) has to originate at the early stage of the reaction. Later, thermalization efficiently suppresses production of new pions.

Many experimental and theoretical studies have been devoted in the past to the properties of the Δ-resonance, free and inside the nuclear medium (see [3]). However, mainly because of technical limitations such studies were constrained to charge-exchange reactions of the type (p,n)

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or (^{3}He,t) or to photonuclear reactions in which the nuclear medium remains in its ground state, at saturation density. Direct (both decay particles detected) experimental evidence for Δ-resonance excitation in nuclear matter was reported in p-induced peripheral [4,5] and rather central [6] reactions. Such studies in central heavy-ion induced reactions have been realized only recently thanks to the advent of highly efficient and segmented detectors. First results were recently discussed [7–10]. Here we exploit the ability of the photon spectrometer TAPS [11] to detect and identify neutral pions in coincidence with protons and deuterons [12]. We chose reasonable experimental conditions by searching for the Δ-resonance at a bombarding energy below the pion threshold where we still can cope with the hadron multiplicities. The results of this measurement are reported here.

The experiment has been performed using the 180A MeV ^{40}Ar beam delivered by the synchrotron SIS at GSI Darmstadt. The beam intensity was 5×10^8 particles in spills of ~9 s. The natural Ca target corresponded to 1% interaction probability. A set of 32 fast plastic scintillators (start detector SD) was placed at forward angles (15°–30°) and close to the target (10.1 cm). The efficiency of SD for reactions, where a π^0 was produced, was equal to 90% [13]. The photon pairs needed for the π^0 identification were detected in the TAPS electromagnetic calorimeter composed of 384 BaF$_2$ scintillation modules arranged in 6 blocks of 64 modules each. Each BaF$_2$ module was equipped with an individual plastic scintillator counter CPV (Charged-Particle Veto), enabling to trigger on neutral hits only. The blocks were placed in two towers positioned symmetrically with respect to the beam axis at a distance of 80 cm from the target. The position of the blocks ($\vartheta = \pm70°, \phi = 0, \pm30°$) was optimized for the detection of neutral mesons emitted from a midrapidity source ($0.26 < y/y_{\mathrm{beam}} < 0.71$). The data presented here were taken with a trigger condition for π^0 . This required that at least two detector modules in one block per tower detect a neutral hit of at least 10 MeV deposited energy. This trigger condition favours pions of low transverse momentum. The average transverse momentum p_{t} of measured pions equals to 93 MeV/c, while the maximum p_{t} reaches 330 MeV/c.

Photons detected in TAPS were identified through their TOF and pulse-shape analysis of BaF$_2$ scintillation light by requiring adequate conditions on the correlation between these two variables. Photon energies and directions were reconstructed from the electromagnetic showers using a cluster analysis described in ref. [14]. The energy resolution of TAPS for photons can be approximated as σ/E=1.91%+0.59%/$\sqrt{E[\,\mathrm{GeV}]}$ (ref. [15]). The angular resolution is better than given by the size of a crystal (75 mrad) as high energy photons generally deposit shower energy in several adjacent modules. This allows to reconstruct the impact point more accurately [15]. Neutral pions were identified through an invariant-mass analysis of events with at least two photons. The invariant mass of each photon pair was reconstructed observing a maximum allowed time difference between the photon hits. The π^0 invariant-mass resolution is 11% FWHM. This value is close to the one predicted by the response-function calculations [14] performed with the GEANT code. The signal-to-background ratio is 100. Events with more than one pion candidate represent only 0.2% of the global pion sample and were rejected. As the opening angle between two photons is measured in TAPS more precisely than photon energies, we used the prescriptions of ref. [16] to reconstruct the energy and momentum of pions from the measured photon energies, the spatial coordinates and the known invariant mass. After correction for the TAPS acceptance, the transverse-mass distribution of pions has an exponential shape with the inverse-slope parameter equal to 24±1 MeV [13], in agreement with the systematics of the ‘temperature’ parameters for meson spectra [17].

The charged-hadron events were identified in TAPS with the appropriate two-dimensional cut on the TOF *versus* pulse-shape distribution. The identification of hydrogen isotopes was based on a simultaneous measurement of TOF and deposited energy, from which the mass can be determined. As TAPS operates in air, the initial hadron energy had to be reconstructed from the energy deposited in the BaF$_2$ scintillators and the energy loss, calculated for each module individually. The procedure of the particle identification and energy reconstruction is described in ref. [12]. The proton identification procedure introduces 5% systematical error on the observed yield. The energy spectra of the identified protons have an exponential shape [18]. Proton energies are below the punch-through value (approx. 380 MeV) for the 25 cm long BaF$_2$ crystals of TAPS. The detection of charged particles was not required as a trigger condition. Among events where a neutral pion was detected, only 22% were accompanied by a charged particle. The average multiplicity of protons in proton-π^0 events was 1.1.

The presence of correlated proton-π^0 events from Δ^+ decay can be detected in the correlation function calculated as a function of the invariant mass. From the proton-π^0 events the invariant mass was evaluated according to the formula

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

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

$$C_{p\pi} = \frac{Y_{p\pi}}{Y_p \otimes Y_\pi}\ , \qquad (2)$$

Pions and protons used for the construction of mixed-event spectrum were chosen from the same multiplicity class as measured by the SD detector. Special care was taken to ensure that an event constructed from a proton and a pion (originating from different events) is detectable, *i.e.* does not contain overlapping electromagnetic and hadronic showers. The correlation function was normalized to unity in the region of low invariant mass, where

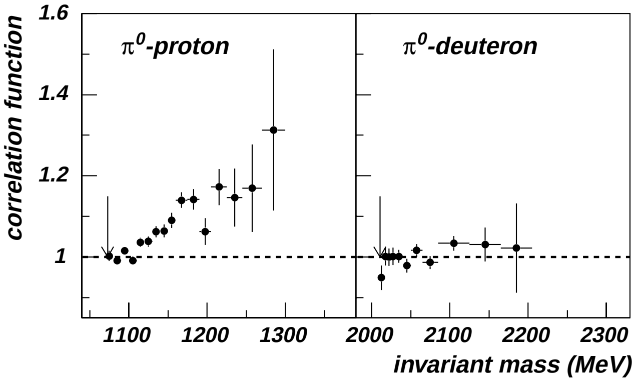

Fig. 1. Baryon-π^0 correlation function as a function of the invariant mass for the proton-π^0 and the deuteron-π^0 events. The arrows indicate the sum of rest masses.

it stays constant (fig. 1). The correlation function rises in the region of the Δ-resonance and reaches a maximum value of about 1.15 at the free Δ mass. Due to the limited statistics, the high-mass region could not be observed.

To verify the sensitivity of the correlation signal we have applied a similar analysis to the deuteron-π^0 system. We do not expect any signal in the deuteron-π^0 correlation function, as there is no established evidence for any particle decaying through this channel. The whole procedure applied to protons was repeated for deuterons and the deuteron-π^0 correlation function was obtained (fig. 1). This correlation function does not exhibit any significant signal. This result confirms that the signal observed in the proton-π^0 system is caused by the Δ-resonance and not by an artifact due to the limited acceptance.

While the presence of Δ^+ decay products has been observed in the correlation function, the yield of Δ^+ and in particular its distribution can be extracted only as a difference between the measured invariant-mass spectrum and the background obtained by the mixed-event technique. The normalization of the background with respect to the coincident spectrum is not known *a priori*, as well as the shape of the Δ-signal. We have followed the technique of ref. [6], searching for the Δ-signal Y_Δ by fitting the coincident spectrum $Y_{p\pi}$ to

$$Y_{p\pi} = \lambda \times Y_p \otimes Y_\pi + Y_\Delta \ , \tag{3}$$

where λ is the normalization constant applied to the mixed-event spectrum $Y_p \otimes Y_\pi$. Least χ^2 fit with $Y_\Delta = 0$ (no signal) yields χ^2/NDF=3.44, where NDF is the number of degrees of freedom. We attempted to describe the Y_Δ signal with a Gaussian or Lorentzian distribution (3 free parameters). The χ^2/NDF value was then significantly reduced to 0.76 for a Gaussian and 1.40 for a Lorentzian shape. The ratio of λ parameters obtained from fits with Gaussian and Lorentzian shapes equals to 1.026±0.021. The error-weighted average of the λ parameters from both fits was finally used to normalize the mixed-event spectrum (fig. 2).

The difference between the coincident and mixed-event spectra (fig. 2) exhibits a broad structure centered at 1150 MeV and containing Y_{Δ^+}=1940±740 events, integrated over the whole spectrum. The error includes the statistical uncertainty and the contribution due to the normalization of the background. The width of the observed distribution cannot be precisely established and varies from 30 MeV for a Lorentzian shape up to 60 MeV for a Gaussian. The experimental resolution was estimated to be about 15 MeV and is mainly due to the accuracy of the pion energy measurement. The acceptance as a function of the Δ-resonance mass, evaluated in the Monte Carlo simulation assuming a thermal source with the 'temperature' taken from the systematics [17] and moving at half beam rapidity, is roughly constant in the region of the observed bump while it rises for higher masses. The observed position of the Δ^+ yield is shifted by about 80 MeV compared to the free Δ-resonance mass. The signal above the combinatorial background is a convolution of the Δ spectral function and the probability to have the given energy. In our case of subthreshold beam energy, the limited energy available in NN collisions even after the inclusion of the Fermi motion causes that only the low-energy tail of the Δ-resonance is effectively populated, distorting the normal shape of the resonance. A simulation of collisions of a nucleon from

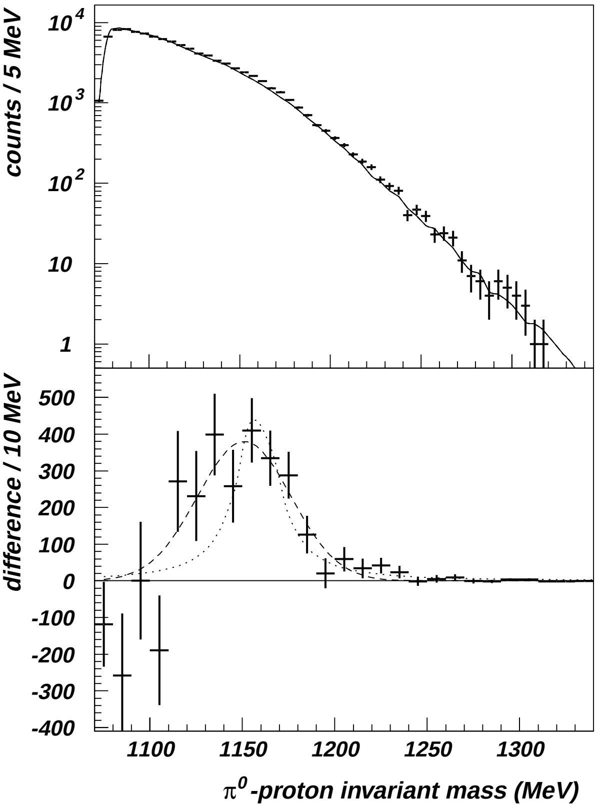

Fig. 2. Invariant-mass spectrum for coincident proton-π^0 events (upper panel). The solid line shows the shape of the background obtained by event-mixing (fluctuations in the high-mass tail are due to the limited statistics). The difference (lower panel) between the coincident invariant-mass spectrum and the background shows the Δ-resonance mass distribution. For the normalization of the background, see text. The fitted shapes are Lorentzian (dotted) and Gaussian (dashed line) parametrizations.

Table 1. Numerical values of parameters of eq. (4).

Y_{Δ^+}	Y_{π^0}	f_{π^0}	f_{Δ^+}	$f_{\Delta^+\to\pi^0 p}$	$\frac{\varepsilon_{\pi^0}}{\varepsilon_{\Delta^+\to\pi^0 p}}$
1940	429000	1/3	0.2414	2/3	84.

the target with a nucleon from the projectile, including their Fermi motion and the energy-dependent probability of Δ-resonance excitation, shows a distribution centered at about 1175 MeV. Thus, the principal part of the observed shift can be attributed to the limited available energy in the NN system, populating only the low-energy tail of the Δ-resonance mass distribution.

The π^0 and Δ^+ yields provide the necessary ingredients to attempt the experimental evaluation of the N_Δ/N_π ratio, where N_Δ (N_π) is the number of all Δ-resonances (pions) leaving the reaction zone, respectively. Assuming isospin symmetry, this ratio can be written as

$$\frac{N_\Delta}{N_\pi} = \frac{Y_{\Delta^+}}{Y_{\pi^0}} \times \frac{f_{\pi^0}}{p_{\Delta\to N\pi} f_{\Delta^+} f_{\Delta^+\to\pi^0 p}} \times \frac{\varepsilon_{\pi^0}}{\varepsilon_{\Delta^+\to\pi^0 p}}\,, \qquad (4)$$

where Y_{Δ^+} and Y_{π^0} are the observed yields, f_{π^0} is the neutral-pion fraction, $p_{\Delta\to N\pi}$=0.994 is the branching ratio of the nucleon+pion channel, f_{Δ^+} is the fraction of Δ^+ among all Δ-resonances, $f_{\Delta^+\to\pi^0 p}$ equals the probability of the decay into neutral pion and proton $\left(C^{\frac{3}{2}\,1\,\frac{1}{2}}_{\frac{1}{2}\,0\,\frac{1}{2}}\right)^2$, $\varepsilon_{\pi^0}/\varepsilon_{\Delta^+\to\pi^0 p}$ is the ratio of detection efficiencies for the respective channels. The Δ^+ fraction f_{Δ^+} of all Δ-resonances has been calculated by taking into account the relative fraction of pp, pn and nn collisions:

$$f_{\Delta^+} = \frac{\left(C^{1\,\frac{1}{2}\,\frac{3}{2}}_{1\,\frac{1}{2}\,\frac{1}{2}}\right)^2 Z_p Z_t + \left(C^{1\,\frac{1}{2}\,\frac{3}{2}}_{0\,-\frac{1}{2}\,\frac{1}{2}}\right)^2 \frac{Z_p N_t + Z_t N_p}{2}}{Z_p Z_t + \frac{Z_p N_t + Z_t N_p}{2} + N_p N_t}\,, \qquad (5)$$

where $C^{j\;j_1\;j_2}_{m\,m_1\,m_2}$ are isospin Clebsch-Gordan coefficients ($\mathbf{J} = \mathbf{J_1} + \mathbf{J_2}$) and Z_p, N_p (Z_t, N_t) denote the number of protons and neutrons in the projectile (target) nucleus. The numerical values of the parameters of eq. (4) are summarized in table 1.

The ratio of experimental efficiencies has been obtained through Monte Carlo simulations. The ratio of efficiencies needed here is much less susceptible to systematic uncertainties than the absolute efficiencies. In the NN center of mass, forward and backward emission of π^0 produced in quasi-symmetric heavy-ion collisions is favoured compared to the perpendicular emission [19,20]. However, this rise is not very pronounced and is well below a factor 2. Experimentally, nothing is known about the angular distribution of Δ-resonances. Since for the N_Δ/N_π ratio only the relative efficiency is relevant (eq. (4)), we assumed isotropic thermal emission from the NN center of mass in both cases. It was assumed, that the particles emerging from the decay of the Δ-resonance are not absorbed in the nuclear medium, so the detection efficiencies are not disturbed by secondary processes. For the N_Δ/N_π ratio, only the proton scattering would be relevant and it would affect the ratio through the reduction of the $\varepsilon_{\Delta^+\to\pi^0 p}$ efficiency, thus leading to an even larger value of N_Δ/N_π.

The N_Δ/N_π ratio (eq. (4)) is found to be 0.79 ±0.30(stat) ±0.2(syst). The systematic error originates from the efficiency calculations and from the method of proton identification [12]. As the Δ-resonance decays predominantly through pion emission (99.4%), this ratio should not be larger than one. The obtained value of the N_Δ/N_π ratio indicates that, within the experimental accuracy, most of the subthreshold pion yield is connected to the Δ-resonance.

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