Vol. 29 (1998) *ACTA PHYSICA POLONICA B* No 1–2

OBSERVATION OF $\Delta^+ \to p\pi^0$ DECAY IN NUCLEAR MATTER *

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(Received November 25, 1997)

Proton-π° 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° invariant mass spectrum we evidence a significant excess of counts above the background obtained by event mixing. We assign this signal to the strength distribution of the Δ baryonic resonance. From the measured yields we deduce a π/Δ ratio of 0.9±0.3 (preliminary value), pointing that most (if not all) pions produced in subthreshold energy heavy-ion reaction are mediated by the Δ-resonance.

PACS numbers: 14.40. –n, 25.90. +k

1. Introduction and motivation

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 creation threshold to higher energies well above this threshold. They are excited in direct two-body nucleon–nucleon (NN) collisions and subsequently propagate through nuclear matter, collide with other nucleons or resonances, or decay through particle (mainly meson) emission. The last process is believed responsible for the bulk of meson production at beam energies around the NN threshold. Energetic elementary collisions involving

* Presented at the XXV Mazurian Lakes School of Physics, Piaski, Poland, August 27–September 6, 1997.

already produced resonances can subsequently excite heavier ones, the decay of which produces more massive mesons, rarely produced if only nucleon–nucleon collisions are considered. In this way baryonic resonances act also as an intermediate energy storage, influencing the thermal equilibration of nuclear matter. Compared to reactions at and above the pion production threshold (280 MeV), production of pions at *subthreshold* energies (*i.e.* per nucleon energy below threshold in free nucleon–nucleon collision) occurs only at the early stage of the reaction. In the later stage of the collision, thermalization efficiently suppresses pion production. Therefore, subthreshold particles witness a well localized space and time of the reaction, when the maximum energy density is reached.

2. Experimental setup

The experiment has been performed using the 180A MeV Ar beam delivered by the heavy-ion synchrotron SIS at GSI Darmstadt. The beam intensity was 5×10^8 particles in spills of about 9 s. The Ca target corresponded to 1% interaction probability. At forward angles (approx. 15°–30°) and close to the target (9.4 cm) a set of 32 fast plastic scintillators was placed. It was used to sign the occurrence of a nuclear reaction and to give the start signal for time-of-flight (TOF) measurements. 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 positioned symmetrically with respect to the beam axis 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 ($\vartheta = \pm 70^\circ, \phi = 0, \pm 30^\circ$). 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. Photons energy and direction were reconstructed from the electromagnetic shower using an original cluster analysis described in Ref [1]. Photon pairs from the π° decay were selected with respect to their relative timing as well. Neutral pions were identified through an invariant mass analysis of two or more photon events. The π° peak in the invariant mass spectrum had a resolution of 11% FWHM. The signal-to-background ratio was about 100. The neutral pions were selected from events in the 90–150 MeV range in the invariant mass spectrum. The energy and momentum of pions were reconstructed from the photon energies and directions according to the prescriptions of Ref. [2]. When corrected for the TAPS acceptance, the transverse mass distribution of pions has an exponential shape with the inverse slope parameter equal to 26±2 MeV, in agreement with the systematics.

3. Proton–π° coincidencies

The charged-hadron events were identified in TAPS with the appropriate gate using the TOF versus pulse-shape distribution. As TAPS operates in air, the initial hadron energy had to be reconstructed from the energy deposited in BaF_2 scintillators and energy loss calculations, individual for each module. The procedure of the particle identification and energy reconstruction is described in Ref. [3] The energy spectra of the identified protons have an exponential shape properly described by the Dubna Cascade model calculations [4].

In order to search for a Δ-resonance signal in the invariant mass spectrum of π°–proton events (Fig. 1) 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).

The normalization of the background with respect to the coincident spectrum is a priori not known. We have followed the technique of Ref. [5], searching for the Δ-signal Y_Δ by fitting the coincident spectrum $Y_{p\pi}$ to:

$$Y_{p\pi} = \lambda \times Y_p \otimes Y_\pi + Y_\Delta \,, \tag{1}$$

where λ is the normalizing constant applied to the mixed event spectrum $Y_p \otimes Y_\pi$. The Δ signal is described by a gaussian or lorentzian distribution (3 free parameters). The mixed-events spectrum, normalized by λ from the fit, superpose exactly with the coincident one except in a region around 1150 MeV (Fig. 1). The difference between the coincident and mixed-events spectra (Fig. 1) exhibits a broad structure centered at 1150 MeV and containing 2100$\pm$550 events. We attribute this structure to the Δ resonance, shifted down by 80 MeV with respect to its free mass. No correlation is seen in the case of π°–deuteron coincidencies [6]. Large statistical error bars in the low-mass tail of the Δ peak make the width estimate very uncertain, between 40 and 65 MeV. A shift in the effective Δ-mass was found in charge-exchange reactions on massive targets when compared to proton target. In our case of subthreshold beam energy, the observed shift of the Δ strength distribution might be attributed to limited available energy. Simulation of collisions of a nucleon from target with a nucleon from the projectile, including their Fermi motion and energy-dependent probability of Δ-resonance excitation, shows a distribution centered around 1175 MeV. Thus, the principal part of the observed shift can be attributed to the kinematical effect.

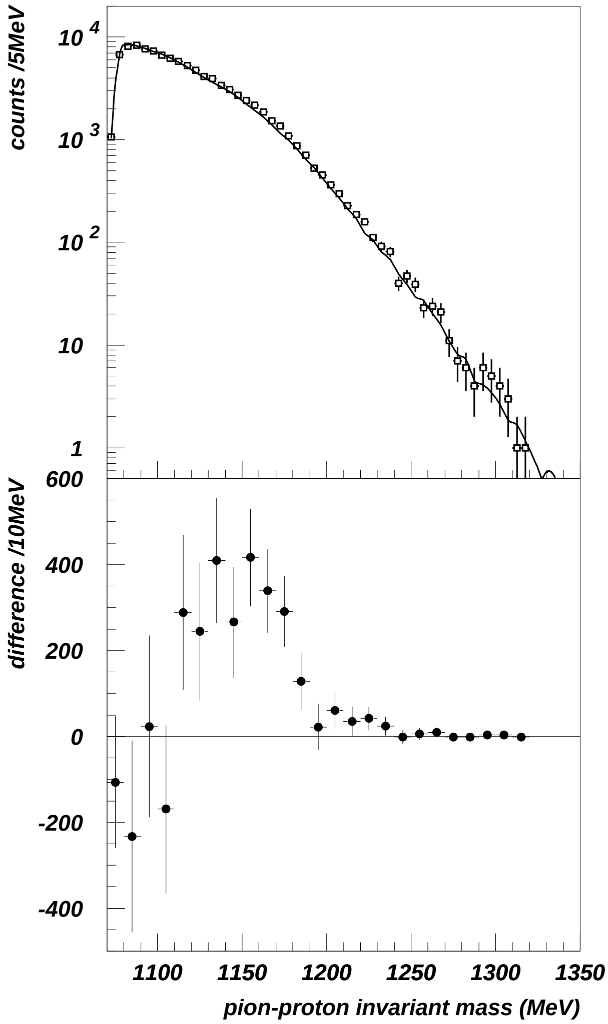

Fig. 1. Invariant mass spectrum for coincident π°–proton events (upper panel). The solid line shows the shape of the background obtained by event-mixing. The difference (lower panel) between the coincident invariant mass spectrum and the background shows the Δ-resonance mass distribution.

4. π/Δ ratio

The π° and Δ yields provide us with necessary ingredients to the first experimental evaluation of the π/Δ ratio. The observed neutral pion yield $Y_{\pi^{\circ}}$ can be written as:

$$Y_{\pi^{\circ}} = N_{\pi} \times f_{\pi^{\circ}} \times \varepsilon_{\pi^{\circ}} \, , \tag{2}$$

where N_π is the number of all pions leaving the reaction zone, f_{π° is the neutral pions fraction ($\sim 1/3$), and ε_{π° is the experimental detection efficiency for neutral pions. Similarly, the observed Δ^+ yield Y_{Δ^+} can be written as

$$Y_{\Delta^+} = N_\Delta \times p_{\Delta \to N\pi} \times f_{\Delta^+} \times f_{\Delta^+ \to \pi^\circ p} \times \varepsilon_{\Delta^+ \to \pi^\circ p}\,, \tag{3}$$

where N_Δ is the number of all delta resonances, $p_{\Delta \to N\pi}$ is the probability to decay via the nucleon+pion channel (99.4%), f_{Δ^+} is the Δ^+ fraction (1/5), $f_{\Delta^+ \to \pi^\circ p}$ equals the probability of the decay into neutral pion and proton (2/3), and $\varepsilon_{\pi^\circ p}$ is the experimental detection efficiency for neutral pion and proton coincidences. The f_{Δ^+} and $f_{\Delta^+ \to \pi^\circ p}$ probabilities were obtained from isospin Clebsch–Gordan coefficients. Experimental detection efficiencies have been determined by detailed Monte-Carlo simulations, including thresholds for proton detection. From the above equations, the π/Δ ratio in nuclear matter is found to be 0.9±0.3 (preliminary value). The value of the π/Δ ratio points that, within experimental accuracy, most if not all observed pion yield is mediated by the Δ-resonance. This experiment provides, for the first time, direct experimental evidence on the quantitative relation between pion and delta resonance population in heavy-ion collision. Also, the π/Δ ratio close to one gives confidence to models which directly relate observed pion yields with the abundance of the Δ-resonance in nuclear matter.

5. Summary

Concluding, we have measured π°–proton coincidences in Ar+Ca reaction at 180A MeV performed at SIS accelerator at GSI Darmstadt. Photons from π°-decay and protons were recorded in the TAPS calorimeter. Neutral pions were identified through appropriate window in the two-photon invariant mass spectrum. Time-of-flight and deposited energy were used to identify hydrogen isotopes. The difference of the invariant π°–proton mass spectra for coincident events and mixed events shows a prominent Δ-mass peak at 1150 MeV, *i.e.* 80 MeV below the free resonance mass. We find this to be a direct evidence of the $\Delta^+ \to \pi^\circ p$ decay in nuclear medium. The experimental Δ and π° yields allow to extract the π/Δ ratio to be 0.9±0.3 (preliminary value), pointing that most, if not all of the observed pions were mediated by the Δ resonance.

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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