PHYSICAL REVIEW C VOLUME 54, NUMBER 5 NOVEMBER 1996

Search for $\Delta(1232)$-resonance excitation in heavy-ion collisions around 100 MeV/nucleon

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(Received 22 July 1996)

Correlations among protons and neutral pions emitted in the reaction ${}^{36}\text{Ar}+{}^{27}\text{Al}$ at 95 MeV/nucleon have been studied. The analysis of the (π^0-p) invariant-mass and relative-angle distributions shows evidences of $\Delta(1232)$-resonance excitation. The experimental data are in agreement with the predictions of microscopic theoretical calculations. [S0556-2813(96)51511-6]

PACS number(s): 25.70.Ef, 14.20.Dh, 24.30.Gd

The study of $\Delta(1232)$-resonance excitations in nucleon-nucleus and nucleus-nucleus collisions is a topic of great importance in nuclear physics since it allows a direct investigation of the influence of nuclear matter (Pauli-blocking, reabsorption, etc.) on subnucleonic degrees of freedom such as Δ-mass and lifetime. Isobar excitations represent, on the one hand, an incomparable tool in the analysis of spin-isospin modes in nuclei [1] and, on the other hand, an interesting doorway channel that could be responsible of the large energy pooling needed in the far-subthreshold particle production [2–10].

Up to now, Δ production has been mainly observed in deep-inelastic and charge-exchange reactions induced by photons, electrons, pions, protons, and complex nuclei at bombarding energies ranging from the nucleon-nucleon production threshold (about 650 MeV) to a few GeV per nucleon [1]. In the last years, the availability of large-solid-angle multidetectors has allowed, with proton beams at 800 and 1600 MeV [11], Ni and Au beams at 1.9 GeV/nucleon and 1 GeV/nucleon [12], and Si beam at 14.6 (GeV/c)/nucleon [13], a more direct observation of Δ-resonance excitation by means of the simultaneous detection of pion and proton coming from its main decay mode. No data exist at lower bombarding energies.

In this paper we report on the very first search for far-subthreshold Δ-isobar excitation in heavy-ion collisions at intermediate energies through the analysis of the invariant-mass and relative angle distribution of neutral pions and protons simultaneously detected in the reaction ${}^{36}\text{Ar}+{}^{27}\text{Al}$ at 95 MeV/nucleon.

The pairs of photons coming from the π^0 main decay mode and the protons have been detected by the BaF_2 ball of the MEDEA multidetector [14] that covered the whole azimuthal angular range between the polar angles $\theta=40°$ and $\theta=138°$ with respect to the beam direction. Owing to this angular acceptance, the unwanted contribution of all those particles coming from more peripheral processes (such as projectile spectator protons) is avoided. The aim of the undertaken study is the observation of a definite correlation between pion and proton due to the energy-momentum-conservation constraints acting on each single nucleon-nucleon collision. The reliability of the results is guaranteed by the small value of $\nu_p=1.30\pm0.01$ of the efficiency-corrected mean proton multiplicity detected (within the above-mentioned angular dynamics) in those events where a pion is also present. When building the pion-proton invariant mass distribution one must, in fact, take care to treat in the same way all the pion-proton couples present in the event because it is not possible to *a priori* decide which proton, if any, comes from Δ decay. This means that if ν_p protons are present in the event one has to calculate ν_p different values of the (π^0-p)-invariant mass for each pion-proton pair and fill the invariant mass spectrum ν_p times in that event. Thus, if the proton multiplicity in pion events was very large, the combinatorial background introduced would become so large as to invalidate any result.

Photons and protons have been selected and identified by means of the usual shape analysis of the analog signal coupled with the time-of-flight information. The energy calibration for photons has been carried out using both a 6.13 MeV γ-ray PuC source and cosmic rays, while that for protons has been carried out using momentum-tagged secondary beams of charged particles (the so-called $B\rho$ technique). The kinetic energy ranges in which particles have been detected and identified span from about 20 MeV to 230 MeV for photons and from about 10 MeV to 230 MeV for protons. Neutral pions have been identified in the kinetic energy range from zero to about 120 MeV and in the whole 4π solid angle by imposing severe conditions on the relative-angle and invariant-mass distributions of all detected two-γ events as functions of the total energy of the two photons [15,16]. Reports on the performances of the BaF_2 ball of MEDEA as a neutral pion and proton detector can be found in Refs. [17–20].

For those events where a neutral pion is detected in coincidence with at least one proton, the (π^0-p) invariant mass distribution has been calculated using the formula

$$m=\sqrt{m_p^2+m_\pi^2+2E_pE_\pi(1-\beta_p\beta_\pi\cos\theta_{\text{rel}})}, \tag{1}$$

with an obvious meaning of the symbols. Since pions are not directly recorded (due to their very short lifetime) but identified by detecting the couples of photons coming from their main decay mode, pion detection angles are then distributed in the whole solid angle (not only that covered by the detector). The minimum measurable relative angle between a pro-

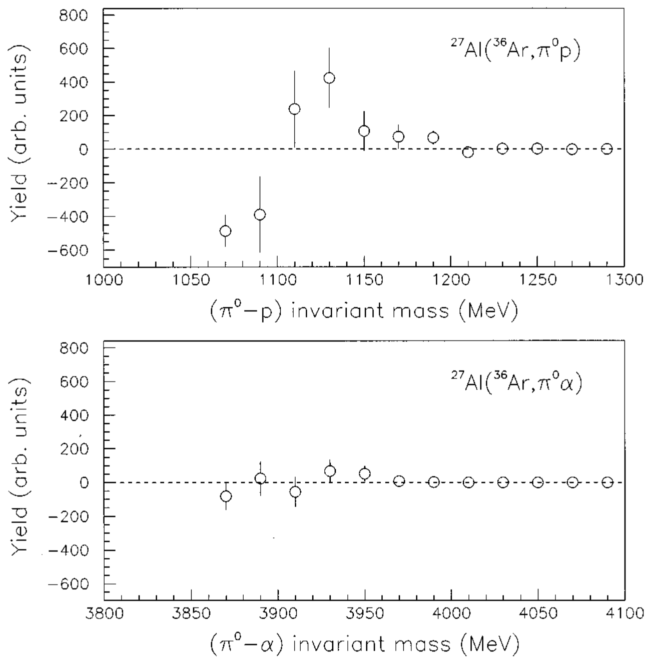

FIG. 1. Upper panel: difference spectra between normalized real- and *mixed*-event (π^0-p) invariant-mass distributions. Lower panel: difference spectra between normalized real- and *mixed*-event $(\pi^0-\alpha)$ invariant-mass distributions.

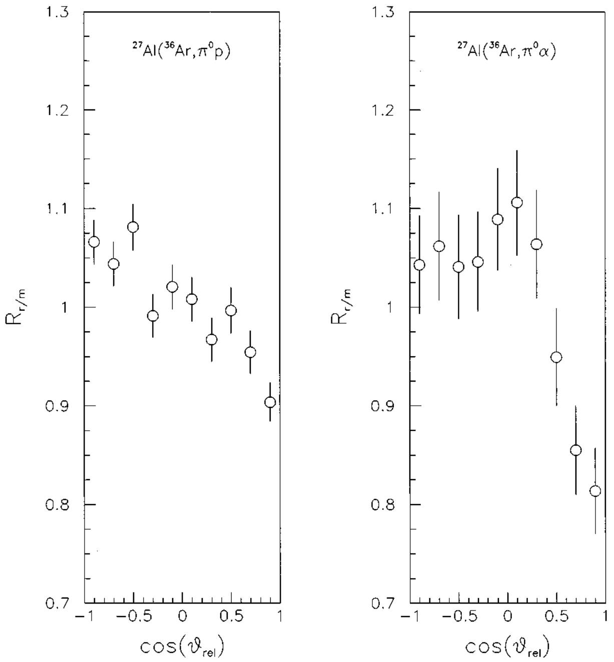

FIG. 2. Ratios between real- and *mixed*-event yields as a function of the cosine of the correlation angle. Left panel refers to experimental data relative to (π^0-p) coincidence events. The right panel refers to experimental data relative to $(\pi^0-\alpha)$ coincidence events.

ton and a pion is practically zero degrees. In order to be safe from any possible stray angular correlation, proton detection angles (which enter into the calculation of $\theta_{\rm rel}$) have also been randomized within the angular range covered by the touched detector. The experimental resolution of $\theta_{\rm rel}$ has been evaluated (by the Monte Carlo simulations discussed below) to be about 6 degrees.

In order to extract a true correlation signal above any combinatorial background level, the same distribution has also been calculated for a sample of so-called *mixed* events that has been generated in accordance with the prescriptions of Ref. [21], i.e., taking the neutral pion from one event and the proton from another randomly chosen event. In order to minimize the statistical error in the *mixed*-event invariant-mass distribution, the total number of *mixed* events is 150 times larger than that of real events. The difference spectrum between the real- and *mixed*-event invariant mass distributions (normalized to the same integral) is shown in the upper panel of Fig. 1. It is worth emphasizing that both in real and *mixed* distributions the detector efficiency $\epsilon(E_\pi,\theta_\pi)$ for pion detection, as a function of both pion energy and detection angle, has been properly taken into account. From a technical point of view this means that when building all distributions reported in this paper, each event, no matter if it was real or *mixed*, has been included with a weight equal to $1/\epsilon(E_\pi,\theta_\pi)$ instead of 1, where E_π and θ_π are the kinetic energy and detection angle, respectively, of the pion detected in that event. This efficiency has been calculated through full GEANT3 [22] simulations using an exact software replica of the real experimental setup. All details can be found in Ref. [17]. For protons having an energy above threshold ($E_{\rm th}\simeq$ 12 MeV), the detection efficiency is, for this kind of detector, practically equally to 1 at all angles. This ensures that the difference spectrum reported in Fig. 1 is free from any inefficiency in the coincident proton-pion pair measurement that could not be present in the *mixed* pairs. The characteristic ‘‘negative-positive-zero’’ shape of this kind of plot, expected if Δ resonance has been excited (see, for example, Fig. 2 of

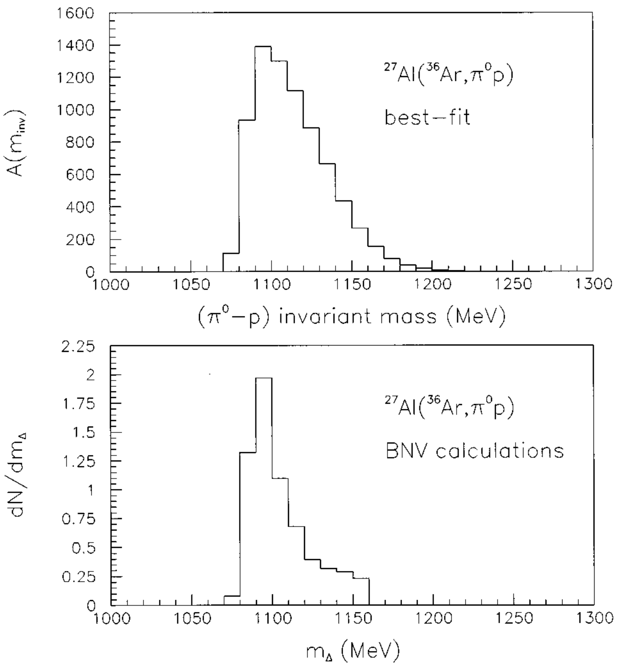

FIG. 3. Comparison between the ‘‘indirect’’-channel (π^0-p) invariant-mass distribution $A(m_{\rm inv})$ (upper panel), extracted from the best-fit procedure discussed in the text, and the Δ mass distribution (lower panel) predicted by the BNV theoretical calculation for the same system at the same bombarding energy.

Ref. [11], Figs. 2 and 3 of Ref. [12], Fig. 3 of Ref. [13], and Fig. 8 of Ref. [21]), is indeed observed. It is worth noting that the used bin of 20 MeV has been chosen equal to the invariant mass resolution that has been evaluated by the above-cited GEANT3 simulations.

In order to be sure that the signal shown in the upper panel of Fig. 1 is not due to statistical fluctuations, both the χ^2 test [23] and the Kolmogorov test [24] have been performed. The probability that the difference spectrum is incompatible with the null distribution is, in both tests, greater than 99%. In order to show further on that no experimental bias can invalidate the results shown in Fig. 1, we also plotted the invariant mass distribution relative to the $(\pi^0-\alpha)$ events. It is reported in the lower panel of Fig. 1. No significant signal above the constant zero level is evidenced in this case. The χ^2 and Kolmogorov probabilities that the $(\pi^0-\alpha)$ difference spectrum is incompatible with the null distribution are smaller than 1%. The correlation observed in the difference spectrum can then be attributed to the excitation of the Δ resonance. Other possible explanations, such as correlations with the reaction plane and/or correlations among all final-state particles can be, in fact, rejected observing that (a) the bombarding energy used to perform this experiment (95 MeV/nucleon) is very close to the balance energy for Ar induced reactions, and (b) subthreshold pion production in heavy-ion collisions at intermediate energies mostly takes place in quite central collisions with a many-body final state characterized by a large particle multiplicity (see, for example, Fig. 4 of Ref. [19]); the excitation energy of the participant system (the so-called *fireball*) is also so large [10,25] that the four-momenta carried away from the pion and the few protons (practically only one in this experiment) emitted in coincidence with it are only a very small fraction of the total available phase space.

The excitation of Δ resonance can be investigated looking not only at the momentum-energy correlations (as done so far) but also at the geometrical ones. Pions and protons coming from Δ decay should indeed evidence definite correlations in their relative angle distribution. Starting from the (π^0-p) invariant mass, it is easy to calculate the Δ kinetic energy using the formula

$$K_\Delta=\left[\frac{2m_\Delta^2}{(1-X^2)(1-\beta_p\beta_\pi\cos\theta_{\rm rel})+2[(m_p^2+m_\pi^2)/(E_p+E_\pi)^2]}\right]^{1/2}-m_\Delta \tag{2}$$

where

$$X=\frac{E_p-E_\pi}{E_p+E_\pi}. \tag{3}$$

The obtained distribution results are strongly peaked at about 20 MeV only, which allows us to expect an almost *back-to-back* angular correlation in the laboratory frame between the pion and the proton. In the left panel of Fig. 2 is plotted the ratio

$$R_{r/m}=\frac{(dN/d\theta_{\rm rel})_{\text{real events}}}{(dN/d\theta_{\rm rel})_{\text{mixed events}}} \tag{4}$$

between the normalized (π^0-p) real- and *mixed*-event relative-angle distributions (note that a bin larger than the experimental resolution of $\theta_{\rm rel}$ has been used). The overall trend of the distribution does evidence a continuous and monotonic increase of $R_{r/m}$ going from forward to backward direction. Even in this case the situation is completely different for $(\pi^0-\alpha)$ coincidence events. The $R_{r/m}$ distribution for those events, reported in the right panel of Fig. 2, shows a strong increase from $\theta_{\rm rel}=0°$ up to $\theta_{\rm rel}\simeq 70°$ and then becomes almost flat, within the statistical uncertainties, for larger relative angles.

One of the most important goals when searching for Δ-resonance excitation in pion-proton correlation studies is to evaluate the amount of the contribution of the "indirect" channel $NN\rightarrow N\Delta\rightarrow NN\pi$ separating it from the combinatorial background. In the most general way, the raw (π^0-p) invariant mass distribution (corrected for the detector efficiency) can be written as $F(m_{\rm inv})=A(m_{\rm inv})+B(m_{\rm inv})$ where the first term in the right-hand side is the searched "indirect"-channel contribution and the second term refers to the background. As $A(m_{\rm inv})$ we took an asymmetric Gaussian function defined as

$$A(m_{\rm inv})=\begin{cases} C\exp[(m_{\rm inv}-m_\Delta)^2/2\sigma_{1,\Delta}^2] & \text{if } m_{\rm inv}<m_\Delta, \\ C\exp[(m_{\rm inv}-m_\Delta)^2/2\sigma_{2,\Delta}^2] & \text{if } m_{\rm inv}>m_\Delta, \end{cases} \tag{5}$$

where C, m_Δ, $\Gamma_{1,\Delta}\equiv\sigma_{1,\Delta}\sqrt{2\ln 2}$, and $\Gamma_{2,\Delta}\equiv\sigma_{2,\Delta}\sqrt{2\ln 2}$ are free parameters to be fitted to the experimental data. $B(m_{\rm inv})$ has been chosen equal to the *mixed*-event invariant mass distribution, which correctly gives the shape of the combinatorial background [21], multiplied by a numeric factor λ (which has to be fitted to the data too) that gives the amplitude. The result of the best-fit procedure gave $m_\Delta=1091.6\pm2.4$ MeV and $\Gamma_\Delta=\Gamma_{1,\Delta}+\Gamma_{2,\Delta}=49.7\pm2.1$

TABLE I. Δ mass and width extracted from the best-fit procedure discussed in the text as a function of the pion transverse momentum.

$p_t^{\pi^0}$ (MeV/c)	m_Δ (MeV)	Γ_Δ (MeV)
<70	1085 ± 4	25 ± 4
$70-120$	1105 ± 2	42 ± 3
>120	1127 ± 5	57 ± 4

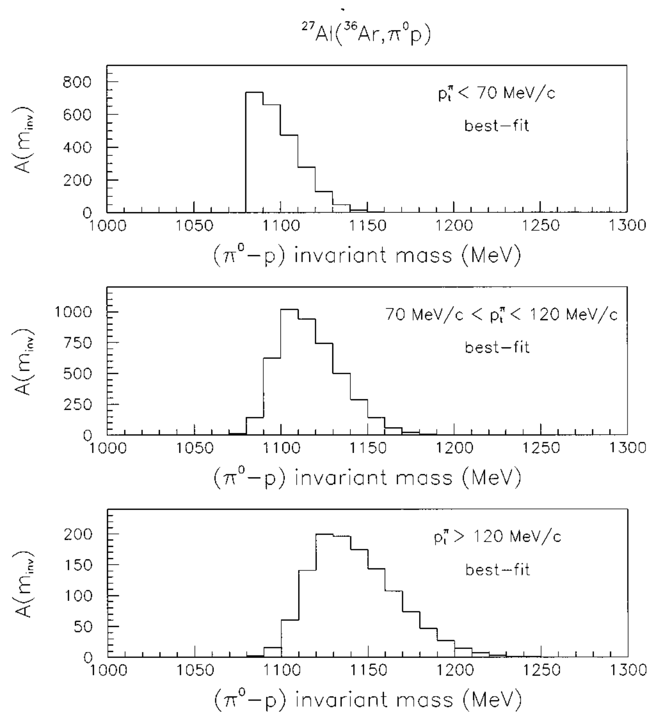

FIG. 4. ‘‘Indirect’’-channel (π^0-p) invariant-mass distribution $A(m_{\text{inv}})$ for various bins of the pion transverse momentum.

MeV with a reduced χ^2 of 0.992. A rough estimation of the ‘‘indirect’’-channel cross section σ_Δ can then be made using the formula

$$\sigma_\Delta = \left(\frac{N_\Delta}{N_\pi}\right)\sigma_\pi, \tag{6}$$

where N_π is the total number of inclusive pion events (corrected for the detector efficiency), N_Δ is the integral of the function $A(m_{\text{inv}})$, expressed as the number of events where pions are detected everywhere in coincidence with protons detected within the detector angular coverage, and σ_π is the measured inclusive total pion production cross section. For the studied system we found a value of $\sigma_\Delta = 21 \pm 4$ μb, which represents about 16% of the total pion cross section [19]. Owing to the above-cited limits in the proton detection this value obviously represents a lower limit.

Figure 3 shows the comparison between the correlated part $A(m_{\text{inv}})$ of the experimental invariant-mass distribution (extracted from the best-fit procedure discussed above) and the Δ-mass distribution foreseen for the same system at the same bombarding energy by a microscopic theoretical model [3,10] based on the numerical solution of the Boltzmann-Nordheim-Vlasov (BNV) transport equation. This model has already been successfully used in the study of subthreshold pion production in heavy-ion collisions at intermediate energies [10,18–20]. As the other existing models [8,25], it explicitly includes the Δ channel within the parametrization of Ver West and Arndt [26], who take into account the dependence of m_Δ on the available energy in the nucleon-nucleon center-of-mass frame. The position of the peak is well reproduced while the experimental spectrum evidences a width quite larger than the theoretical one. This widening is explainable by the fact that the theoretical calculations do not take into account the experimental energy and angular resolutions. It is worth noting that both the experimental and calculated values of the centroid and width of the distribution are smaller than the corresponding ‘‘free’’ ones equal to 1232 MeV and 120 MeV [27], respectively. This should not have to be surprising as there is a quite strong correlation, depending of the nuclear medium density, between the value of the Δ mass and its width as it is shown in Ref. [7] (see Fig. 4 of that paper) through the results of Boltzmann-Uheling-Uhlenbeck (BUU) calculations. In two recent papers [28,29] S. Bass *et al.* have demonstrated, by means of some calculations performed with the IQMD model, which uses the same parameterization of Ref. [26], that both the values of m_Δ and its width are strongly dependent on the available phase space. They shift towards the ‘‘free’’ values as the violence of the collision, measured by the value of the pion transverse momentum p_t^π, increases (see Fig. 7 of Ref. [29]). This trend is indeed observed in our experimental data. The (π^0-p) invariant-mass distributions, relative to the Δ contribution $A(m_{\text{inv}})$, are plotted in Fig. 4 for various bins of the pion transverse momentum. The best-fit values of the Δ mass and width are reported in Table I.

In conclusion, pion-proton correlation represents a powerful method to investigate possible isobaric excitations in nucleus-nucleus collisions even in the extremely low bombarding energy regime. The analysis described in this paper does provide evidence of Δ(1232)-resonance excitation in heavy-ion reactions at 100 MeV/nucleon.

The authors wish to thank S. Bass and J. Quebert for very fruitful discussions.

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