Δ RESONANCE PRODUCTION AND PROPAGATION IN INTERMEDIATE-ENERGY HEAVY-ION COLLISIONS*

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The role of the Δ resonance in subthreshold pion production is discussed and illustrated with π^0 data measured in heavy-ion collisions at 95 MeV/u with the photon spectrometer TAPS at GANIL. Particular emphasis is put on the Δ capture reaction and a cross section for this process is obtained.

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1. Introduction

Over the last decade it has become increasingly clear that the $\Delta(1232)$ isobar, as well as higher-lying baryon resonances, play a major role in the dynamics of heavy-ion collisions in the few GeV/nucleon range [1, 2]. Calculations suggest that these resonant states serve as an intermediate energy storage and greatly enhance through multi-step processes the cross sections at threshold of high-p_t pion, as well as eta and kaon production, *i.e.* of high-energy particles in general. On the other hand, as mesons, and in particular pions, are subject to strong final-state interactions, which often involve resonance excitation, any interpretation of their propagation in the nuclear medium has to rely on an accurate knowledge of not only the resonance production, but also the destruction processes. However, elementary cross sections involving resonances in the input channel are usually unknown and have to be estimated from the inverse process, if known, by applying the principle of detailed balance [3, 4].

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The theoretical framework in which subthreshold particle production is commonly described is given by microscopic transport theories [4] of the Boltzmann–Uehling–Uhlenbeck (BUU) [5] or quantum-molecular-dynamics (QMD) [6] styles, although some success had already been obtained with first-chance-collision models [7]. Apart from a correct description of the dynamical features of the collision itself, such calculations need as further input precise cross sections of the so-called "elementary" particle production, as well as destruction processes on the nucleon-nucleon level. In particular for mesonic probes, knowledge of the meson final-state interactions in nuclear matter is an important ingredient needed.

In case of the pion the relevant processes are largely mediated by the Δ resonance through the elementary reaction $N + N \rightarrow \Delta + N$ (resonance creation) and its inverse $\Delta + N \rightarrow N + N$ (resonance capture). Whereas the first one is accessible to direct measurement, the cross section of the latter is obtained with the aid of detailed balance [3] from the cross section $\sigma_{N+N\rightarrow\Delta+N}$. However, it has been pointed out [8] that, as these reactions involve a resonance of short lifetime, the finite width of the resonance has to be corrected for [8, 9], leading to the so-called 'extended detailed-balance principle'. The latter still needs to be verified, which can be done through an experimental determination of $\sigma_{\Delta+N\rightarrow N+N}$ and by comparison with the known cross section $\sigma_{N+N\rightarrow\Delta+N}$ [10].

This paper presents results from the 1992 campaign of TAPS (the Two-Arm Photon Spectrometer) at the GANIL accelerator facility. Heavy-ion induced hard-photon and subthreshold π^0 production has been investigated in a variety of reaction systems at intermediate bombarding energies, both inclusively, and in coincidence with light charged particles and projectile-like fragments. A number of novel results have been obtained and are discussed *e.g.* in Refs. [11–13]. Here we concentrate on neutral-pion production, with particular emphasis on processes involving the Δ resonance.

2. Some experimental details

In one of the measurements done with the photon spectrometer TAPS at GANIL, carbon and gold targets were irradiated with an ^{36}Ar beam of 95 MeV/u. Photons were registered in 320 BaF_2 detectors of the two-arm photon spectrometer TAPS [14], arranged in 5 blocks of 64 scintillators each. The blocks were placed in the horizontal plane at a distance of 62 cm from the target, with their centers at angles of 65°, 109°, 212°, 258°, and 309° with respect to the beam axis. All BaF_2 crystals were equipped with individual plastic charged-particle veto (CPV) detectors. This setup yielded a detection efficiency of 12.3% for photons (with $E_\gamma \geq 30$ MeV) and of 1.6% for neutral pions (detected via their two-photon decay). Coincident light charged particles (LCP) were detected and identified in the KVI forward wall (FW) made of 60 plastic-scintillator phoswich detectors [15], covering a range of polar angles $\theta = 3.5°$-$24°$, with charge separation up to about $Z = 5$. In addition, projectile-like fragments (PLF) were registered in the GANIL magnetic spectrograph SPEG positioned at 0°, with an angular acceptance of $\pm 2.0^o$, both horizontally and vertically.

In the data analysis, a very clean separation of γ rays from charged particles and neutrons was achieved by requiring : *(i)* no signal in the CPV modules covering the hit BaF_2 detectors, *(ii)* prompt time of flight and, *(iii)* the γ pulse shape of the BaF_2 signals. High-energy background produced by cosmic muons traversing a BaF_2 block was eliminated by a cut on the lateral extension of the hit pattern in the detector block. For more details see *e.g.* Refs. [11, 12].

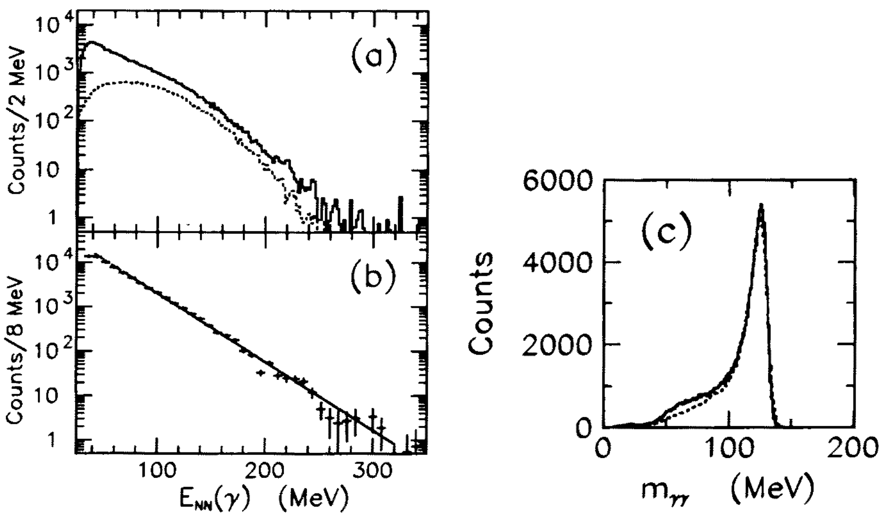

Fig. 1. (a) Response-corrected inclusive photon energy spectrum measured for ^{36}Ar+^{197}Au at 95 MeV/u. The dashed line represents the contribution from π^0 decay photons. (b) π^0-corrected hard photon spectrum. (c) Two-photon invariant mass distribution (solid), shown together with a GEANT simulation of π^0 decays (dashed).

Typical results of this analysis procedure are demonstrated in Fig. 1 for the reaction ^{36}Ar+^{197}Au at 95 MeV/u. As seen in part (a), at this bombarding energy the hard-photon spectrum contains, besides bremsstrahlung events, also a sizable contamination from π^0 decay photons. To subtract this component, amounting at 95 MeV/u to about 30%, a Monte-Carlo simulation has been performed with a π^0 event generator, carefully adapted to the measured pion energy and angular distributions. The resulting clean bremsstrahlung spectrum (shown in Fig. 1(b)) displays an exponential shape up to the highest measured energies, *i.e.* 300 MeV, with an inverse slope parameter of $E_0^{NN} = 29.0 \pm 1.4$ MeV in the NN c.m. frame. Neutral pions were identified through an invariant-mass analysis of two-photon events, yielding a distribution dominated by the π^0 peak ($\simeq$85%), with a fwhm resolution of 13% (see Fig. 1(c)). The results on hard-photon production are presented in [11], results on π^0 polar and azimuthal angular distributions in [11, 12].

3. The Δ capture cross section

From the shape of the π^0 kinetic-energy spectrum, obtained for ^{36}Ar+^{197}Au at 95 MeV/u, which is strongly affected by the pion final-state interactions in the nuclear medium, we have extracted a pion absorption cross section $\sigma_{\rm abs}$. Within the standard assumptions of the Boltzmann–Uehling–Uhlenbeck (BUU) transport theory, *i.e.* supposing in particular that $\sigma_{\rm abs}$ encompasses both the $\pi + N \to \Delta$ and $\Delta + N \to N + N$ processes, we have obtained an experimental estimate of the elementary cross section $\sigma_{\Delta+N\to N+N}$ for center-of-mass energies $\sqrt{s} \simeq 2050 - 2250$ MeV, allowing for a test of the extensions applied to the detailed-balance principle within that framework. Below we give only a schematic outline of this analysis; more details can be found in Ref. [16].

In a BUU calculation, where pion production is treated perturbatively, we find a primordial pion spectrum, *i.e.* the one prior to all final-state interactions, which can be well approximated by a maxwellian distribution. As shown in [17], these calculations reproduce very well the shape of the concurrently measured pn bremsstrahlung spectrum, offering a direct check of their predictive power. The present BUU result suggests that, for inclusive pion events at least, the folding of the nucleon Fermi momenta with the elementary pion production cross section results in a very close to thermal phase-space occupancy. Deviations from the pure maxwellian shape are however expected and are presumed to hold information on the pion rescattering and reabsorption processes [18].

To describe the π^0 final-state interactions, we made use of Monte-Carlo calculations on the basis of a model [7, 11, 18] in which the pions are emitted uniformly from a mid-rapidity source, formed by the overlap region of the two colliding nuclei, and propagated until they are absorbed or leave the reaction system. The measured π^0 angle-integrated kinetic-energy spectrum, transformed into the NN c.m. frame, is compared in Fig. 2 with the calculated one. The ratio of the two gives the pion escape factor which can be transformed [18, 16] into the momentum-dependent pion absorption length $\lambda_{\rm ABS}(p)$ shown in Fig 3a. From this, in turn, a momentum-dependent π^0 ab-

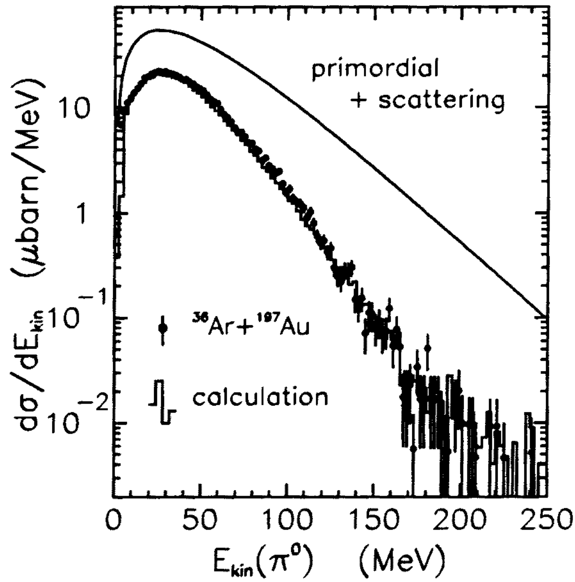

Fig. 2. Angle-integrated π^0 kinetic-energy spectrum in the NN c.m. system (symbols), corrected for the detector acceptance and response. The solid line is a $E_{\rm kin} \cdot \exp(-E_{\rm kin}/T)$ distribution, with $T = 26$ MeV, representing the primordial pions after rescattering (see text for details) and the histogram is the corresponding spectrum calculated including also reabsorption.

sorption cross section $\sigma_{\rm abs}$ is obtained (Fig. 3c). This cross section has to be decomposed into an s-wave part, corresponding to the Born and rescattering terms, and a p-wave part, corresponding to the Δ resonance. We have used the p-wave fraction calculated from an pion-nucleus optical-potential [16]. This calculation is supported by an analysis of the measured π^0 c.m. angular distributions [12], fitted with an isotropic s-wave term and an $(1+3\cos^2\theta_{cm})$ p-wave term, yielding the p-wave shown as data points in Fig. 3b.

Subsequently an estimate of $\sigma_{\Delta+N\to N+N}$ has been obtained in the following way: when a Δ is excited on a nucleon in the process $\pi + N \to \Delta$, it can either decay with a decay length $\lambda_{\rm decay}$ or be captured on a second nucleon with a capture length $\lambda_{\rm capt}(s)$ [3]. We define now a Δ capture probability which, on the one hand, is related [3] to the above quantities by $P_{\rm capt} = \lambda_{\rm decay}/(\lambda_{\rm decay} + \lambda_{\rm capt})$ and, on the other hand, can be obtained experimentally from the ratio of the p-wave part of the measured π^0 absorption cross section $\sigma^p_{\rm abs}$ and the Fermi-smeared total π^0N cross section $\sigma_{\rm tot}$, *i.e.* $\sigma^p_{\rm abs} = P_{\rm capt} \cdot \sigma_{\rm tot}$. Next, from the experimental value of $P_{\rm capt}$ and the calculated $\lambda_{\rm decay}$, the capture length $\lambda_{\rm capt}$ has been evaluated. In a last

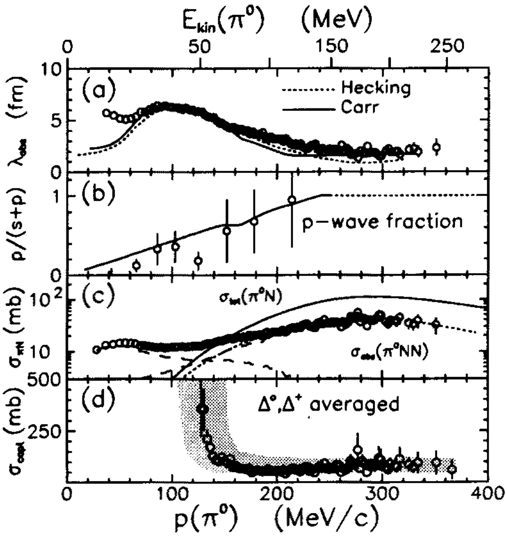

Fig. 3. (a) π^0 absorption length as function of the pion momentum. Pion-nucleus optical-model calculations done for $\rho_0 = 0.17$ fm^{-3} [16] are also shown as lines. (b) Calculated p-wave fraction of the π^0 absorption (solid line) and obtained from an measured angular distributions (open symbols). (c) In-medium π^0 total (σ_{tot}) and absorption (σ_{abs}) cross sections. The long-dashed lines represent an optical-model s-wave/p-wave decomposition, *i.e.* σ^s_{abs} and σ^p_{abs}, and the short-dashed curve is a Breit-Wigner fit to σ^p_{abs}. (d) Δ capture cross section extracted from the data. Error bars are statistical, systematic errors of the analysis are indicated by the shaded band.

step, from λ_{capt} we have obtained the cross section for Δ capture (Fig. 3d), with $\sigma_{\text{capt}} = 1/(\lambda_{\text{capt}} \cdot \rho_0)$.

The resulting estimate of the elementary, *i.e.* free, capture cross section $\sigma_{\Delta+N\to N+N}$ obtained after unfolding for Fermi smearing, is finally shown in Fig. 4 as function of the c.m. energy. As we deal here with neutral pions, in first order, only processes involving the Δ^+ and Δ^0 states have to be considered. From the comparison of the data with calculations [8, 9] it clearly appears that the correction for the finite width of the Δ is required in order to reproduce the steep increase observed at low $\sqrt{s}$. More sophisticated calculations based on a relativistic BUU model allow to calculate the genuine Δ in-medium capture cross section as function of the nuclear density [19]. They give reasonable agreement with our experimental result shown in Fig. 3d.

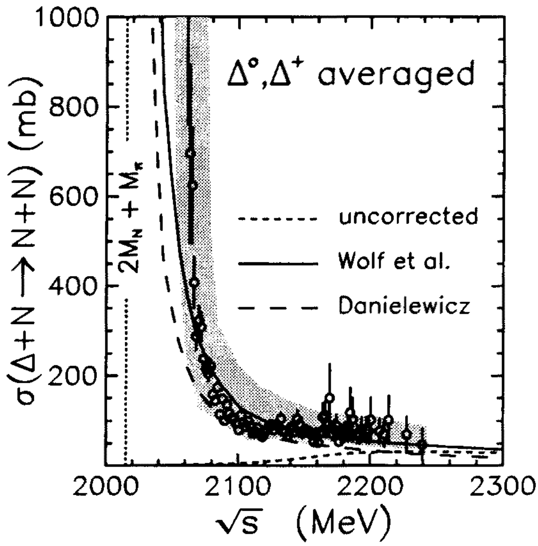

Fig. 4. Elementary Δ capture cross section as function of the ΔN c.m. energy $\sqrt{s}$. The shaded band corresponds to systematic errors. Lines are detailed-balance calculations without the finite-width correction (short-dashed), and with correction according to Wolf *et al.*[9] (solid), and to Danielewicz and Bertsch [8] (long-dashed), respectively. The absolute threshold at $2M_N + M_\pi$ is also indicated.

4. Summary and outlook

In summary, we have investigated inclusive, as well as exclusive π^0 emission in heavy-ion reactions at 95 MeV/u. The behaviour of neutral-pion production displays many similarities with the emission of very hard photons, pointing to the fact that essentially the same reaction phase is probed [11, 12]. The strong final-state interactions of pions have to be taken into account, however, and we have shown that they can even be put to good profit. We have indeed deduced an experimental estimate of the Δ capture cross section from an analysis of the pion kinetic-energy spectrum. Comparing our results with BUU calculations allows for an important consistency check of microscopic transport theories describing hadronic matter dynamics and particle production in the 50 MeV/u to few GeV/u range.

Future studies using unpolarized, as well as polarized proton beams at AGOR and the projected pion beam at GSI will further our present knowledge. With methods similar to the ones already applied to tagged-photon meson production [20], particularly the pion-induced reactions promise access to an investigation of in-medium properties of heavy mesons and baryon resonances.

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REFERENCES

[1] R. Stock, *Phys. Rep.* **135**, 259 (1986); H. Stöcker, W. Greiner, *Phys. Rep.* **137**, 277 (1986).
[2] V. Metag, *Prog. Part. Nucl. Phys.* **30**, 75 (1993).
[3] Z. Fraenkel, *Phys. Rev.* **130**, 2407 (1963).
[4] G.F. Bertsch, S. Das Gupta, *Phys. Rep.* **160**, 189 (1988).
[5] W. Cassing *et al.*, *Phys. Rep.* **188**, 364 (1990).
[6] J. Aichelin, *Phys. Rep.* **202**, 233 (1991).
[7] W. Cassing, *Z. Phys.* **A329**, 487 (1988).
[8] P. Danielewicz, G.F. Bertsch, *Nucl. Phys.* **A533**, 712 (1991).
[9] Gy. Wolf, W. Cassing, U. Mosel, *Nucl. Phys.* **A545**, 139c (1992) and *Nucl. Phys.* **A552**, 549 (1993).
[10] B.J. Ver West and R.A. Arndt, *Phys. Rev.* **C25**, 1979 (1982).
[11] A. Schubert *et al.*, *Phys. Rev. Lett.* **72**, 1608 (1994).
[12] A. Schubert *et al.*, *Phys. Lett.* **B328**, 10 (1994).
[13] A. Schubert *et al.*, *Nucl. Phys.* **A583**, 385c (1995).
[14] R. Novotny , *IEEE Trans. Nucl. Sci.* **38**, 379 (1991).
[15] H.K.W. Leegte *et al.*, *Nucl. Instrum. Methods* **A313**, 26 (1992).
[16] R. Holzmann *et al.*, *Phys. Lett.* **B366**, 63 (1996).
[17] R. Holzmann, in *Proceedings of the 7th International Conference on Nuclear Reaction Mechanisms*, Varenna, June 6-11, 1994, edited by E. Gadioli.
[18] R.S. Mayer *et al.*, *Phys. Rev. Lett.* **70**, 904 (1993).
[19] Guangjun Mao *et al.*, to be published.
[20] M. Röbig-Landau *et al.*, *Phys. Lett.* **B373**, 45 (1996).