Impact-parameter dependence of neutral pion production in the ^{36}Ar on ^{27}Al collision at 95 MeV/nucleon

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Neutral pion production has been studied in the ^{36}Ar + ^{27}Al reaction at 95 MeV/nucleon with the aim to get a quantitative estimate of its impact-parameter dependence. A near 4π multidetector has been used to detect both the gamma rays originating from the π^0 decay and the associated charged particles. The charged particle multiplicity has been used in the present analysis as a global variable to extract the impact parameter scale. A comparison with a Boltzmann-Nordheim-Vlasov calculation, which takes into account the effect of pion reabsorption in the nuclear medium, has been performed.

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I. INTRODUCTION

Several evidences on the central character of heavy ion collisions producing pions at subthreshold energies have been accumulated over the last few years by semiexclusive experiments [1–4]. Light charged particles (LCP) have been used as an indicator of the violence of the collision. As an example, the multiplicity distributions of LCP show large differences when measured in inclusive and when in coincidence with a pion trigger [2]. Velocity spectra at forward angles of LCP, such as Z=2 ions, show evidence of two different contributions originating from peripheral and from more violent collisions [3], the latter being associated to pion events. Moreover the LCP angular distributions exhibit larger slopes when pions (or other energetic products, such as high transverse momentum protons) are selected [2]. The small yield of projectilelike fragments (PLF) at forward angles and the relatively large yield of intermediate mass fragments (IMF) at large angles in pion-triggered events have also provided a signature for central collisions in heavy ion reactions around 100 MeV/nucleon [3,4]. All these experiments were carried out detecting charged pions by a range telescope which triggered large area multidetectors.

Unfortunately, quantitative estimates of the impact parameter scale for the pion production could not be extracted by these experiments due to the incomplete coverage of the total solid angle for the LCP detector and also to the small solid angle usually subtended by range telescopes which reveal charged pions only around few selected directions. In case of neutral pions, which mainly decay into two gamma rays, some of the experimental difficulties which are inherent to the detection of charged pions could be overcome, due to the recent availability of large-efficiency multidetectors having high granularity which are able in principle to detect both gamma rays and charged particles [5,6].

This paper reports an investigation on the impact parameter dependence of pion production in the ^{36}Ar + ^{27}Al reaction at 95 MeV/nucleon. The charged particle multiplicity was used in the present analysis as a global variable to extract the impact parameter scale within the modified fireball model (MFM) [7].

II. EXPERIMENT AND DATA REDUCTION

The experiment was performed at GANIL with the multidetector array MEDEA [6], coupled to a forward hodoscope of plastic scintillators, to detect π^0 and charged particles. For this experiment MEDEA had 168 BaF_2 modules, arranged into seven rings of 24 detectors each, covering the zenithal angular range between 30° and 138° and 120 phoswiches arranged into five rings of 24 detectors each, covering the angles from 10° to 30°. The hodoscope was made by two rings of eight plastic scintillators each and covered the angular range from 2.5° to 10° to detect light charged particles and heavier fragments. The π^0 trigger was generated by any twofold coincidence of the six BaF_2 rings around 90° associated with 20 MeV γ-equivalent energy threshold. The inclusive trigger was given by events with multiplicity larger than one in the whole multidetector (MEDEA + hodoscope). The properties of such a detector as a π^0 spectrometer were already reported [8]. For further details on the experiment and data analysis we direct the reader to a previous paper [9]. Figure 1 shows the invariant mass spectrum which has been obtained in the present experiment compared with the result of a simulation by means of the code

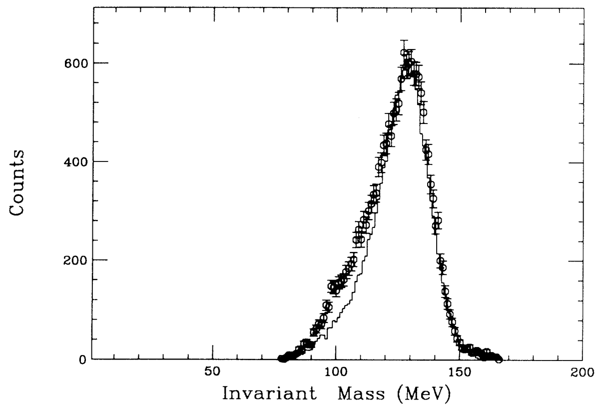

FIG. 1. Invariant mass spectrum obtained by the multidetector MEDEA from the $^{36}Ar+^{27}Al$ reaction at 95 MeV/nucleon (points). The solid line is the result of a GEANT3 simulation.

GEANT3 [10] which takes into account the geometrical and physical properties of the detector. The good agreement supports the use of our calculated π^0 efficiency to correct data wherever required. Extensive simulation of the heavy ion collision was carried out to investigate the impact parameter dependence of the π^0 production cross section in the $^{36}Ar+^{27}Al$ reaction [11]. The simulations have been done in the framework of the modified fireball model [7], which has been successfully used in the past to reproduce several features of the heavy ion dynamics at intermediate energies [2,3,7,12,13]. Several global variables were tested to look for a good correlation with the impact parameter. Among these, the average parallel velocity and the charged particle multiplicity were seen to give the best results [11]. In the present analysis only the charged particle multiplicity was chosen. Events generated from the MFM were filtered through the experimental setup, incorporating the geometrical and physical structure of the detector, its dead zones, velocity thresholds, multihit events, etc. The possibility that neutrons contribute to the charged particle multiplicities in the BaF_2 and phoswich detectors by (n,hadron) processes was also included. The overall apparatus efficiency for neutron detection was estimated by Monte Carlo calculations and incorporated in the filtering process. A good correlation between charged particle multiplicity and the impact parameter was found as to classify, within 2 fm bins, the events in three classes, roughly corresponding to central, intermediate, and peripheral collisions.

III. RESULTS AND DISCUSSION

The inclusive results of π^0 production at 95 MeV/nucleon for the $^{36}Ar+^{27}Al$ system can be summarized as follows:

(i) Kinetic energy spectra in the laboratory frame for different regions of pion emission angle show the typical behavior with a maximum at low kinetic energy and an exponentially decreasing tail (points in Fig. 2). However, the inverse slope parameter E_0 needed to reproduce the exponential falloff does not reflect the kinematics of a moving source. If a simultaneous fit to all spectra with a Maxwell-Boltzmann function is performed, a source velocity $\beta = 0.1$ can be extracted. This is in contrast to what was observed for lighter systems [9] at the same bombarding energy, where source velocities close to that of the nucleon-nucleon system were observed. However, by fitting the invariant transverse momentum distribution with a Maxwell-Boltzmann function a "temperature" of 19±5 MeV is obtained in agreement with recent systematics [14].

(ii) The angular distribution of the emitted pions, in the laboratory frame, has a forward rise and is nearly flat beyond 80°. However, gating on different ranges of the pion kinetic energy, a nearly isotropic behavior for low energy pions (0–20 MeV) shows up, while the forward rise seems associated to pions of higher kinetic energy (see points in Fig. 3).

(iii) The integrated cross section for π^0 production in the $^{36}Ar+^{27}Al$ reaction at 95 MeV/nucleon is about 150 μb, which is in general agreement with the well-known $\sigma_{tot}/(A_p A_t)^{2/3}$ scaling law on the pion production excitation function [15]. However, a very close value was also obtained [9] for the lighter system $^{16}O+^{27}Al$ at the same bombading energy per nucleon, suggesting a reduced yield of pions for this heavier system.

(iv) Boltzmann-Nordheim-Vlasov (BNV) calculations, carried out with the same procedure as in Ref. [16] (in the following denoted as standard BNV), which gave good agreement to the data on protons as well as on neutral and charged pions measured in the $^{16}O+^{27}Al$ reaction [9,13], overestimate the pion yield especially at forward angles. They predict inverse slope parameters larger than the experimental ones even when corrected for pion reabsorption in the usual way, namely by a mean attenuation factor [17].

All these points clearly show the possibility of strong reabsorption effects, which increase with the mass of the interacting nuclei, claiming for proper inclusion of this feature in the dynamical calculations. In Ref. [18] the importance of the pion source location was stressed, since it changes the measured yields, slopes of the energy spectra as well as the angular distribution. For this reason the selection of impact parameters in pion-producing heavy ion collisions could help, together with dynamical calculations, to investigate the role of reabsorption effects. Along this line, a preliminary analysis of these data was undertaken by means of the associated charged particles. Figure 4 shows the inclusive and π^0-triggered charged particle multiplicity distributions. Both areas are normalized to one. The two distributions are severely different. The weighted average multiplicity goes from 4.4 for the inclusive distribution to 9 for the pion events. About 60% of the pion events come, within this analysis, from collisions with impact parameters ranging from 0 to 2 fm. This filter can be used to investigate how different features of the process depend on the character of the collision. As an example, Fig. 5 shows in the lab system the angle-integrated kinetic energy spectra of the emitted pions extracted for central, intermediate,

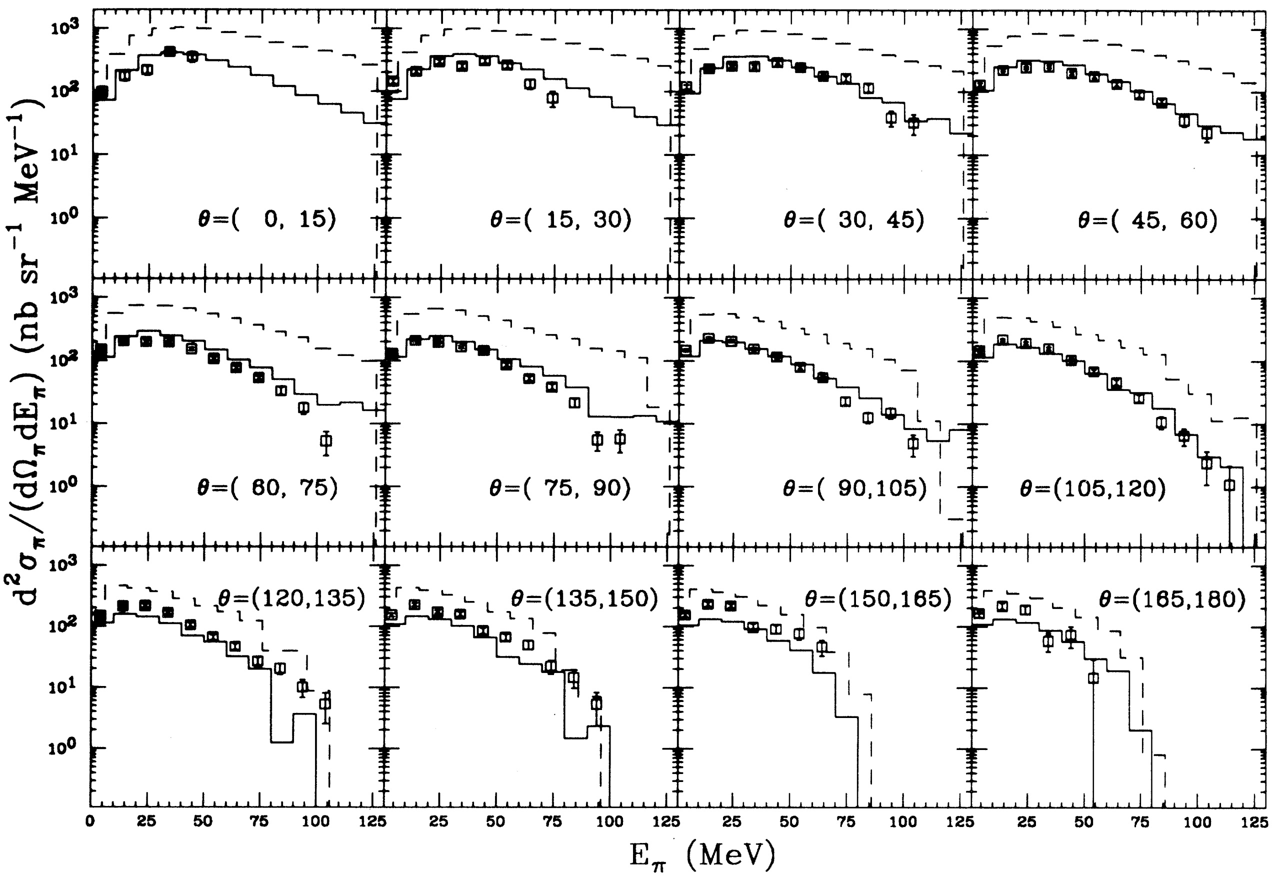

FIG. 2. Comparison between experimental (points) pion energy spectra at different detection angles and the results of a BNV dynamical calculation taking into account the effect of pion reabsorption in the nuclear medium (solid histogram). The dashed histograms represent the BNV calculations without reabsorption effect.

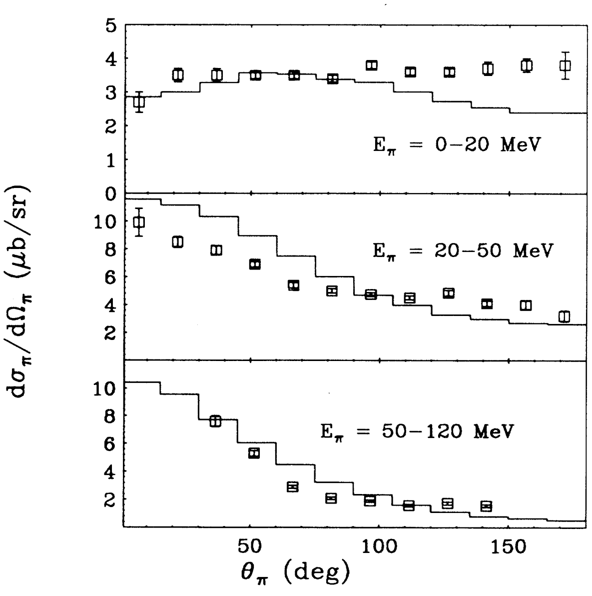

FIG. 3. Comparison between experimental and theoretical BNV calculation of pion angular distribution for different energy bins. The same symbols as in Fig. 2 are used.

and peripheral collisions (full points). Some indication of a different slope can be observed for peripheral collisions, corresponding to small multiplicities. In fact, the inverse slope parameter ranges from 19.3±2.4 for central collisions to 24.0±6.1 for peripheral collisions. This could be also a signature of strong reabsorption effects

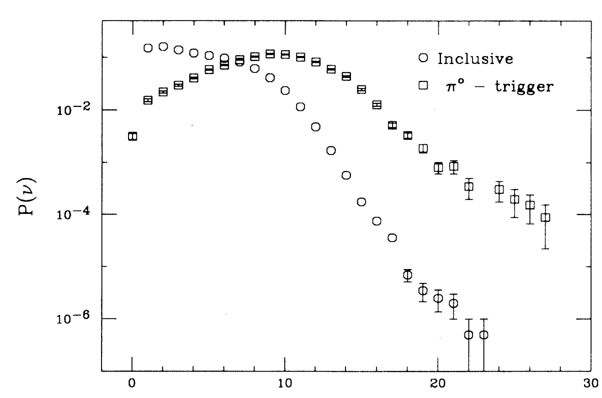

FIG. 4. Charged particle multiplicity distribution of the inclusive and π^0-triggered events for the reaction $^{36}Ar+^{27}Al$ at 95 MeV/nucleon.

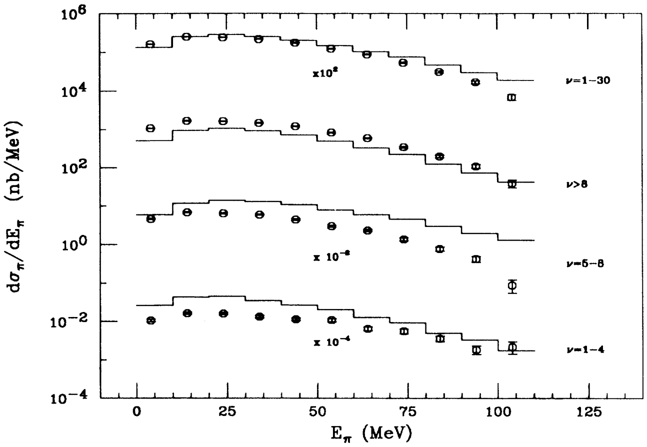

FIG. 5. Experimental angle-integrated pion energy spectra (points) for three bins of charged particle multiplicity, namely m=1–4, m=5–8, and m >8. They are compared with the BNV calculations for three bins of impact parameter namely b=5–7, b=3,4, and b=1,2 fm, respectively. In the upper part of the figure, angle and impact parameter integrated energy spectra are also reported.

(more important for pions with higher kinetic energies) in central collisions. Peripheral collisions give pion spectra which are apparently harder at forward and backward angles, suggesting the importance of reabsorption effects at sideward angles, where the average pion path length in the nuclear medium should be larger. All these effects could only be taken into account in a fully dynamical microscopic calculation with an energy dependent pion reabsorption.

IV. COMPARISON WITH KINETIC CALCULATIONS

In the BNV code described in Ref. [16], the pion production in a heavy ion reaction at intermediate beam energies is calculated in a perturbative way. Pions are assumed to originate mainly from incoherent superposition of individual nucleon-nucleon (NN) collision probabilities. Under this assumption the Lorentz invariant triple differential pion production cross section is

$$\frac{1}{p_\pi}\frac{d^3\sigma_\pi}{dE_\pi d\Omega_\pi db} = 2\pi b \sum_{NN\text{coll}(b)} \int \frac{d\Omega_q}{4\pi}\frac{1}{p'_\pi}\frac{d^2P^{\text{elem}}_{NN\pi}}{dE'_\pi d\Omega'_\pi} P_B P_{\text{esc}} \; . \tag{1}$$

The primed and unprimed denote quantities in the individual NN center of mass and laboratory frames, respectively. Ω_q is the solid angle of the relative momentum between the final nucleons which is not fixed by energy and momentum conservation and has to be averaged out. $P^{\text{elem}}_{NN\pi}$ represents the π-production probability in a NN elementary collision, P_B is the final-state Pauli blocking factor determined from the occupation probabilities of the final nucleons in the phase-space, and P_{esc} represents the pion escape probability.

Some kinetic calculations of π^0 production [19], assuming a reabsorption length of 3 fm independent of pion energy, were already carried out to reproduce some inclusive data. Recently, a pion absorption mean free path depending on the pion energy was successfully extracted from the data on the ^{129}Xe + ^{197}Au reaction at 44 MeV/nucleon [20], assuming the slope of the π^0 transverse-momentum spectrum independent on the absorption and calculating an average pion path within the nuclear medium according to a simple geometrical model [17].

Since a consistent treatment of pion reabsorption in the subthreshold region was not yet achieved, we improved the BNV code of Ref. [16] through a phenomenological approach. Whenever a pion is created, we follow its path inside the nuclear medium assuming it moves on a straight line determined by its momentum $\mathbf{p}_\pi$. Thus, the pion has to travel inside the nuclear region an effective distance dynamically depending on the surrounding medium and given by

$$d(\mathbf{r}_\pi, \hat{p}_\pi, t) = \frac{1}{\rho_0}\int_0^{+\infty} \rho(\mathbf{r}_\pi + \hat{\mathbf{p}}_\pi s, t) ds \; , \tag{2}$$

where ($\mathbf{r}_\pi$,t) are the pion production space-time coordinates, ρ is the nucleon density, and ρ_0 the saturation value for the normal nuclear matter. The escape pion probability is then given by $P_{\text{esc}} = \exp(-d/\lambda_0)$ where $\lambda_0 = (\sigma_{\text{abs}}\rho_0)^{-1}$ represents the mean absorption length in nuclear matter. Both optical model [21] and transport [22] calculations predict a pion absorption mean free path which is depending on the pion energy. For our calculation we have used the parametrization of energy dependence for λ_0 given in Ref. [22].

Preliminary results are promising in this respect since both the slopes and the absolute values of the pion spectra as well as the pion angular distributions for selected bins of pion kinetic energy (histograms of Figs. 2 and 3, respectively) are correctly reproduced at variance with the standard BNV version. However, we remark that the BNV calculation corrected for the absorption by a mean attenuation factor already gave a good agreement for neutral pion spectra obtained in the reaction with a lighter system [9]. Actually, we have found that there are no significant differences between the two calculations for lighter colliding systems due to small dispersion on the pion path lengths in the nuclear medium [23].

In Fig. 5 the angle-integrated theoretical pion energy spectra, as calculated in the present BNV approach, are also reported for different bins of impact parameter. While we observe a very good agreement between the overall energy spectra, namely integrated over the whole impact parameter range (see upper part of the figure), some discrepancies exist on the impact parameter dependence between calculated and experimental ones. Although the "experimental" impact parameter bins are model dependent, it seems that the measured pion production cross section as a function of the impact parameter shows a different trend with respect to the prediction of microscopic BNV calculations which include pion reabsorption on an event-by-event basis. This could be an indication of the presence of cooperative processes, based on interactions between clusters of nucleons, or coherent bremsstrahlung which are not taken into account in our BNV calculation.

V. CONCLUSIONS

At last, we find that the pion reabsoption is a very important effect especially for heavy nuclear systems. It plays an essential role for the degree of asymmetry and anisotropy in the final pion spectra, altering the slopes and, consequently, the data extracted directly from these (for example, the source velocity). We find a general agreement between the inclusive pion data and the microscopic BNV calculations in which reabsoption effects are taken into account in an event-by-event analysis.

Exclusive experiments on pion production give more useful information on the dynamics of the process, especially when collisions can be classified according to their impact parameter. This selection can be achieved by the associated charged particle multiplicity. However, we find that the BNV approach based on an incoherent mechanism for the pion production and the data are not fully consistent. Indeed, there are some features in the impact parameter dependence of the experimental yields, which seem to indicate also the possible existence of cooperative contributions in pion production which are presently not included in our BNV calculations. This point requires further support and it will be the subject of forthcoming investigations.

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