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NUCLEAR MATTER EXCITATION IN PION-XENON COLLISIONS AT 3.5 GeV/c

Inclusive Spectra of Neutral Pions

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1. INTRODUCTION

In traversing atomic nucleus, fast projectile deposits its energy in the intranuclear matter. The mechanism leading to projectile energy deposition and nuclear matter excitation has intensively been discussed recently [1,2,3]. Various aspects are considered: stopping power, thermal equilibrium, formation zone, collective flow, high densities and temperatures, jet and plasma formation and many others. Experimental trends are mainly directed to highest projectile energies and heaviest target nuclei. The results, gained so far, point out however at the similarities between hadron-nucleus and nucleus-nucleus collisions; the latter seem to be a superposition of many hadron-nucleus constituents [4,5]. Nucleus-nucleus interactions can be considered as a sort of different impact parameter hadron-nucleus collisions. It is useful therefore to have some reference information taken from hadron-nucleus data when searching for a new phenomena in nucleus-nucleus collisions.

The aim of our investigations is to get data on incident particle energy deposition and nuclear matter excitations at a given value of impact parameter. We would like to pursue a smooth transition from peripheral collisions to the central ones. The xenon nucleus seems to be a good example of nuclear matter layer; ($Z=54$, $\langle A \rangle = 131$, $\langle r^2 \rangle^{1/2} = 4.8$ fm - where Z, A and $\langle r^2 \rangle^{1/2}$ are respectively, charge, mass and rms radius of the xenon nucleus). We apply the number of emitted protons as an indicator of the impact parameter. The inclusive distributions of neutral pions are used to find the main features of the investigated process.

2. EXPERIMENT

A sample of 6301 minimum bias events of π^--Xe collisions at 3.5 GeV/c incident momentum has been collected. All events were recorded on the photographs of 180 litre xenon bubble chamber of ITEP, Moscow. The details of data analysis are described in our earlier papers [6,7]. Here, we consider two kinds of secondary particles: protons and neutral pions.

We accept as protons all the particles stopping within the chamber and showing track length greater than 5 mm. This track length corresponds to the proton kinetic energy of 22 MeV. The admixture of positive pions in this class of particles is negligible as their decays in the chamber are simply recognizable. The chamber operated without magnetic field and some negative stopping pions could be taken as protons. This fraction was estimated to be no more than 2%. The admixture of deuterons and heavier nuclear fragments should not exceed a few percent as most of them produce shorter tracks. The momentum range of detected protons extends between 200 and 800 MeV/c. The protons of momenta less than 600 MeV/c are identified in full 4π geometry while some of faster protons leave the chamber without stopping. The corresponding loss should not exceed 4%.

Neutral pions are detected and identified through the gamma quanta conversion pairs and electron-photon showers registered in the chamber. The efficiency of gamma quantum registration is more than 90% and does not depend essentially on the energies and multiplicities of gammas. In the predominant part of events gamma quanta occur in even numbers. It was found that neutral pions are the main source of the gammas observed; η° decays and others are in a few percent only. For identified π° mesons the energy correction was done under the condition that effective mass of corresponding gamma quanta pair coincides with the mass of π° meson. The mean accuracies of energy and angle determination are 9.3% and 1.9 degrees correspondingly; mean π° meson weight equals 1.18.

It is significant for the present data analysis that neutral pions are registered with very high efficiency in 4π geometry conditions and in full energy range, including zero kinetic energy and up to the highest possible.

3. INCLUSIVE π° DISTRIBUTIONS IN LABORATORY FRAME

It is well established that the number of emitted protons in high energy hadron-nucleus collisions can be used as an indicator of the number of collisions between the incident particle and the target nucleons at a given impact parameter [8] or, in other words, it measures the thickness of the nuclear matter layer involved in the interaction process [9]. In the emulsion experiments the number of grey particles is applied in the sense mentioned above. In the present analysis we consider the inclusive distributions of neutral pions depending on the number of emitted protons. First, we perform the analysis in laboratory reference frame.

The investigated reaction is:

$$\pi^- + Xe \to \pi^{\circ} + N_p + X, \qquad (1)$$

where N_p is the number of emitted protons, X stands for the rest of outgoing particles.

The invariant distribution function is defined as:

$$f(T,\theta) = \frac{E}{\sigma}\frac{d^3\sigma}{d^3p} = \frac{1}{2\pi\sigma p}\frac{d^2\sigma}{dT\,d\cos\theta}, \qquad (2)$$

where p, T and θ are π° momentum, kinetic energy and emission angle, respectively; σ is the cross section of considered reaction. For each selected reaction and given angular interval the distributions were approximated by the exponential function, or by the sum of two exponents in the form:

$$f(T) = f_1(T) + f_2(T) = A_1\exp(-T/T_{0_1}) + A_2\exp(-T/T_{0_2}), \qquad (3)$$

where A_1, A_2, T_{0_1}, T_{0_2} are fitted parameters. The values of T_{0_1}, T_{0_2} characterize the average kinetic energy of emitted pions and are often considered as a temperature of nuclear matter at the moment of pion emission. Although this parametrization implies the thermal concept and we call these parameters - "temperature", it is introduced as a convenient way to describe the form of experimental spectra, and to reveal their main peculiarities.

Table 1 presents the results of approximations for different selected reactions. The examples of some distributions are shown in Fig. 1 and Fig. 2. Strong dependence of fitted temperatures upon the number of emitted protons and upon the angle of pion emission is observed. This dependence is displayed in Fig. 3 where the results are collected for comparison. In all the cases (with the exception of one distribution) two exponents are necessary to obtain reasonable χ^2 values. The fitted temperatures are well separated and their values decrease with increasing N_p number and with the growth of pion emission angle. Strongest dependence occurs for smallest angles of pion emission. The dependence upon N_p is nonlinear and their character differs in different angular intervals. The detailed discussion of these dependences will be performed in the next section.

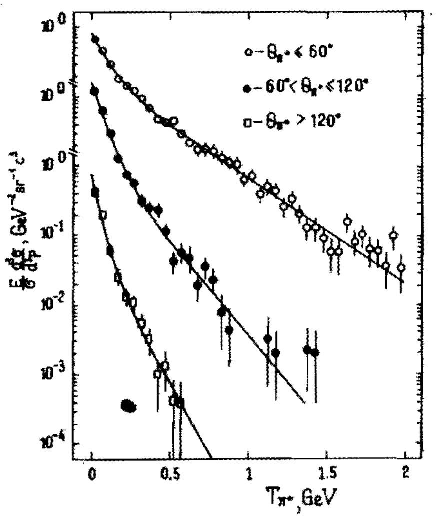

Fig. 1. Inclusive spectra of neutral pions for different angular intervals in laboratory reference frame. The curves represent results of approximations with the formula (3).

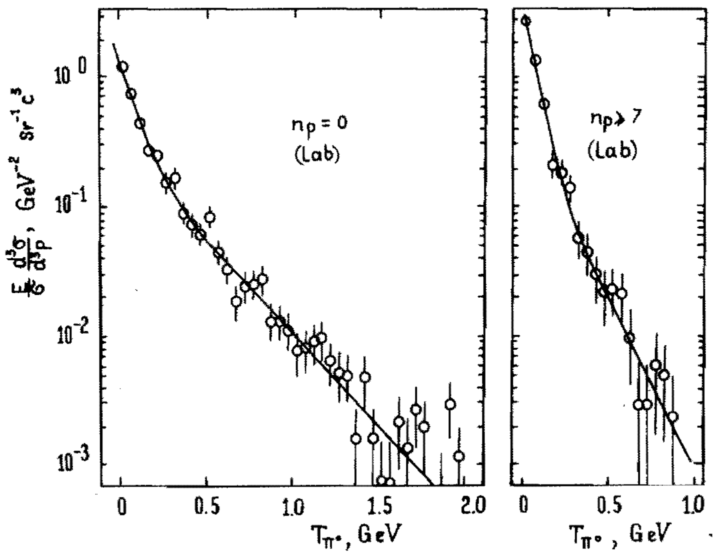

Fig. 2. Two examples of pion inclusive spectra for smallest and greatest numbers of emitted protons. The curves show the results of approximations with the formula (3). (lab) - laboratory reference frame.

Table 1

Statistical data and results of approximations of inclusive pion spectra in laboratory reference frame.

N_p	Number of events	T_{0_1}, MeV	T_{0_2}, MeV	χ^2/ND
0	1309	302 ± 17	85 ± 13	37.4/35
1	1119	270 ± 16	72 ± 8	30.9/35
2÷3	1634	233 ± 11	63 ± 6	30.4/34
4÷6	1553	199 ± 12	57 ± 5	26.1/25
≥ 7	686	167 ± 31	54 ± 8	12.6/16
≥ 0	6301	261 ± 7	66 ± 3	49.7/36

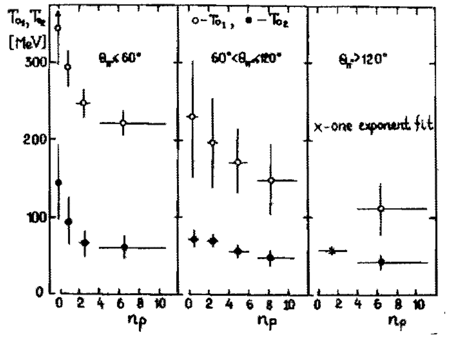

Fig. 3. The temperatures, fitted with the formula (3), for different numbers of emitted protons and different angular intervals in the laboratory reference frame.

4. INCLUSIVE DISTRIBUTIONS IN THE MOVING SYSTEM

The observed features of pion inclusive spectra seem to be rather complicated and, at first sight - unclear - like epicycles created by Ptolemy. Following Copernicus, let us look for a more suitable reference frame.

It was pointed out by T.Siemiarczuk/10/ that the reference frame of projectile hadron - target nucleon "moves too fast" when considering hadron nucleus collisions. System of symmetric pion emission was proposed instead /10,11/ . Similar approach was used by J.Bartke et al. for nucleus-nucleus collisions /12/ .

We have investigated the rapidity and angular distributions of π^0 mesons depending on the number of emitted protons[13]. Some conclusions will be useful for the purpose of present analysis.

1. It was shown that rapidity and angular distributions of neutral pions depend much on the number of fast protons emitted N_p.

2. For given number of emitted protons the reference frame can be defined in which the angular and rapidity π^0 distributions show forward-backward symmetry. We denote this system - (sym).

3. For smallest N_p number the velocity of this system in laboratory corresponds to the velocity of the cms system of incident pion and target nucleon. With increasing N_p, the velocity of this moving system decreases systematically approaching values close to zero, that corresponds to symmetrical pion emission in the laboratory frame.

The above observations are consistent with the assumption that pions are emitted from the systems moving in the laboratiry with the velocities depending on the number of emitted protons or, in other words, on the nuclear matter involvement in the interaction process. Considering this assumption as a working hypothesis we transformed the longitudinal pion momenta to the systems moving in laboratory with the velocities defined as:

$$\beta_s = \tanh(\langle y \rangle_{N_p}), \qquad (4)$$

where $\langle y \rangle_{N_p}$ is the mean value of neutral pion rapidity for given number of emitted protons.

The β_s values, computed according to the formula (4), are plotted in Fig. 4. The extend of these values covers full range of possible velocities, from the cms system velocity of incident pion and target nucleon and down to zero, that corresponds to laboratory frame.

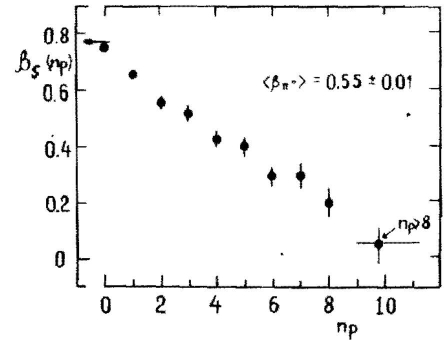

Fig. 4. Dependence of the pion source velocity on the number of emitted protons. The arrow indicates the cms system velocity of incident pion - target nucleon.

Table 2

Results of approximations of inclusive pion spectra in the moving system

N_p	T_{0_1}, MeV	T_{0_2}, MeV	χ^2/ND
0	155 ± 5	7 ± 4	23.7/23
1	175 ± 16	65 ± 17	20.7/21
2÷3	161 ± 15	75 ± 15	27.1/26
4÷6	160 ± 13	56 ± 8	26.5/20
≥ 7	164 ± 29	53 ± 9	4.7/15
≥ 0	164 ± 5	61 ± 6	28.5/29

After performing transformations we repeated the procedure applied for pion inclusive distributions in laboratory system. The distributions were again approximated with the formula (3). Table 2 contains the results of approximations performed for different numbers N_p. These results can be directly compared with those in Table 1. In Fig. 5 these results are plotted together for comparison. After the transformation we obtain also two, well separated temperatures, but their values do not depend on the number of emitted protons (with the exception of one point for $N_p = 0$). Figure 6 shows similar comparison for different angular intervals. Strong dependence, seen in laboratory system, vanishes after transformation. Slight opposite tendency is even seen for lower temperature.

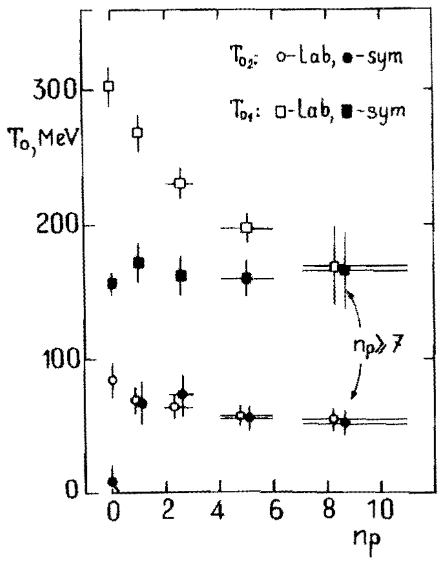

Fig. 5. Dependence of the fitted temperatures on the number of emitted protons for two different reference frames. (lab) - laboratory reference frame, (sym) - moving system of symmetric pion emission.

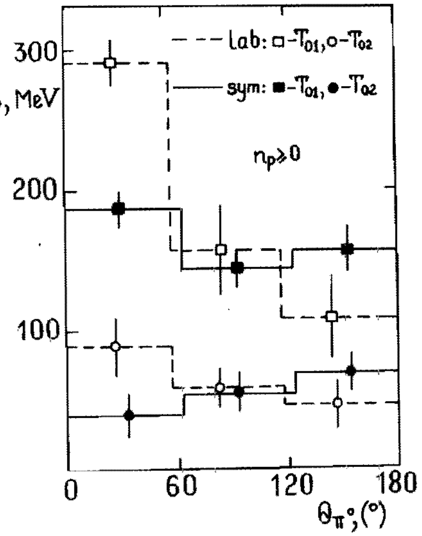

Fig. 6. The values of fitted temperatures for three different pion angular intervals. (lab) - laboratory ref. frame, (sym) - system of symmetric pion emission.

To shed some light on the properties of π^0 distributions after transformation we compared the shapes of pion spectra corresponding to smallest and greatest N_p numbers (Fig. 7). The slope of both distributions, giving the values of higher temperature, equals each other. For $N_p = 0$ does not exist practically the lower temperature component however. (One point located highest gives the value of very low temperature, as it is seen in Fig. 5). The question arises therefore: how much is the fraction of lower temperature component in the total inclusive cross section and how does it depend on the number of emitted protons. This fraction can be computed as:

$$R = \frac{\int E^{-1} f_2(T)\, d^3p}{\int E^{-1} f(T)\, d^3p}, \tag{5}$$

where $f_2(T)$ corresponds to the lower temperature component of the fitted function. In Fig. 8 this fraction is plotted in dependence on the number N_p. Systematicall growth is seen with the increase of the number of emitted protons.

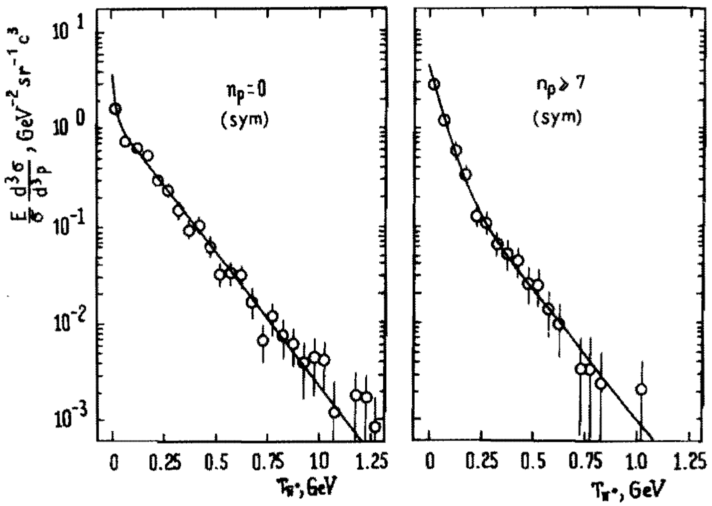

Fig. 7. Two examples of pion inclusive spectra for smallest and greatest numbers of emitted protons. The curves show the results of approximations with the formula (3). (sym) - system of symmetric pion emission.

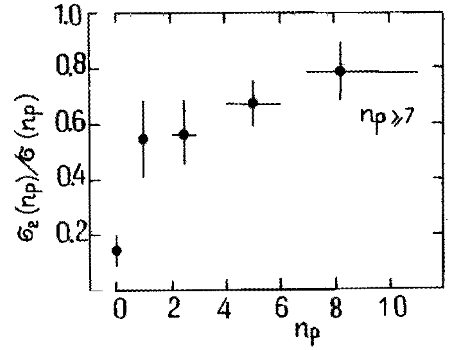

Fig. 8. The fraction of lower temperature component in the total inclusive cross section for the reactions with different numbers of emitted protons.

5. NONINVARIANT INCLUSIVE DISTRIBUTIONS

It was pointed out[1] that thermodynamical models[14,15] predict the exponential slope of noninvariant inclusive distributions. As we have mentioned above, we use the exponential parametrization as a convenient method to describe our experimental spectra. By obtaining good fits for invariant inclusive distribution we can, in principle, visualize the deviations from characteristic thermalized pion emission.

We have obtained good fits with two-exponential formula and reveal some regularities in the invariant pion distributions. The same procedure was applied then for noninvariant spectra of neutral pions. It turns out that the same dependencies are seen in this case as well. Main results are given in Table 3. The temperatures listed there correspond to

Table 3

Results of approximations with the formula (3) of noninvariant pion spectra in the moving system for different numbers of emitted protons and in different pion angular intervals

π^0 angular interval	T_{0_1}, MeV	T_{0_2}, MeV	χ^2/ND
$0^\circ < \theta < 60^\circ$	149 ± 6	46 ± 7	28.2/27
$60^\circ < \theta < 120^\circ$	117 ± 5	48 ± 5	14.6/20
$120^\circ < \theta < 180^\circ$	127 ± 10	55 ± 5	18.6/19
N_p	T_{0_1}, MeV	T_{0_2}, MeV	χ^2/ND
0	142 ± 16	75 ± 14	25.1/21
1	143 ± 11	57 ± 5	21.6/21
2÷3	130 ± 8	57 ± 5	25.1/23
4÷6	128 ± 8	47 ± 4	25.2/21
≥ 7	128 ± 16	43 ± 5	4.2/15
≥ 0	135 ± 4	52 ± 3	29.6/29

the moving systems is described by the formula (4). Two temperatures are necessary as well but their values are systematically less than in the case of invariant distributions. Obtained χ^2 values show sufficiently good quality of approximations and the temperatures are distinctly separated. The attempt to fit these distributions with one exponent function does not give reasonable results. It can be seen from Table 3 that there is no significant dependence of the fitted temperatures upon the

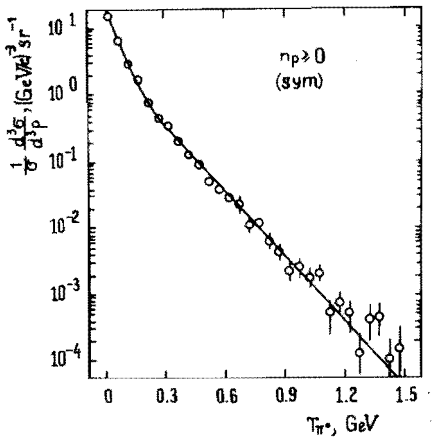

Fig. 9. The total noninvariant pion distribution in the moving reference frame.

number of emitted pions. The total noninvariant distribution is shown in Fig. 9. Corresponding values of fitted temperatures are listed in the last row of Table 3.

6. CONCLUSIONS

In this paper we continue our investigations of neutral pion characteristics with the aim to find the main properties of hot nuclear matter the fast particles are ejected from. Using the number of emitted protons as an indicator of impact parameter we select the collisions with different nuclear involvement into the interaction process. We have found that the characteristics of neutral pions depend strongly on the number of emitted protons. The majority of π^0 characteristics become similar when presenting them in the reference frame moving with the velocity depending on the number N_p. This approach resembles the moving source model, often used in the experimental data analysis. The results of this work are similar to those obtained by K.Nakai and co-workers in the frame of two moving source model [16]. There are some differencies however between the standard method of data analysis and the approach applied here. We defined the velocity of moving system using the property of rapidity variable only. The characteristics of angular and momentum distributions after the transformation, their shapes, symmetry properties and others are not imposed by the method of presentation and reflect the characteristic features of emitting systems.

It turns out that two types of sources can be distinguished. One of them, with the temperature about 135 MeV appears in peripheral collisions but its yield diminishes when the nuclear involvement increases. The second one, with the temperature about 50 MeV, seems to reflect the degree of nuclear matter excitation. Its yield growth when impact parameter decreases. The temperature of this source is close to that obtained for protons earlier [17].

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Плюта Я. и др. E1-88-450
Возбуждение ядерной материи в пион-ксенон столкновениях при 3,5 ГэВ/с. Инклюзивные спектры нейтральных пионов

Проанализированы инклюзивные спектры нейтральных пионов в π^-Xe-взаимодействиях при 3,5 ГэВ/с с целью получения данных о передаче ядру энергии налетающей частицы и возбуждение ядерной материи для разных значений параметра столкновения. Результаты показали, что можно выделить два типа источников вторичных пионов. Первый, с температурой около 135 МэВ, преобладает в периферических столкновениях, но его эффективность снижается с уменьшением параметра столкновения. Второй источник, с температурой около 50 МэВ, доминирует в центральных столкновениях.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Pluta J. et al. E1-88-450
Nuclear Matter Excitation in Pion-Xenon Collisions at 3.5 GeV/c. Inclusive Spectra of Neutral Pions

Inclusive spectra of neutral pions have been analysed in π^--Xe collisions at 3.5 GeV/c in order to obtain data on incident particle energy deposition and nuclear matter excitation at a given value of impact parameter. The results show that two types of pion sources can be distinguished. The first source, with the temperature about 135 MeV, prevails in peripheral collisions but its yield diminishes when the impact parameter decreases. The second one, with the temperature about 50 MeV, dominates in central collisions.

The investigation has been performed at the Laboratory of High Energies, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1988