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PROTON MULTIPLICITY DISTRIBUTIONS IN PION-XENON NUCLEUS COLLISIONS AT 3.5 GeV/c

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1. INTRODUCTION

We have already reported that there exist high energy pion-nucleus collision events in which the multiparticle creation act does not accompany intensive emission of nucleons [1,2]. The emitted nucleons are of kinetic energies from nearly 20 to nearly 400 MeV, as we may conclude from the energy spectra of protons observed in experiments. We call "fast" these nucleons later on.

So far we know that various characteristics of fast nucleons following from the accurate investigation of such collision events can contain important information for a more deep understanding how the high energy hadron penetrates the nuclear matter, and how the nucleon emission is going on [2], in more detail experimental studies of the nucleon emission were undertaken by us. We have studied in fact various characteristics of the observed in our experiment fast protons only [2-4]. From these investigations we have concluded that the distribution of the hadron-nucleus collision events versus the nucleon emission intensity is the characteristic of fundamental importance which gives us a clue as to the direction in which we should try to understand the fast nucleon emission process. Therefore, more accurate investigations of the proton multiplicity distributions have been performed.

In this paper we present our experimental data. We give the qualitative and quantitative interpretation of these data. By doing it, we intend to obtain some picture of the nucleon emission process in the hadron-nucleus collisions.

2. EXPERIMENT

The hadron-nucleus collision events used for this analysis were registered in the 180 litre xenon bubble chamber [5]. This chamber is built as the rectangular parallelepiped of nearly 100 x 40 x 40 cm^3 volume, without magnetic field.

2.1. Beam and Exposure

The chamber was exposed to negative charged pion beam of 3.5 GeV/c momentum. During the exposure time no more than five pions were introduced into the chamber, along its length perpendicular to the front wall. The beam pion tracks were parallel and widely spaced within a distance limits of a few centimeters from the chamber axis. Such exposure conditions were of great convenience in studying the pion-xenon nucleus collision events, as we will see later.

2.2. Scanning and Measurements

The photographs of the chamber were carefully scanned and rescanned for the pion-xenon nucleus collision events which could occur in a chosen parallelepipedal region of nearly $42 \times 10 \times 10\ cm^3$ volume situated coaxially and centred inside the chamber.

Any sharp change in the straight line track of any beam pion was considered as an indication that this pion undergoes the interaction with the xenon nucleus. The end or deflection point of any beam pion track we accepted to be the pion-xenon nucleus interaction location. In fact we were able to detect the collision events in which the beam pion track ends off or deflects at an angle of no less than 2 degrees, in accompaniment or not by any number of tracks outgoing from the interaction place.

The secondary neutral pions of any kinetic energy, including zero, are recorded and identified in our chamber by the simply visible tracks of the negaton-positon conversion pairs and by the observed electron-photon showers created by the gamma quanta appearing in the neutral pion decay process. The minimal energy of the gamma quanta detected with the constant probability amounts nearly 5 MeV. The positive pions stopped within the chamber are identified simply by the characteristic track sequence left by the charged secondaries emerged in the decay process. We have some difficulties in attempts to identify the negative pions stopping inside the chamber and to distinct them from the stopping protons. But, we estimate, as we will see later, the contamination of the tracks of such pions in the sample of tracks accepted as being left by the stopping protons. Stopping kaons are identified without difficulties as well. Similarly we can identify hyperons, if they decay inside the chamber. The neutrons which are emitted in the collision process interact with the xenon nuclei frequently leaving characteristic "neutral stars".

Tracks of the lengths larger than nearly 5 mm are visible well and detectable with the constant efficiency which is close to 100%. To this minimal length corresponds the minimal kinetic energy of the registered protons of 20 MeV and of the registered charged pions of 15 MeV. The tracks of smaller lengths are visible as well but in this case the detection probability is not constant. The protons of kinetic energies from nearly 15 up to nearly 220 MeV, the secondary pions: the negative charged of kinetic energies from nearly 10 up to nearly 150 MeV, positive charged of kinetic energies from 0 up to nearly 150 MeV, and the neutral pions of any kinetic energy, including zero MeV, are recorded with the registration efficiency being near to 100% within the total 4π solid angle. For example, the registration probability of any neutral pion equals to 0.9999... . The kinetic energy of protons emitted within the 60 degree cone and stopping inside the chamber is nearly 350 MeV.

The scanning effeciency for all pion-xenon nucleus collision events registered in our experiment were better than 99.5%. In nearly 9% of the registered events the tracks of stopped negative charged pions were indistinguishable from those of the proton tracks; it amounts roughly 3% of all the proton tracks. This estimation follows from the analysis based on the experimental data from the studies of nuclear collisions in nuclear emulsions exposed to the negative pion beam[6]. The contamination of the deuteron, triton, and alpha particle tracks in the sample of all the tracks considered to be left by protons was estimated to be no larger than 10%. But, in the majority of cases, the tracks of such heavy particles are shorter than 5 mm and were not taken into account in this experiment. We analyse the emission of protons of energies larger than 20 MeV.

The accuracy of the proton energy measurement, using the range-energy relation, was 10% for the protons of 15 MeV kinetic energy and 1% for those of 200 MeV [7]. The proton emission angles were measured with an accuracy of 1-8 degrees. In most cases the average accuracy of the proton energy measurement is nearly 4% and that of the emission angle estimation nearly 3 degrees. The accuracy of the charged pion energy estimation by this method is almost the same. The accuracy of the neutral pion energy estimation[8] amounts nearly, in average, 12%. The accuracy of the pion emission angle estimation, for the charged and neutral pions, is nearly 1 degree.

We have estimated that roughly 90% of all emitted protons are stopping inside the chamber.

3. EXPERIMENTAL DATA

A sample of 2800 pion-xenon nucleus collision events with any number of secondaries were selected in scanning of 20000 chamber photographs. From among these events 286 with one secondary charged pion, 78 with one secondary neutral pion, and 35 events without any secondary pion were found in which any number of fast protons stopping inside the chamber without any interaction is emitted. These 399 events may be considered as such pion-xenon nucleus collisions in which intensive emission of fast nucleons is not accompanied by the multiparticle creation act [2]. In these three groups of events 1146 fast protons were found: 214 protons in the zero secondary pion events, 749 in one charged secondary pion events, and 183 protons in one neutral secondary pion events.

The proton multiplicity distribution of the 399 events is shown in fig. 1. This distribution appears to be inmonotonous - irregularity is seen at proton multiplicity $n_p = 6$. Two

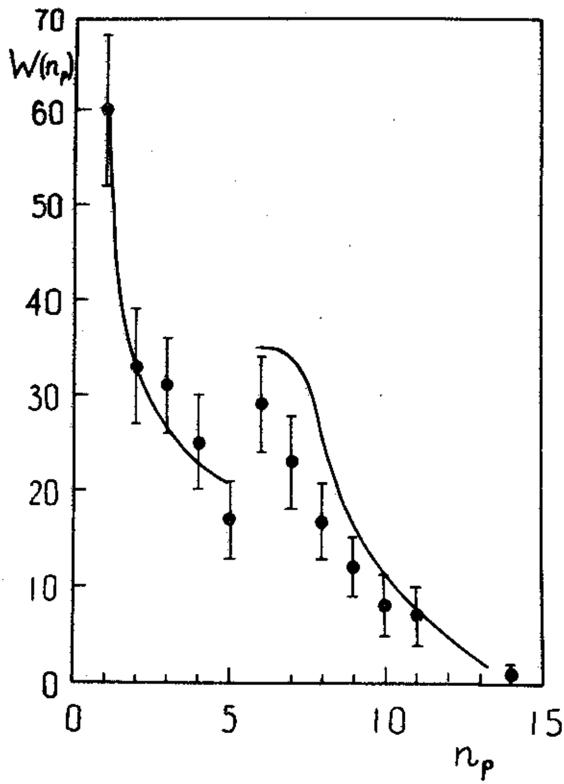

Fig. 1. Distribution of fast proton multiplicities in pion-xenon nucleus collision events at 3.5 GeV/c momentum not accompanied by the multiparticle creation act. For comparison the distribution predicted by formula (2) is drawn by the solid line. Normalization is performed to the value at $n_p = 1$.

Table 1.

Proton multiplicity distributions in the pion-xenon nucleus collision events at 3.5 GeV/c momentum in which any number n_p of emitted protons is accompanied by one secondary charged pion deflected through different angles θ_π°.

n_p	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–150	150–180
0	91	14	3	0	0	0	0	0	0	0	0
1	18	15	0	4	1	2	0	2	0	2	0
2	7	7	1	2	2	2	1	1	0	2	0
3	2	5	1	2	0	2	0	0	4	4	0
4	4	2	1	5	1	0	1	2	0	1	0
5	0	2	1	2	1	1	1	1	1	1	0
6	1	4	0	7	1	2	5	0	0	4	0
7	0	0	2	0	0	1	4	1	3	2	0
8	0	0	0	1	1	3	0	0	0	0	0
9	0	1	0	1	2	0	0	1	0	2	0
10	0	0	1	0	2	0	0	0	1	2	0
11	0	0	1	1	1	2	0	0	0	0	0
≥12	0	0	0	0	0	0	0	0	0	0	0

different smooth parts in this distribution may be distinguished, at first sight; one within the n_p value limits 0-5 and the second one at n_p larger than 6. The χ^2 - test shows that in fact this distribution fits to two separate smooth curves which correspond to the proton multiplicity values: from 0 to 5 and from 6 to 14. But, this distribution differs from the one smooth curve on the level of confidence $P(\chi^2_{14} \geq 18) \leq$ ≤ 0.20. Then, we have impressive experimental indication that inmonotony exists in the proton multiplicity distribution of the pion-xenon nucleus collision events without multiparticle creation acts.

It is of great importance, therefore, to see how is this proton miltiplicity distribution changing in dependence on the pion deflection angle θ_π . In order to show this, we have prepared the table 1 in which the 286 events with one charged secondary pion are distributed versus the proton multiplicities in classes of events with different value intervals of θ_π : 0-10°, 10-20°, ... , 80-90°, 90-150°, and 150-180°. We see that the irregularity in the proton multiplicity distribution disappears at smaller deflection angles $\theta_\pi \lesssim 30$ degrees.

Table 2.

Proton multiplicity distributions in the pion-xenon nucleus collision events at 3.5 GeV/c momentum without miltiparticle creation acts and with any number n_p of emitted fast protons and one or zero secondary pions.

n_p	Secondary pions			
	0π	$1\pi^0$	$1\pi^-$	$(0+1)\pi$
0	0	29 ± 5	108 ± 10	137 ± 12
1	5 ± 2	11 ± 3	44 ± 6	60 ± 8
2	0	8 ± 3	25 ± 5	33 ± 6
3	3 ± 2	8 ± 3	20 ± 4	31 ± 5
4	4 ± 2	4 ± 2	17 ± 4	25 ± 5
5	2 ± 1	4 ± 2	11 ± 3	17 ± 4
6	3 ± 2	3 ± 2	24 ± 5	29 ± 5
7	3 ± 2	5 ± 2	14 ± 4	23 ± 5
8	9 ± 3	2 ± 1	5 ± 3	16 ± 4
9	2 ± 1	3 ± 2	7 ± 3	12 ± 3
10	2 ± 1	0	6 ± 2	8 ± 3
11	1 ± 1	1 ± 1	5 ± 2	7 ± 3
12	0	0	0	0
13	0	0	0	0
14	1 ± 1	0	1 ± 1	1 ± 1
15	0	0	0	0

In table 2 the proton multiplicity distributions: of 35 events without any secondary pion, 78 events with one neutral pion, 286 events with one secondary charged pion, and 399 events without secondary pion and with one secondary pion together are presented.

Table 3 contains the proton multiplicity distributions in the sample of all the 2800 pion-xenon nucleus collisions and separately in the sample of 2401 events singled out by subtraction the 399 events without multiparticle production acts from the total sample of collisions registered in experiment. We see that the resulting sample of events does not contain practically such collisions in which more than $n_p = 8$ protons are emitted, the contamination being smaller than 1%. We have singled out in scanning only such collisions without multiparticle creation act in which emitted protons do not interact, we are prone therefore to think this contamination to be far and away smaller, being nearly zero.

All these above presented distributions we shall discuss in more detail in the next section.

4. DISCUSSION AND RESULTS

We shall try now to give an explanation of the above presented experimental information.

In order to elucidate the properties of the proton multiplicity distributions in various classes of the hadron-nucleus collision events a simple working hypothesis has been sug-

Table 3.

Proton multiplicity n_p distributions in the pion-xenon nucleus collision events at 3.5 GeV/c momentum in different classes of collisions.

n_p	Total sample of collision events	Collision events without multiparticle creation	Collision events with multiparticle creation
0	687 ± 26	137 ± 12	550 ± 24
1	517 ∓ 23	60 ∓ 8	457 ∓ 21
2	411 ∓ 20	33 ∓ 6	378 ∓ 19
3	310 ∓ 18	31 ∓ 5	279 ∓ 17
4	257 ∓ 16	25 ∓ 5	232 ∓ 15
5	217 ∓ 15	17 ∓ 4	200 ∓ 14
6	175 ∓ 13	29 ∓ 5	146 ∓ 12
7	94 ∓ 10	23 ∓ 5	71 ∓ 8
8	76 ∓ 9	16 ∓ 4	60 ∓ 8
9	29 ∓ 6	12 ∓ 3	≤17 ∓ 5
10	12 ∓ 4	8 ∓ 3	≤ 4 ∓ 2
11	12 ∓ 4	7 ± 3	≤ 5 ∓ 2
12	1 ± 1	0	≤ 1 ∓ 1
13	0	0	0
14	1 ± 1	1 ± 1	0
15	0	0	0

gested [3,9,10]. We rewrite this hypothesis here: high energy hadron traversing the target-nucleus causes the monotonous emission of the fast protons in numbers n_p being equal to the numbers of protons met in the neighbourhood to its path inside this nucleus:

$$n_p = \pi \cdot D_0^2 \cdot \frac{Z}{A} \cdot \bar{\rho} \cdot \lambda \doteq 2\pi \cdot D_0^2 \cdot \frac{Z}{A} \cdot \bar{\rho} \sqrt{R^2 - d^2}, \qquad (1)$$

where D_0 denotes the nucleon diameter; Z, the atomic number; A, the mass number; $\bar{\rho}$, the average nucleon density along the hadron path λ inside the target-nucleus; R, the radius of the target-nucleus; d, the impact parameter - the distance of the hadron path from the target-nucleus center.

If the incident hadron traverses the target nucleus along its diameter, we have for the xenon nucleus: $n_p = 8$, according to formula (1). In calculation we have used $Z = 54$, $A = 131$, $D_0 = 1$, used as length unit, $d = 0$, $\bar{\rho} = 1$, and $R = \sqrt[3]{\frac{A3}{4\pi}} = 3.2D_0$. Therefore, the appearing excess of the number of emitted fast protons at $n_p = 8$ in the sample of events without any secondary pion, table 2, might be considered as the result of the hadron absorption in traversing by it the nuclear matter thickness being just equal to the xenon target-nucleus diameter.

Simple formula has been derived for the proton multiplicity distribution $W(n)$ of the hadron-nucleus collision events [3,10], applying this working hypothesis and accepting that: a) high energy hadron-nucleon collisions inside target-nucleus may occur in which fast recoil nucleons appear being able in ones turn to cause the monotonous nucleon emission in traversing target-nuclei; b) the multiparticle creation acts go on via some intermediate states which decay after having left the target-nuclei; c) the intermediate states behave just as usual hadrons do in traversing nuclear matter. We rewrite this formula here:

$$W(n) = W_0(n)\, e^{-\mu_s \cdot \lambda(n) \cdot \bar{\rho}(n)} +$$

$$+ \sum_{i=1}^{i=E(\frac{n-1}{2})} k\{(n-i) \to n\} W_0(n-i)[1 - e^{-\mu_s \lambda(n-i)\bar{\rho}(n-i)}] \times \qquad (2)$$

$$\times [1 - e^{-\mu_s [n-2i] \Delta\lambda(n-i) \cdot \bar{\rho}(n-i)}]\, e^{-\mu_s \cdot i \Delta\lambda(n-i) \bar{\rho}(n-i)},$$

where $W_0(n)$ is the function defined by the target-nucleus geometry - by the nuclear radius R and the radial nucleon density distribution $\rho(r)$; μ_s denotes the attenuation coefficient which accounts the single hadron-nucleon scattering acts resulting in the appearance of the fast recoil nucleons; $\lambda(n)$ denotes the projectile hadron path inside the target nucleus on which n protons are met, according to formula (1); $\bar{\rho}(n)$ denotes the average nucleon density along the path $\lambda(n)$; $i = 1, 2, 3, \ldots, E(\frac{n-1}{2})$; $k\{(n-i) \to n\}$ denotes the coefficient accounting the probability that the recoil nucleon traverses appropriate part of the target-nucleus, causing the monotonous emission of i protons; $\Delta\lambda(n-i)$ denotes the piece of the path $\lambda(n-i)$ on which one proton should be monotonously emitted.

The first term in formula (2) gives the proton multiplicity distribution in the sample of events in which the monotonous nucleon emission takes place only. The second term accounts the disturbance of the monotonous emission process by the appearance of the fast recoil nucleons and expresses the contamination with such disturbed events of the total sample of the hadron-nucleus collisions.

We shall compare our experimental data with the predictions following from formula (2). We start with the comparison of the proton multiplicity distribution in the class of events without multiparticle creation acts; the attenuation coefficient μ_s should be estimated in this case using the experimental data at $W(1)$ and $W(2)$, and the corresponding values of $W_0(1)$ and $W_0(2)$. The result is presented in fig. 1. We pass now to the comparison of the proton multiplicity distribution of the all pion-xenon nucleus collision events predicted by formula (2) with the experimental one. This distribution was calculated taking into account appropriate registration and scanning conditions in our experiment - we do not find and select all the hadron-nucleus collision events without multiparticle creation acts. Therefore, we have calculated firstly the distribution $W(n)$ for the events with multiparticle creation acts, applying the corresponding attenuation coefficient μ_s evaluated from the experimental data at $W(1)$ and $W(2)$ in this class of events, and, similarly, we have calculated separately such distribution $W(n)$ for the events without multiparticle creation acts which are selected in our experiment. The distribution $W(n)$ which we compare with the experimental data is appropriate composition of both the distributions calculated separately for two different classes of events registered in experiment. The result is presented in fig. 2. In this figure the proton multiplicity distribution predicted by the intranuclear cascade model[11], in which the registration and scanning conditions in our experiment were taken into account, is superimposed too.

We have seen that the inmonotony in the proton multiplicity distribution of the events without multiparticle creation acts disappears at small deflection angles $\theta_{\pi} \lesssim 30$ degrees. We have mentioned too that the contamination by the events with the proton numbers n_p larger than $n = 8$, which corresponds to the number of protons met along the xenon target-nucleus diameter, is very small in the total number of events with the multiparticle creation acts, being less than 1%. Then, taking into account the physical meaning of both the terms in formula (2), we can compare the predictions of the first term in this formula with appropriate experimental data: a) with the experimental proton multiplicity distribution of the events without multiple particle productin and with $\theta \leq 30$ degrees, and

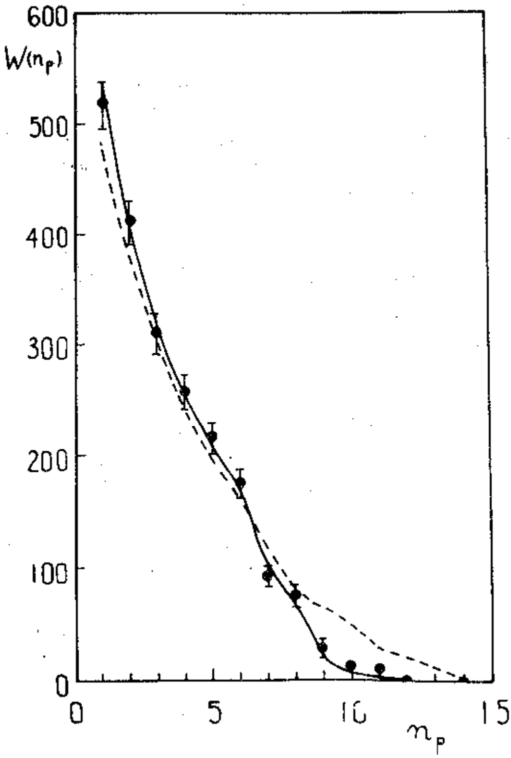

Fig. 2. Comparison of the fast proton multiplicity distribution of all pion-xenon nucleus collision events at 3.5 GeV/c momentum with the predicted distribution expressed by formula (2), and with the distribution predicted by the intranuclear cascade model, dotted line. Normalization is performed to the total number of the events recorded in experiment.

Table 4.

Comparison of the fast proton multiplicity distributions in various classes of pion-xenon nucleus collision events at 3.5 GeV/c momentum with appropriate distributions predicted by the first term of the formula (2).

n_p	Sample of events with single one secondary pion deflected through an angle $\vartheta_\pi \leq 30^\circ$		Sample of events with multiparticle creation acts	
	Experiment	Prediction	Experiment	Prediction
1	33 ± 6	33	457 ± 21	470
2	15 ± 4	18	378 ± 19	373
3	8 ± 3	10	279 ± 17	299
4	7 ± 3	6	232 ± 15	236
5	3 ± 2	3	200 ± 14	186
6	5 ± 2	2	146 ± 12	135
7	2 ± 1	1	71 ± 8	73
8	0	0	60 ± 8	48

b) with the experimental proton multiplicity distribution of the events with the multiparticle production and with the numbers of the emitted protons being equal to or less than 8. The results are shown in table 4.

From the results presented in table 4 and shown in fig. 2 we can conclude that formula (2) describes precisely appropriate experimental data. This formula gives too, well enough, the shape of the proton multiplicity distribution in the class of collision events without the multiparticle creation act, fig. 1. Therefore, we are able to think that the working hypothesis [3,10] used as the basis in derivation of formulas (1) and (2) corresponds to the reality. Then, we can conclude that the fast proton emission accompanies monotonously the high energy pion by its passage through nuclear matter; the number of ejected protons equals the number of the protons met along the pion path.

Within the frames of such picture of the fast nucleon emission process in hadron-nucleus collisions it seams to be clear the appearence of the hadron-nucleus collisions in which intensive proton emission goes on without accompaniment of the multiparticle creation acts [1,2].

The emitted protons are of the average kinetic energy being nearly 80 MeV[1,2]. We may accept that the emitted neutrons which are not observed in our experiment are of the same kinetic energies. Therefore, it must be concluded that high energy pion traversing the nuclear matter undergoes the monotonous energy loss, like any charged particle by its passing through materials[3]. Obviously, this energy loss process differs in its nature from the electromagnetic one, being caused by the nuclear interactions.

We postulate that such monotonous nucleon emission accompanies any high energy hadron by its passage through atomic nucleus. This emission is connected with monotonous energy losses of the hadron. Such postulate has been suggested too in our other papers[3,10].

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