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EXPERIMENTAL STUDY OF THE PION-XENON NUCLEUS COLLISIONS WITHOUT PARTICLE PRODUCTION AT 3.5 GeV/c MOMENTUM:

Physical Meaning of the Proton Multiplicity Distribution

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1. INTRODUCTION

It was communicated, more than ten years ago, that we have observed such collisions of pions with xenon nuclei, at 3.5 GeV/c momentum, in which "fast" protons - with kinetic energy from about 20 to about 400 MeV - are intensively emitted without produced particle ejection [1]. Such collision events were studied later in details in our experiments and the results were described in the series of papers [2-5]. Two classes of such events can be distinguished: a) The class of events in which none of secondary pions is emerged, the incident pion is absorbed in the target nucleus, and the absorption is accompanied by fast nucleon emission; we called such events the "stopped" ones. b) The class of events in which the incident pion underwent a deflection only in its passage through the target nucleus, accompanied by fast nucleon emission; we called such events the "deflected" ones. The distribution of the multiplicities of the fast protons emitted in the stopped events differs by much from the distribution in the deflected events, which shape is rather similar to the distribution in the sample of events with ejection of the produced particles at 3.5 GeV/c momentum [6].

The subject matter in this paper is to put on record results of our investigations of a physical meaning of the observed proton multiplicity distribution in the class of the stopped events, and to present our interpretation of this distribution.

This work is arranged as follows: after the short introduction, in section 1, experimental procedure applied in selection of the stopped events is described in section 2; in section 3 - experimental material is presented; in section 4 an analysis of the experimental data is described; section 5 closes the paper with short conclusions and remarks.

2. EXPERIMENTAL PROCEDURE

The stopped and the deflected collision events were discovered at first and studied later on using the 180 litre xenon bubble chamber [7] of the Institute of Theoretical and Experimental Physics in Moscow; the chamber was exposed to negatively charged pion beams at 3.5 GeV/c momentum.

The characteristics of the xenon bubble chamber and detailed information about the experimental procedure can be found in our previous works [1,8,9] and it was not found necessary to repeat it here; we limit ourselves here to the presentation of the most important information, therefore.

Tracks of the length larger than nearly 5 mm are visible well and detectable with the constant efficiency which is close to 100%. To this minimum length there corresponds the minimum kinetic energy of the registered protons of nearly 20 MeV and of the registered charged pions of nearly 10 MeV. Shorter tracks are visible as well, but in this case the detection efficiency is not constant. The emitted protons with kinetic energies from nearly 20 up to nearly 200 MeV, the secondary pions; the negatively charged with kinetic energy from nearly 10 up to nearly 100 MeV, positively charged with the energy from 0 up to 100 MeV, and the neutral pions with any kinetic energy over 0 MeV, including 0 MeV, are recorded and identified with the efficiency near to 100% within the total solid angle 4π ; the kinetic energy of the protons emitted forward and backward from the center of the chamber within the 60 degree cone and stopping inside the chamber is no more than nearly 350 MeV.

We are able, therefore, to select pion-xenon nucleus collisions in which incident pion is absorbed without causing particle production, without ejection of the pions in particular. In fact, in the stopped events only pions absorbed inside the target nucleus may be produced, if any.

According to the scanning and selection criteria, the emitted fast protons stopped inside the chamber were recognized as particles leaving the characteristic straight tracks ended inside the chamber; any sharp change of a track - a sharp deflection or a branching at its end - was accepted as an indication that the track leaving particle could be not the proton. It was estimated that the number of fast protons emitted from points located near to the chamber center and having left the chamber or forming the deflected or branched tracks is no more than about 10% of the total number of the proton track registered. The rest of the tracks, qualified as the non-proton tracks are qualified as the tracks leaving by charged pions; the positively charged pions stopped inside the chamber are identifiable in it, because they decay into simply recognizable positrons, even if the kinetic energy of the positive pions equals 0. Neutral pions, eta and omega mesons decaying via neutral channels are detectable by registration of the gammas from the neutral pions decays and from radiative decays, with an efficiency near to 100%; the detection efficiency of a gamma quantum with energy above 5 MeV, emitted from the center of the chamber, is in average $\epsilon = 0.92$. Etas and omegas are rarely produced and, besides, their neutral decay channels are detectable more efficiently than the neutral pions are. Therefore, it will be sufficient to estimate the detection efficiency of the neutral

pions only. Let us do it. The average multiplicity of the registered gammas in any-type pion-xenon collision events at 3.5 GeV/c is 1.7 and it is almost independent of the multiplicity of the emitted fast protons. A neutral pion will be lost when the two of the two gammas from its decay convert outside the chamber. The events which can imitate the stopped ones are mainly those in which one neutral pion is produced in the reactions $Pi^- + p \to Pi^- + PiO + p$ or $Pi^- + n \to PiO + p$ in which the secondary negatively charged pion is unidentifiable and the neutral pion is not recorded in the chamber; in the rest of cases, when more than one neutral pion or when two, four or six charged pions are produced the events cannot be wrongly qualified as the stopped ones, because at least positively charged pions are always detectable. In the total sample of the pion-xenon collision events of any type - with particle production - the number N of events with $N_{PiO} = 1$ and $N_{Pi^\pm} = 0$ is N = 239. The number of the events of such a kind which can imitate the stopped ones is then: $N \cdot (1-\epsilon)^2 = 1.52$.

The second source of the events which may be recognized wrongly as the stopped ones is the production of the V-shape track leaving particles, mainly of the lambda particles and K mesons escaping the chamber. For estimation of the number of the false stopped events, let us apply the data on the V-particle production in 26 litre xenon bubble chamber [10]. In this chamber the registration probability of the lambda particles is 0.46 and of the K-mesons - 0.25; among the V-events the two-prong neutral stars are recognized as well. The probability of registration in the bigger chamber, in the 180 litre xenon bubble chamber, should be about 0.6 and 0.35 correspondingly for lambdas and K mesons. In the total sample of the events without ejected pions only 10 events with V-shaped tracks were found. Therefore, the number of "stopped" events in which in fact two V particles are produced and no one of them is registered is about 2. The charged strange particles are always distinguished from the emitted protons without difficulties.

Some number of direct tracks of the particles stopped within the chamber and recognized, according to the scanning and selection criteria, as the proton tracks, can be in fact tracks left by "slow" Pi^- mesons - with kinetic energies smaller than about 120 MeV. Such mesons may appear in result of the energy loss of the incident negatively charged pion in its passage through nuclear matter, in our case - when as projectile the negatively charged pions are used; production of such mesons should be accompanied by production of positively charged meson, mainly pion, which is detectable directly and simply when with kinetic energy higher than 0 MeV or equal to 0 MeV. Let us estimate now the number of the "wrong" protons due to the slowing down of the projectile pions; we use, in order to do it, the observed and measured in our experiment strong dependence of the kinetic energy of the deflected pion on its deflection angle, observed in charge-exchange type collision events with one neutral pion and any number of the emitted protons. Average energy of the neutral pions ejected through the angles larger than about 70 degrees is nearly 100 MeV, and about a half of the number of the mesons is with energy lower than 100 MeV. Approximately, the same situation should be when the negatively charged pions are deflected through the angles larger than about 70 degrees, due to the deceleration in nuclear matter. In our total experimental material, which the "stopped" events were singled out from, there are $N = 118$ events with one negatively charged secondary pion ejected through an angle larger than 70 degrees; let us accept that one half of the events are with pions with kinetic energy smaller than 120 MeV. The probability that these pions will form unobservable "stars", when stopping inside the chamber, is [11] 0.28. Therefore, the number of events in which the stopped Pi^- mesons are recognized wrongly as the protons is about 17.

Total number of "wrong" stopped events is 21. Predominantly, the wrong stopped events are due to the deceleration of the projectile pions.

Let us introduce corresponding corrections into the proton multiplicity distribution in the sample of the stopped events; we use additionally one experimentally stated, by us, property of the proton multiplicity distribution in the sample of the deflected events, when the projectile deflection angle is larger than 70 degrees: the proton multiplicity distribution in such sample of deflected events is similar to the distribution in the sample of the stopped events. It means, obviously, that the deflected events with large deflection angles are in fact the almost stopped events in which incident pion passed through the target nucleus near to its diameter. We should use, therefore, the proton multiplicity distribution in the sample of such deflected events for accounting of the corrections of the observed proton multiplicity distribution in the sample of events selected as the "stopped" ones.

3. EXPERIMENTAL MATERIAL

The observed proton multiplicity n_p distribution $N(n_p)$, in the sample of events recognized as the "stopped", is shown in fig.1; the proton multiplicity distribution in the sample of any-type pion-xenon nucleus collision events is shown on this fig.1 as well. Histogram represents the distribution of the proton multiplicity in the wrong "stopped" events. In fig.2, the proton multiplicity distribution $N(n_p)$ in the corrected sample

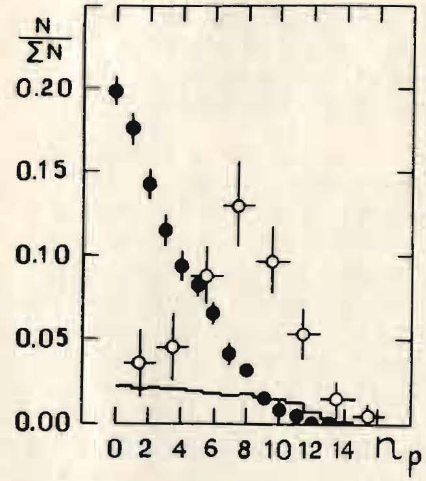


Fig.1. Proton multiplicity n_p distribution $N(n_p)$ in samples of pion-xenon nucleus collision events, at 3.5 GeV/c momentum: o – the stopped events from reactions $Pi^- + Xe \to n_p + f$, where $n_p = 0,1,2,\ldots$ are numbers of the emitted protons, f – nuclear fragments; total number of the stoppings is 95. • – any-type events from reactions $Pi^- + Xe \to n_p + x$, where x is any outcome with produced secondaries. Histogram – proton multiplicity distribution in the "wrong" stopped events, normalized to the total number of the wrong events.

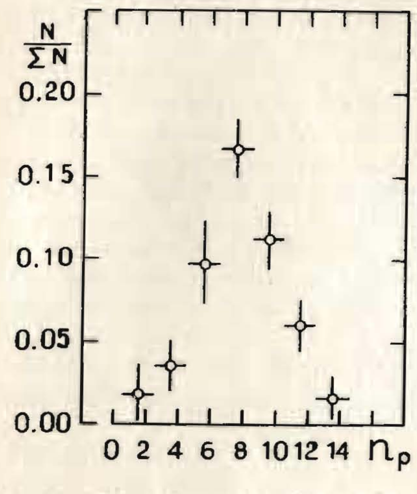
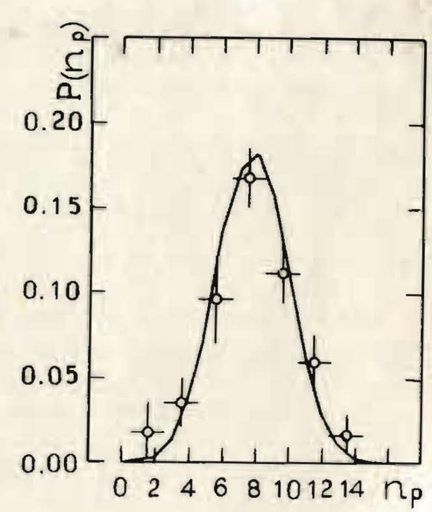


Fig.2. Proton multiplicity n_p distribution $N(n_p) = N/\Sigma N$ in the corrected sample of the stopped events.

Fig.3. The binomial distribution $P(n_p)$ expressed by formula (4) prepared at $n_N = 19$ and $p = Z/A = 0.412$. The experimental distribution from fig.2 is superimposed on the calculated one. Poligon represents the binomial distribution.



of the "stopped" events is shown. In figs.1-3, the multiplicity distribution $N(n_p)$ for the "stopped" events is shown when experimental data are groupped at the multiplicities $n_p=1$ and 2, 3 and 4,..., and presented at the mean value of $n_p = 1.5$, 3.5, 5.5,..., this presentation is performed for convenience, because the numbers of selected events are relatively small.

4. ANALYSIS OF THE PROTON MULTIPLICITY DISTRIBUTION IN THE SAMPLE OF THE "STOPPED" EVENTS

Let us start firstly with a very rough consideration. The stopping of the incident pion is accompanied by the fast nucleon emission; the intensity of this emission can be characterized by the multiplicity of the emitted nucleons n_N or by the multiplicity n_p of the emitted protons only. The symmetry of the experimentally obtained proton multiplicity distribution indicates that the stoppings of the incident pions occur almost along the diameter D of the target nucleus, and we would like to discover some relation between the number n_N of the nucleons met along the diameter inside cylindrical volume $\pi D_0^2 D$, centered on D, where D_0 is the nucleon diameter, and the observed multiplicity n_p of the emitted protons. From simple relation

$$A = \frac{4}{3}\pi\left(\frac{D}{2}\right)^3, \tag{1}$$

we have that D = 6.2, i.e., the diameter of the target nucleus expressed in the nucleon diameters D_0 is D = 6.3. Then, the number n_N of the nucleons met along the diameter is, for the xenon nucleus with A = 131 and Z = 54:

$$n_N = \pi D_0^2 D = \pi D = 20 \tag{2}$$

when D_0 is the length unit and $D = 6.3\,D_0$.

From the relation between the number of protons n_p and neutrons n_n at the periphery of the xenon nucleus [12]:

$$\frac{n_p}{n_n} \approx \frac{Z}{A-Z} \tag{3}$$

and from the regularity of the nucleon density distribution in the nucleus [13], it can be concluded in first approximation that relation (3) is valid for the atomic nucleus as a whole, at any distance r from the target nucleus center. Then, the probability p for the incident hadron to meet in any time moment a proton in passage through the nucleus is $p = Z/A = 0.412$.

Then, we can describe simply the probability $P(n_p)$ to meet anytime n_p protons along the target nucleus diameter D, by the binomial formula:

$$P(n_p) = \binom{n_N}{n_p} p^{n_p}(1-p)^{n_N-n_p}; \tag{4}$$

the maximum of the probability $P(n_p)$ lies at n_p from:

$$n_N p + p - 1 \le n_p \le n_N p + p. \tag{5}$$

Let us perform now a more accurate analysis of the proton multiplicity n_p distribution $N(n_p)$ in the sample of the stopped events. In order to do it, we use correct number of the nucleons met by incident hadron along the diameter of the xenon nucleus, determined in our previous work [14]. We obtained $n_N = 18.58 \approx 19$. At this value, when the probability p to meet a proton is $p = Z/A = 0.412$, formula (5) gives for n at which the maximum of the distribution $P(n_p)$ is located: $7.24 < n_p < 8.24$, what agrees well with corresponding values obtained in the experiment: $7 \le n_p \le 8$ and $\langle n_p\rangle = 7.4 \pm 0.3$; $E(n_p)_{n_N=19,\ p=0.412} = 7.8$.

In fig.3, binomial distribution $P(n_p)$ for $n_N = 19$ and $p = 0.412$ is superimposed on the experimentally obtained distribution $N(n_p)$ for the stopped events. χ^2- test shows that the distributions $N(n_p)$ and $P(n_p)$ are identical; $\chi^2 = 4.7$ at seven degrees of freedom. It should be emphasized that the distribution $P(n_p)$ is drawn on the experimental distribution $N(n_p)$ without any fitting procedure, it is just directly taken from formula (4) with the experimentally known probability $p = 0.412$ and $n_N = 19$.

We obtained the above presented facts which lead to a very important experimental finding: *The mean proton multiplicity* $\langle n_p\rangle$ *in the stopped events equals the mean number of protons met by the incident pion in its passage through nuclear matter inside the target nucleus; the experimentally obtained proton multiplicity distribution* $N(n_p)$ *in the sample of the stopped events is the same as the binomial distribution* $P(n_p)$ *given by formula (4), what means that the number of the emitted protons equals the number of the protons met along the path* $\ell = D$ *of the pion in nuclear matter within the volume* $\pi D_0^2 D$ *centered on* D.

Obviously, the stamement formulated above is true for the sample of the stopped events at least. But, we should consider it true for the deflected events as well. In fact, the mean proton multiplicity $\langle n_p\rangle$ in the deflected events, $\langle n_p\rangle = 3.2 \pm 0.3$, is equal to the mean thickness $\langle\lambda\rangle$ of the target nucleus measured in units of protons per $S = \pi D_0^2$; $\langle\lambda\rangle = 3.51$ protons/S has been evaluated in our work [14]. Moreover, the mean value $\langle n_p\rangle = 3.2 \pm 0.3$ observed experimentally is almost the same as the value $E(n_p) = 3.3$, evaluated for the binomial distribution $P(n_p)$, when this distribution is prepared for $p = Z/A$ and $n_N = \langle\lambda\rangle \frac{A}{Z} S \approx 8$ nucleons/S, where $\langle\lambda\rangle$ is in protons/S.

5. CONCLUSIONS AND REMARKS

We discussed nucleon emission process in the simplest sample of the pion-xenon nucleus collisions - when the projectile is absorbed inside the target nucleus accompanied by nucleon emission, but without causing ejection from the nucleus of any produced particles.

The preceding considerations were based on purely experimental facts. The distribution $P(n_p)$ was superimposed on the corresponding experimental distribution $N(n_p)$ without any fitting procedure. Direct comparison of parameters of the experimentally obtained proton multiplicity distributions in the samples of the stopped and deflected events with appropriate consequences from commonly known experimental information about the nucleon density distribution [13] in nuclei, and about the ratio between the proton number and neutron number along any path in nuclei [12], allowed to conclude that:

1. Simple and definite relation exists between the nucleon emission intensity, measured by nucleon multiplicity n_N of the emitted nucleons, and the thickness λ in nucleons per S of nuclear matter involved in a collision

$$n_N = \lambda \cdot S, \tag{6}$$

where $S = \pi D_0^2$ is in nucleons/S. In other words - pion, in traversing atomic nucleus, causes the observed emission of nucleons from the nucleus; the nucleon emission intensity measured by n_N is described by formula (6).

2. The stopped and the deflected events appear as a result of the projectile velocity decrease in passage through nuclear matter; when the layer of the nuclear matter is thick enough, the projectile may be completely absorbed on this thickness.

3. The appearance of both of the kinds of events - of the deflected and of the stopped - indicates that some part of the xenon nucleus, around the nuclear diameter, can absorb totally incident pion and the rest of the nucleus is too thin for the total absorption of the projectile, at 3.5 GeV/c momentum of the incident pion. Evident peak observed in the proton multiplicity distribution in the sample of the stopped events indicates that the central part is very narrow - just around the nuclear diameter; this conclusion is supported by the observed symmetry of this distribution relatively to the value of the proton multiplicity n_p equal about 8.

4. The existence of the stopped events may be treated as direct evidence that high energy pions undergo energy loss in their passage through nuclear matter; from formula (6), it follows that the energy loss proceeds monotonically along pion path in nuclear matter. The energy loss is accompanied by intensive emission of the nucleons from the target nucleus.

It should be emphasized that the energy loss may degradate remarkably the incident pion energy at energies smaller than a few GeV, what may lead to various observable phenomena [15].

Ending this section, we can conclude as well: The emission of the fast nucleons, of the fast protons in particular, in pion-xenon nucleus collisions is due to the energy loss of the pion inside the target nucleus; the emission process proceeds independently - whether the produced particles are ejected in the collision or not, and it is strictly predictable phenomenon [2-5]: we can determine which number of fast nucleons will be emitted when the collision impact parameter is given.

From other investigations, it follows that characteristics of the emitted protons - momenta and angles of emission of the protons - are the same for the stopped events and for any-type collision events.

It should be emphasized, as well, that the number n_N of the nucleons involved in a collision at a given impact parameter is always constant, independently of the protons observed.

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Стругальский З., Павляк Т., Плюта Я. E1-85-888

Экспериментальное исследование столкновений пион-ксенон при 3,5 ГэВ/с без рождения частиц: физический смысл распределения по множественности испущенных протонов

Изучалось распределение по множественности протонов в таких столкновениях пион-ксенон при 3,5 ГэВ/с, в которых налетающий пион полностью поглощается, а частицы не рождаются. Распределение симметрично по отношению множественности протонов $n_p = 7,4 \pm 0,3$. Оно точно описывается, без всякой подгонки, биномиальной формулой, на базе информации о размерах ядра-мишени и о распределении в нем нуклонов.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1985

Strugalski Z., Pawlak T., Pluta J. E1-85-888

Experimental Study of the Pion-Xenon Nucleus Collisions without Particle Production at 3.5 GeV/c Momentum: Physical Meaning of the Proton Multiplicity Distribution

Distribution of multiplicities of protons with kinetic energies from about 20 up to about 400 MeV emitted in pion-xenon nucleus collisions was studied in such events in which incident pion is totally absorbed within the target nucleus without causing ejection of any produced particles. The distribution is symmetrical relatively to the proton multiplicity $n_p = 7.4 \pm 0.3$. It is exactly described by binomial formula, without any fitting, on the basis of an information about the size of the target nucleus and nucleon density distribution in it. Discussion of the results and conclusions are presented.

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

Communication of the Joint Institute for Nuclear Research. Dubna 1985