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

Energy and Momentum Spectra of Emitted Protons

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1. INTRODUCTION

We have communicated in our papers [1,2] that pion-xenon nucleus collisions exist, at 3.5 GeV/c momentum, in which particles are not produced but the incident pion is deflected only from its original direction of motion or absorbed; intensive emission of nucleons, as we can conclude from the observed proton emission, accompanies the incident pion deflection or absorption. The emitted protons are "fast" - of kinetic energy from about 20 to about 400 MeV. This kind of collisions occurs frequently - on the average in 10.6±0.5% of any-type collision events in pion-xenon nucleus collisions at 3.5 GeV/c momentum.

In this paper, results obtained in experimental study of energy and momentum spectra of the "fast" protons in collision events without particle production are presented.

What we can learn from the spectra of protons emitted in such special type of collision events? We expect that any information about these spectra can throw light on the mechanism of the nucleon emission process which we do not understand yet. A connection between the properties of the spectra and the nucleon emission mechanism should be mostly simple and clear in the collision events when nucleon emission process occurs in its purest kind - when particles are not produced. A comparison, in future, of the spectra described here with corresponding spectra in collisions of identical hadrons with the same nuclei can provide information about relation between particle production and nucleon emission processes in hadron-nucleus collisions.

It is convenient therefore to investigate the proton spectra in collisions of hadrons with target-nuclei of the mass numbers A large enough, using as projectiles hadrons of kinetic energy much higher than the threshold for pion production. The pion-xenon nucleus collisions being under study in this work satisfy such conditions.

We hope, as well, that the collected and presented here data are mostly useful for quantitative analysis of the proton emission process.

It is known [3,4] that the number n_p of emitted protons in an event is the measure of the nuclear matter layer thickness λ the incident hadron collided with, when λ is measured in protons/S; $S = \pi D_0^2$ fm^2 , $n_p \leq n_p(D)$, $n_p(D)$ is the number of protons contained in the cylinder $\pi D D_0^2$, D_0 is the nucleon diameter,

Table 1a,b

Characteristics of the proton kinetic energy E_{kp} spectra $N(E_{kp})$ in pion-xenon nucleus collisions without particle production at 3.5 GeV/c momentum.

a) In the sample of events of the type (1a) and (1b) together, in classes of collision events with various proton multiplicity n_p . Energy is in MeV.

n_p / Quantity	≥1	1	2	3	4	5	6	7	8	≥9
$\langle E_{kp} \rangle$	87.46	95.96	90.65	91.40	89.62	89.54	84.46	87.71	94.46	82.38
r.m.s.	59.68	59.45	61.39	62.42	59.09	61.41	58.85	62.74	63.12	56.05
Skewness	1.11	0.76	0.99	1.09	1.00	1.11	1.00	1.01	1.25	1.22
Kurtosis	0.69	0.01	0.24	0.48	0.32	0.70	0.08	0.20	0.18	0.78

b) In the sample of events of the type (1a) without any secondary pion, $n_\pi = 0$, and in the sample of events of the type (1a) and (1b) together - with one negatively charged secondary pion or without any secondary pion, $n_\pi \leq 1$, for protons emitted in any direction and for protons emitted into forward "F" or into backward "B" hemisphere. Energy is in MeV.

Quantity	$n_p \geq 1$	
	$n_\pi \leq 1$	$n_\pi = 0$
$\langle E_{kp} \rangle$	87.46	86.49
r.m.s.	59.68	60.77
Skewness	1.11	1.18
Kurtosis	0.69	0.92
$\langle E_{kp} \rangle_F$	96.27	93.95
r.m.s.$_F$	63.35	62.42
Skewness$_F$	0.92	0.93
Kurtosis$_F$	0.08	-0.04
$\langle E_{kp} \rangle_B$	70.86	72.76
r.m.s.$_B$	47.84	55.00
Skewness$_B$	1.45	1.18
Kurtosis$_B$	2.60	4.37

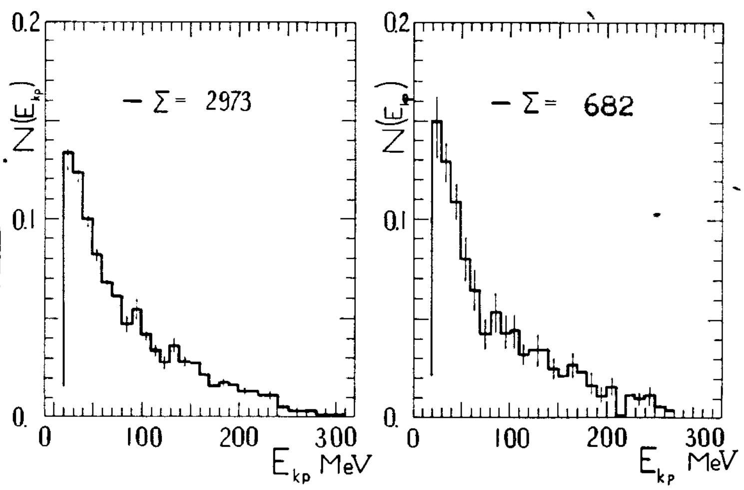


Fig. 1. Proton kinetic energy E_{kp} spectra $N(E_{kp})$ in samples of events of the type (1a), right side, and of the types (1a) and (1b) together, left side; Σ - number of protons in the histogram. Pion-xenon nucleus collisions without particle production at 3.5 GeV/c momentum.

D is the diameter of the target-nucleus. For example, $n_p(D)$ for $^{131}_{54}Xe$ nucleus is about 8. Therefore, we present the energy and momemtun spectra of emitted protons in dependence on the proton multiplicity n_p.

2. EXPERIMENT

The hadron-nucleus collisions without particle production could have been discovered and studied when all the secondary pions, charged and neutrals, all other particles produced, and the emitted protons were registered with an efficiency of about 100%. The 180 litre xenon bubble chamber /5/ without magnetic field satisfies these requirements practically. In our experiment this chamber was exposed to a beam of negatively charged pions of 3.5 GeV/c momentum from the accelerator at the Institute of Experimental and Theoretical Physics in Moscow.

The characteristics of the xenon bubble chamber used and detailed information about the experimental procedure can be found in our previous works /6, 7/; we limit ourselves here to the presentation of the most important information about the experiment.

The photographs of the chamber were scanned and rescanned for pion-xenon nucleus collisions of the type:

$$\pi^- + Xe \rightarrow n_p + f \qquad (1a)$$

and

$$\pi^- + Xe \rightarrow \pi^- + n_p + f \qquad (1b)$$

which could occur in the fiducial region of nearly 42x10x10 cm^3 volume situated coaxially and centered inside the chamber of 104x40x40 cm^3 volume; $n_p = 0,1,2,\ldots$ denotes the number of emitted "fast" protons and f denotes residual fragments of the target nucleus.

Any sharp change in the straight-line track of any beam pion was considered to be an indication that this pion underwent the interaction with the xenon nucleus; the end- or deflection-point of any beam-pion-track was accepted to be the point of impact. We were able to detect the collision events in which the incident pion track ends off or deflects at an angle of no less than 2 degrees, accompanied or not by any number of the proton tracks outgoing from the interaction place.

In any of the selected events, the deflection angle θ_π of the incident pion track, the number n_p of the protons emitted - called the proton multiplicity, the emission angle θ_p and the azimuth angle ϕ_p relatively to the pion deflection plane, the

Table 2

Characteristics of the proton lingitudinal momentum P_{Lp} distributions $N(P_{Lp})$ in pion-xenon nucleus collisions without particle production at 3.5 GeV/c momentum; in the sample of events of the type (1a) and (1b) together, $n_\pi \le 1$, and in the sample of events of the type (1a), $n_\pi = 0$. n_p - multiplicity of emitted protons, P_{Lp} is in MeV/c units.

n_p / Quantity	$n_\pi \le 1$										$n_\pi = 0$
	≥1	1	2	3	4	5	6	7	8	≥9	≥1
$\langle P_{Lp} \rangle$	96.0	165.6	100.5	103.4	101.1	82.8	88.6	95.4	90.7	89.2	89.7
r.m.s.	236.7	194.8	234.0	246.2	234.9	245.2	238.2	231.8	251.6	233.9	242.0
Skewness	0.04	0.26	0.09	0.08	0.22	0.27	0.17	0.26	-0.22	-0.05	-0.17
Kurtosis	0.04	0.32	-0.26	-0.39	-0.14	-0.10	0.07	-0.28	0.69	-0.07	0.23

kinetic energy E_{kp}, the longitudinal momentum $\vec{P}_{Lp}$, and the transverse momentum $\vec{P}_{Tp}$ of each of the emitted protons were determined. The accuracy of the pion deflection angle measurement is about 1 degree; the accuracy of the proton emission angle measurement is about 3 degrees, on the average. Energies of the protons were measured, using the range-energy relation /8/, with the accuracy of about 4%. The number n_p of the protons leaving tracks corresponding to the proton kinetic energy larger than 20 MeV was determined with a constant detection efficiency close to 100%.

3. EXPERIMENTAL DATA

The data, set forth below, are obtained in the analysis of 972 events of the type (1a) and (1b) singled out in the scanning of about 150000 chamber stereophotographs; there are 96 events of the type (1a) and 876 events of the type (1b). In presenting the data we show separately spectra prepared in the sample of events of the type (1a) and (1b) together and in the sample of events of the type (1a) only.

3.1. Proton Kinetic Energy Spectra

The set of histograms shown in figs. 1-4 and the data given in table 1 describe completely kinetic energy distribution of the protons emitted in the pion-xenon nucleus collisions without particle production.

3.2. Longitudinal Momentum Distributions

Longitudinal momenta $\vec{P}_{Lp}$ of the emitted protons are characterized in figs. 5 - 7, and in table 2.

3.3. Transverse Momentum Distributions

Characteristics of the proton transverse momenta are presented in figs. 8 - 11, and in table 3.

4. RESULTS

Let us sum the most important properties of the energy and momentum spectra of the emitted protons.

I. As it concerns the energy spectra:

I.1. Energy spectra $N(E_{kp})$ of the emitted protons are almost identical in both samples of events under analysis - in the

Table 3a

Characteristics of the proton transverse momentum P_{Tp} distributions $N(P_{Tp})$ in pion-xenon nucleus collisions without particle production at 3.5 GeV/c momentum. Characteristics for the sample of events, of the type (1a) and (1b) together, with various number n_p of emitted protons; P_{Tp} is expressed in MeV/c units.

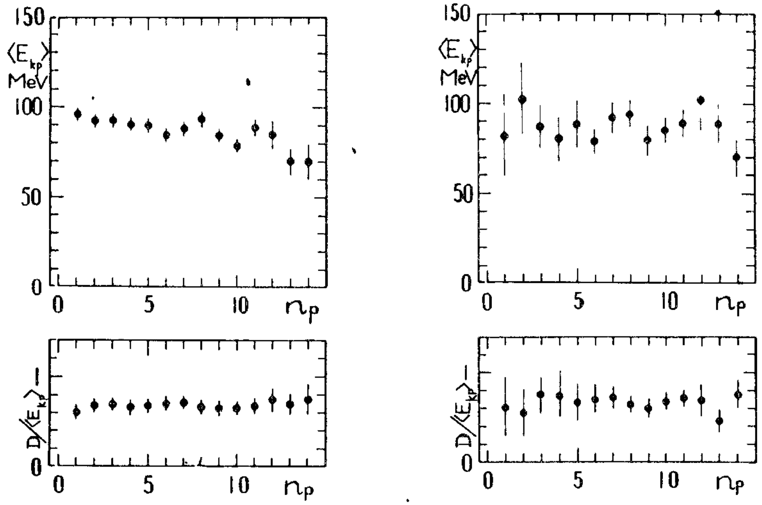
Quantity \ n_p	≥1	1	2	3	4	5	6	7	8	≥9
$\langle P_{Tp} \rangle$	303.10	335.10	311.80	308.40	312.30	305.30	295.00	304.20	315.30	291.10
r.m.s.	134.70	122.80	141.00	131.20	129.50	139.90	131.90	144.20	138.40	130.60
Skewness	0.46	0.18	0.41	0.33	0.29	0.32	0.66	0.53	0.46	0.51
Kurtosis	-0.24	-0.70	-0.54	-0.57	-0.41	-0.35	-0.08	-0.45	-0.16	-0.00

Fig. 2. Dependences of the average kinetic energy $\langle E_{kp} \rangle$ and of corresponding normalized dispersion $D/\langle E_{kp} \rangle$ on proton multiplicity n_p, in pion-xenon nucleus collisions without particle production at 3.5 GeV/c momentum: a) in the sample of events of the type (1a) and (1b) together - left side; b) in the sample of events of the type (1a) - right side.

Table 3b

Characteristics of the proton transverse momentum P_{Tp} distributions $N(P_{Tp})$ in pion-xenon nucleus collisions without particle production at 3.5 GeV/c momentum. Characteristics for the sample of events of the type (1a) - without any secondary pion, $n_\pi = 0$, and for the sample of events of the type (1a) and (1b) together - with one secondary negatively charged pion or without any secondary pion, $n_\pi \leq 1$, for protons emitted in any direction and for protons emitted into forward "F" or into backward "B" hemisphere. Momentum P_{Tp} is expressed in MeV/c units.

Quantity	$n_p \geq 1$	
	$n_\pi \leq 1$	$n_\pi = 0$
$\langle P_{Tp} \rangle$	303.10	299.00
r.m.s.	134.70	132.60
Skewness	0.46	0.54
Kurtosis	-0.24	-0.26
$\langle P_{Tp} \rangle_F$	309.40	-
r.m.s. $_F$	138.90	-
Skewness $_F$	0.39	-
Kurtosis $_F$	-0.40	-
$\langle P_{Tp} \rangle_B$	291.40	-
r.m.s. $_B$	125.60	-
Skewness $_B$	0.59	-
Kurtosis $_B$	-0.10	-



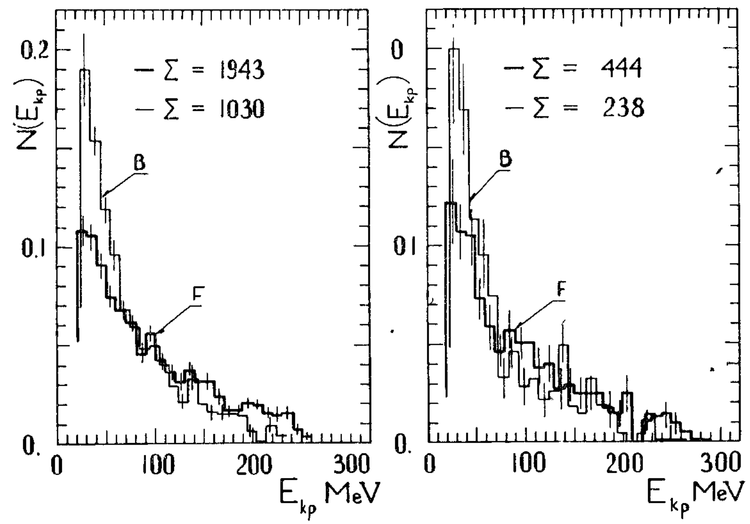


Fig. 3. Proton kinetic energy E_{kp} spectra in pion-xenon nucleus collisions without particle production, at 3.5 GeV/c momentum, in samples of events of the type (1a) and (1b) together - left side, and of events of the type (1a) - right side; "F" and "B" are for the protons emitted into forward and backward hemispheres, correspondingly; Σ - the number of protons in the sample.

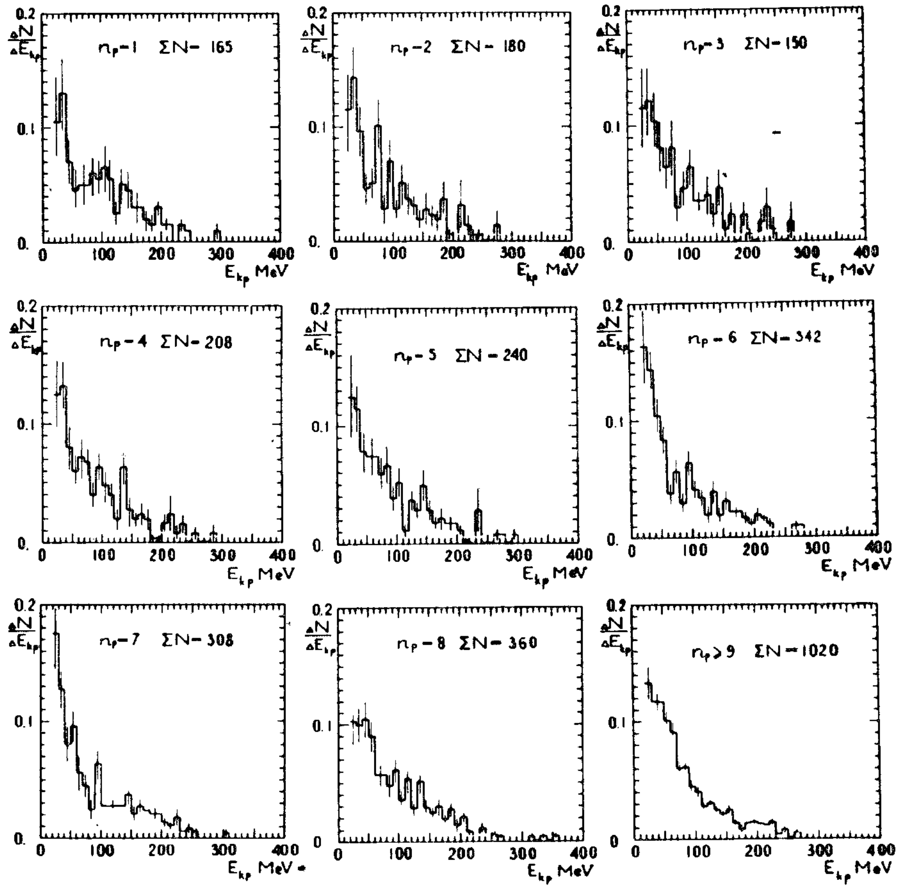


Fig. 4. Proton kinetic energy E_{kp} spectra in pion-xenon nucleus collisions without particle production, of the type (1a) and (1b) together, at 3.5 GeV/c momentum, in classes of events with various multiplicities n_p of emitted protons; ΣN - number of protons in a class.

sample containing events without any secondary pion and with one secondary negatively charged pion together, and in the sample without any secondary pion only, fig. 1 and table 1. There are some indications for a possible existence of irregularities, or peaks, at proton kinetic energy E_{kp}= 90-100 MeV and E_{kp} =130--140 MeV. The kinetic energies of the protons are not larger than about 300 MeV; in the chamber we can register effectively protons of energies up to about 400 MeV.

I.2. Proton average kinetic energy $\langle E_{kp}\rangle$ in events without particle production of the type (1a) and (1b) together changes

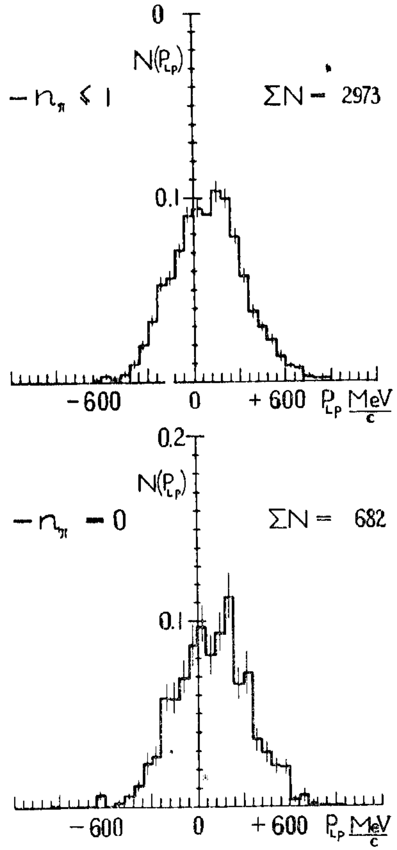
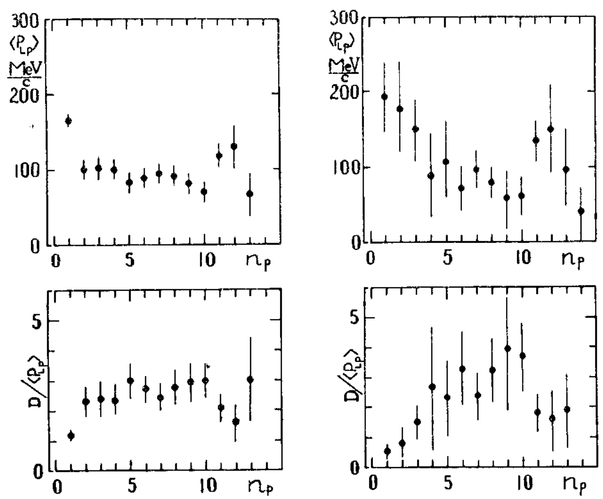


Fig. 5. Proton longitudinal momentum P_{Lp} distributions $N(P_{Lp})$ in pion-xenon nucleus collisions without particle production, at 3.5 GeV/c momentum: a) in the sample of events of the type (1a) and of the type (1b) together - upper; b) in the sample of events of the type (1a) - lower; n_π - number of pions among secondaries in an event, ΣN - number of protons in a histogram.

Fig. 6. Dependences of the proton average longitudinal momentum $\langle P_{Lp}\rangle$ and of the normalized dispersion $D/\langle P_{Lp}\rangle$ on the proton multiplicity n_p, in pion-xenon nucleus collisions without particle production at 3.5 GeV/c momentum. Left - in the sample of events of the type (1a) and (1b) together, right - in the sample of events of the type (1a).



weakly with the increase of the proton multiplicity n_p; the average kinetic energy changes within energy value interval from about 95 MeV to about 85 MeV when the proton multiplicity changes from 1 to 8, fig. 2; at $n_p \geq 9$ the values of $\langle E_{kp} \rangle$ fluctuate evidently - from about 70 to about 90 MeV within n_p change from 9 to 14, fig. 2.

I.3. Proton energy distributions in both the samples of events - including events of the types (1a) and (1b) together and including events of the type (1a) only - do not depend practically on the number n_p of protons emitted in an event, fig. 2 and table 1a.

I.4. Energy spectra of protons emitted into forward and backward hemisphere differ, fig.3 and table 1b; the differences are almost identical in both the samples of events without particle production - in the sample containing events of the type (1a)

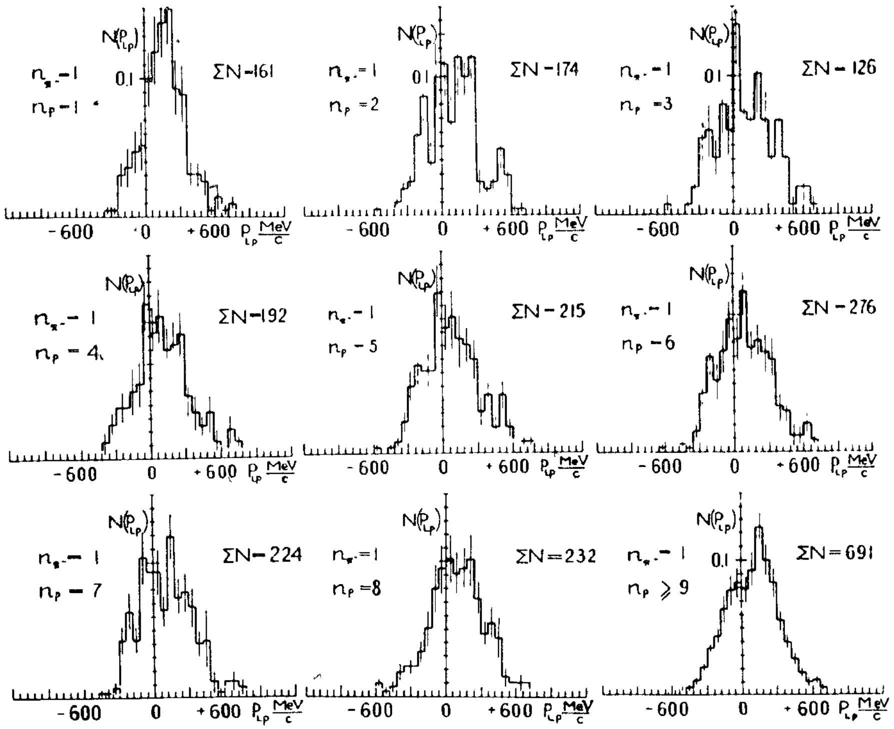


Fig. 7. Proton longitudinal momentum P_{Lp} distributions in samples of pion-xenon nucleus collision events without particle production, at 3.5 GeV/c momentum, in which n_p = 1,2,..., $\geq$ 9 protons are emitted. ΣN - numbers of protons in the histograms.

Fig. 8. Distributions $N(P_{Tp})$ of the transverse mmomenta P_{Tp} of protons emitted in pion-xenon nucleus collisions without particle production, at 3.5 GeV/c momentum. Upper - in the sample of events of the type (1a) and (1b) together; lower - in the sample of events of the type (1a). ΣN - number of protons in the sample.

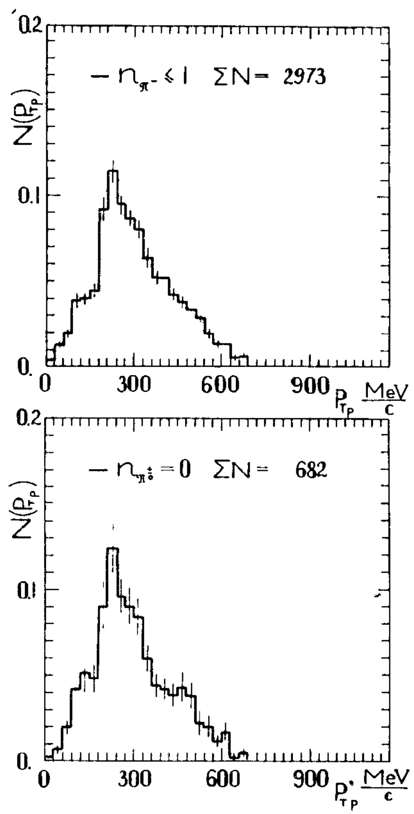
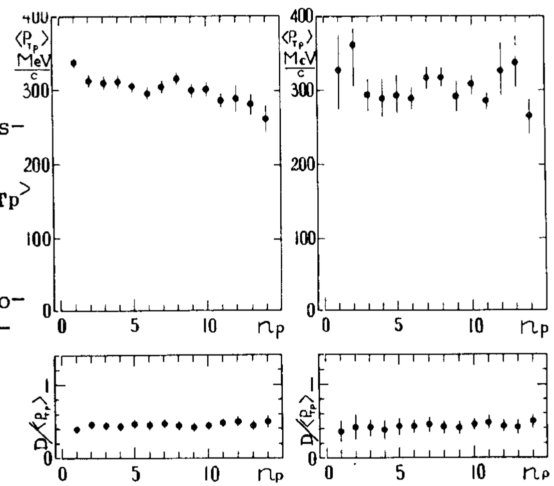


Fig.9. Proton average transverse momentum $\langle P_{Tp} \rangle$ and normalized dispersion $D/\langle P_{Tp} \rangle$ dependences on the proton multiplicity n_p, in pion-xenon nucleus collision events without particle production at 3.5 GeV/c momentum. Left - in the sample of events of the type (1a) and (1b) together, right - in the sample of events of the type (1a).



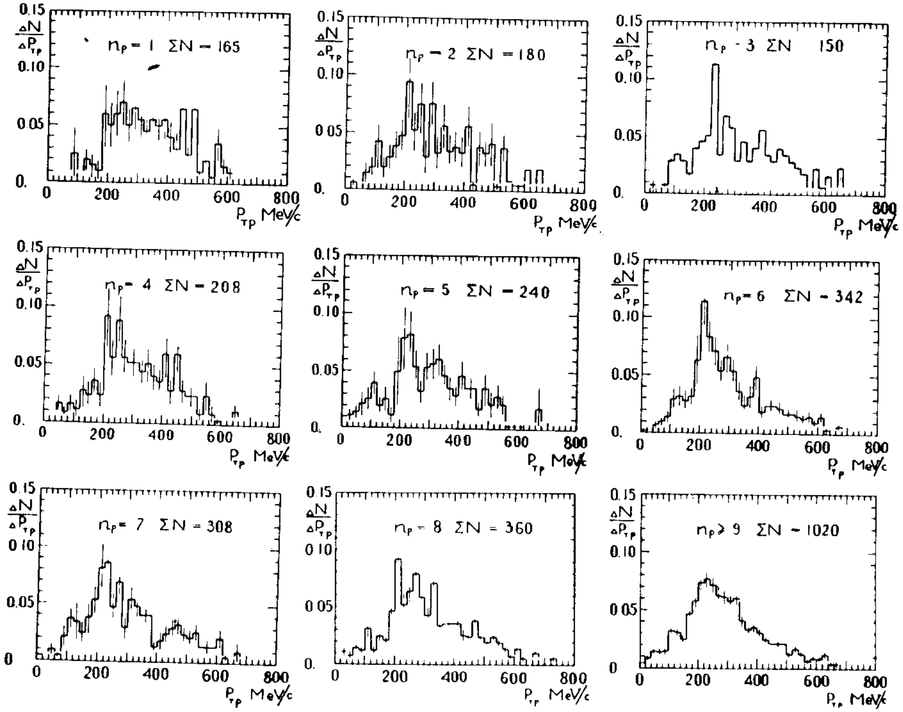


Fig. 10. Distributions of the proton transverse momentum P_{Tp} in pion-xenon nucleus collisions without particle production – of the type (1a) and (1b) together, at 3.5 GeV/c momentum, in classes of events with various numbers n_p of emitted protons. ΣN – number of protons in a class.

and (1b) together and in the sample containing events of the type (1a) only, fig. 3 and table 1b.

I.5. It is not excluded that some irregularities exist in the proton energy spectra in classes of events without particle production in which various numbers n_p of protons were emitted, fig. 4.

II. As it concerns the distributions of the proton longitudinal momenta:

II.1. Longitudinal momenta P_{Lp} of the emitted protons are distributed similarly in both the samples of the pion-xenon nucleus collisions without particle production – in the sample containing events of the type (1a) and (1b) together and in the sample containing events of the type (1a) only, fig. 5 and table 2. Some irregularities occur in the distributions at about 120 – 240 MeV/c.

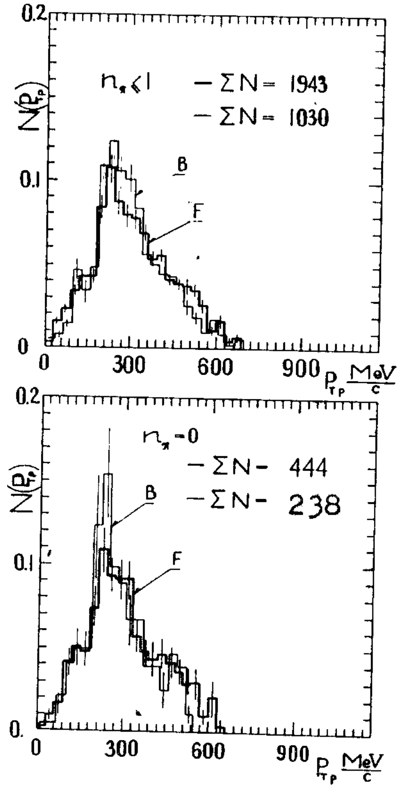


Fig. 11. Proton transverse momentum P_{Tp} distributions $N(P_{Tp})$ in pion-xenon nucleus collision events without particle production, at 3.5 GeV/c momentum; upper – in events of the type (1a) and (1b) together, lower – in events of the type (1a). "F" and "B" are for protons emitted into forward and into backward hemispheres correspondingly, ΣN – numbers of protons in histograms.

II.2. The average value of the longitudinal proton momentum $\langle P_{Lp} \rangle$ in the sample of events without particle production, of the type (1a) and (1b) together, changes weakly with the proton multiplicity increase from $n_p = 2$ to $n_p = 8$, fig. 6 – left upper; the normalized dispersions $D/\langle P_{Lp} \rangle$ do not change practically within this n_p -value interval as well, fig. 6 – left lower.

II.3. The shapes of the proton longitudinal momentum distributions do not change by much with the proton multiplicity change within the n_p-value interval from 1 to 8, fig. 7, table 2.

II.4. It is not excluded that some irregularities exist in the proton longitudinal momentum spectra, fig. 5 and 7.

III. As it concerns the transverse momentum distributions:

III.1. The proton transverse momentum spectra $N(P_{Tp})$ are almost identical in both the samples of pion-xenon nucleus collisions without particle production – in the sample of events of the type (1a) and (1b) together and of the type (1a) only, fig.8 and table 3a and 3b.

III.2. Average value of the proton transverse momentum in sample of collisions containing events of the type (1a) and (1b) together changes weakly with n_p increase from $n_p=2$ to $n_p=8$, from maximal value $<P_{Tp}> \approx 310$ MeV/c to $<P_{Tp}> \approx 295$ MeV/c; in events with $n_p=1$ $<P_{Tp}>=335$ MeV/c, fig. 9.

III.3. There are no, practically, differences between $<P_{Tp}>-n_p$ and $D/<P_{Tp}>-n_p$ dependences in both samples of events without particle production - in the sample containing events of the type (1a) and (1b) together and in the sample containing events of the type (1a) only, fig. 9.

III.4. Transverse momenta in the sample of events without particle production, containing events of the type (1a) and (1b) together, are similarly distributed in classes of events with various multiplicity n_p of emitted protons, fig. 10 and table 3; it is not excluded the existence of some irregularities in the distributions.

III.5. Transverse momentum distributions of protons emitted into forward hemisphere and separately into backward hemisphere differ in both the samples of the pion-xenon collision events without particle production - in the sample of events of the type (1a) and (1b) together and in the sample of events of the type (1a) only, fig. 11; these differences are almost the same in both the samples of events under study, fig. 11.

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Стругальский З., Павляк Т., Плюта Я. E1-82-841
Экспериментальное исследование пион-ксенон столкновений без рождения частиц при импульсе 3,5 ГэВ/с: энергетические и импульсные спектры испущенных протонов

Исследовались энергетические спектры и импульсные распределения протонов, испущенных в таких пион-ксенон столкновениях без рождения частиц, когда налетающий пион подвергается отклонению при прохождении через ядро-мишень или поглощается ядром; испущенные протоны обладают кинетическими энергиями от ~20 до ~400 МэВ. Из экспериментальных данных следует, что: 1/ средняя кинетическая энергия, средний продольный импульс и средний поперечный импульс слабо меняются с кратностью протонов; 2/ энергетические спектры протонов и импульсные распределения протонов почти независимы от кратности протонов; 3/ энергетические спектры и распределения по импульсам протонов почти одинаковы в обоих наборах событий - когда налетающий пион отклоняется при прохождении через ядро и когда он поглощается в ядре.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1982

Strugalski Z., Pawlak T., Pluta J. E1-82-841
Experimental Study of the Pion-Xenon Nucleus Collisions without Particle Production at 3.5 GeV/c Momentum: Energy and Momentum Spectra of Emitted Protons

Energy and momentum spectra of protons emitted in pion-xenon nucleus collision events without particle production, in which incident pion is deflected or absorbed in accompaniment of nucleon emission, are studied; protons are of kinetic energy from about 20 to about 400 MeV. From experimental data presented, it can be concluded that: 1. Proton average kinetic energy, average longitudinal momentum, and average transverse momentum change weakly with the proton multiplicity; 2. Proton kinetic energy spectra and proton momentum spectra are almost independent of the proton multiplicity; 3. Energy spectra and momentum distributions of protons are almost the same in both the samples of events - when incident pion is deflected in its passage through nuclear target and when it is absorbed in the target-nucleus.

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

Communication of the Joint Institute for Nuclear Research. Dubna 1982