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ENERGY AND MOMENTUM SPECTRA OF NUCLEONS EMITTED IN HIGH ENERGY HADRON-NUCLEUS COLLISIONS

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1. INTRODUCTION

When a high energy hadron h, of kinetic energy higher than the pion production energy threshold, collides with an atomic nucleus of a mass number A, emission of nucleons from the target nucleus appears. The nucleons are of various kinetic energies: "slow" or the so-called evaporated nucleons [1,2], of kinetic energy smaller than about 20 MeV, and "fast" - of kinetic energy higher than the kinetic energy of the evaporated nucleons [3-8], up to about 400 MeV. If target nucleus is massive enough, A ≈ 100, the fast nucleon emission may be very intensive - events occur in which tens of nucleons are ejected.

The evaporation process was discussed widely and its nature is regarded to be known [1,2]. It is not the case as it concerns the fast nucleon emission. Many of the fast nucleons are emitted at relatively large emission angles, up to about 180 degrees [3,6], and it cannot be explained simply - as a result of a usual knocking-out mechanism, for example. Therefore, additional experimental data on the fast nucleon emission process and a special analysis of the experimental data available are highly desired in order to obtain a reasonable picture of the process.

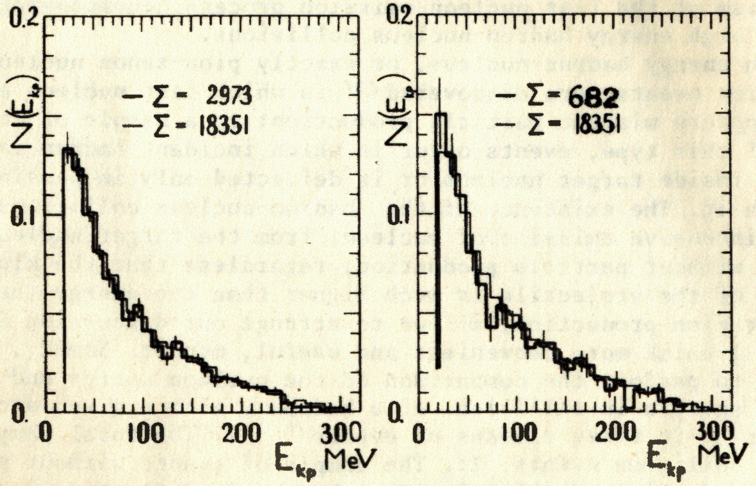
In the present paper, we intend to discuss the properties of energy and momentum spectra of fast nucleons emitted in high energy hadron-nucleus collisions. I wish to direct your attention to some experimental facts which may throw light on the mechanism of the fast nucleon emission process accompanying any of high energy hadron-nucleus collisions.

High energy hadron-nucleus, or exactly pion-xenon nucleus, collision events were discovered [3] in which fast nucleon emission appears without particle production: in a sample of collision of this type, events occur in which incident hadron is absorbed inside target nucleus or is deflected only in passing through it. The existence of the hadron-nucleus collisions in which intensive emission of nucleons from the target nucleus occurs without particle production, regardless that the kinetic energy of the projectile is much higher than the energy threshold for pion production, allows to arrange our discussion in a new, I think more convenient and useful, manner. Namely, it allows to perform the comparison of the nucleon energy and momentum spectra in collisions of a hadron h with a given atomic nucleus A in three classes of events [6]: I. The total sample of h-A collision events; II. The sample of events without particle production in which incident hadron is deflected or absorbed inside the target nucleus with accompaniment by the fast nucleon emission; III. The sample of events without particle production in which incident hadron is absorbed inside the target nucleus with accompaniment by the fast nucleon emission.

Table 1

Characteristics of energy spectra of fast protons emitted in pion-xenon nucleus collisions at 3.5 GeV/c momentum for various classes of events: class I - containing any type of collisions; class II - containing collision events without particle production, with zero or one negatively charged pion; class III - containing events without particle production in which incident pion is absorbed inside the target nucleus. Indices "F" and "B" are for protons emitted into forward and backward hemispheres, correspondingly. Average kinetic energy $\langle E_{kp} \rangle$ is in MeV.

Class of events	Number of events	Number of protons	Quantity			
			$\langle E_{kp} \rangle$	r.m.s.	skew.	kurt.
I	6301	18351	89.20	62.21	1.21	1.15
I_F		12198	98.52	66.50	1.05	0.62
I_B		6153	70.63	47.46	1.34	1.59
II	972	2973	87.46	59.68	1.11	0.69
II_F		1943	96.27	63.35	0.92	0.08
II_B		1030	70.86	47.84	1.45	2.60
III	96	682	86.49	60.77	1.18	0.92
III_F		444	93.95	62.42	0.93	-0.04
III_B		238	72.76	55.00	1.18	4.37



Possible similarities or differences between the energy and momentum spectra in various classes of events I-III should reflect properties of the mechanism of the fast nucleon emission process which proceeds when high energy hadron strucks an atomic nucleus.

Usually, in experiments protons are registered only without difficulties with a registration efficiency close to 100%, neutrons are not registered effectively in most of experiments. The information used here about nucleon spectra is based on the data on the proton spectra only. An argumentation is given later that it is quite permissible and correct procedure.

This work is arranged as follows: After introduction, in section 1, we present a short review of appropriate data available, in section 2, then we discuss the data in section 3; in sections 4 and 5 remarks and conclusions are contained.

2. EXPERIMENTAL DATA

In this work results obtained by means of the 180 litre xenon bubble chamber /9/ are used mainly. In our previous papers /3-8/ some experimental data on energy and momentum spectra were presented for two samples of pion-xenon nucleus collision events at 3.5 GeV/c momentum: for the sample containing any-type collision events /3,8/ and separately for the sample containing collision events without particle production /4,6/. In the present paper, a comparison of proton energy and momentum spectra obtained experimentally in the classes I-III of events is performed. Such a comparison leads to a discovery of experimental facts unknown till now. These facts are expressed using fig.1-6 and tables 1-6.

Three sets of experimental data may be distinguished here: a) the data on proton energy spectra, figs.1 and 2, tables 1 and 2; b) the data on proton longitudinal momentum spectra,

◀ Fig.1. Fast proton kinetic energy E_{kp} spectrum $N(E_{kp})$ in pion-xenon nucleus collisions at 3.5 GeV/c momentum: Fine lines, left and right sides - for the class I of events, containing any-type collisions; solid line, left side - for the class II of events, containing collisions without particle production in which incident pion is deflected or absorbed in passage through the target nucleus; solid line, right side - for the class III of events, containing collisions without particle production when incident pion is absorbed inside the target nucleus. Σ - numbers of protons in histograms.

Table 2

Quantities characterizing distributions of kinetic energy E_{kp} of fast protons emitted in pion-xenon nucleus collisions at 3.5 GeV/c momentum, in classes I and II of events with various numbers n_p of emitted protons. Average value of kinetic energy $\langle E_{kp}\rangle$ is expressed in MeV. Class I contains events of any type. Class II contains events without particle production with one or zero secondary pions. Because the incident pion is negatively charged, the secondary pion may be only of negative charge, in events without particle production.

Class	n_p	1	2	3	4	5	6	7	8	≥9
I	$\langle E_{kp}\rangle$	105.80	100.30	89.92	91.51	87.57	84.36	86.24	84.70	81.46
	r.m.s.	70.06	70.90	62.91	61.64	60.89	58.38	60.80	58.75	56.32
	skewness	0.95	1.29	1.10	1.02	1.20	1.18	1.37	1.27	1.23
	kurtosis	0.19	1.81	0.47	0.30	0.99	0.85	1.92	1.40	0.96
II	$\langle E_{kp}\rangle$	95.96	90.65	91.40	89.62	89.54	84.46	87.71	94.46	82.38
	r.m.s.	59.45	61.39	62.42	59.09	61.41	58.85	62.74	63.12	56.05
	skewness	0.76	0.99	1.09	1.00	1.11	1.00	1.01	1.25	1.22
	kurtosis	0.01	0.24	0.48	0.32	0.70	0.08	0.20	0.18	0.78

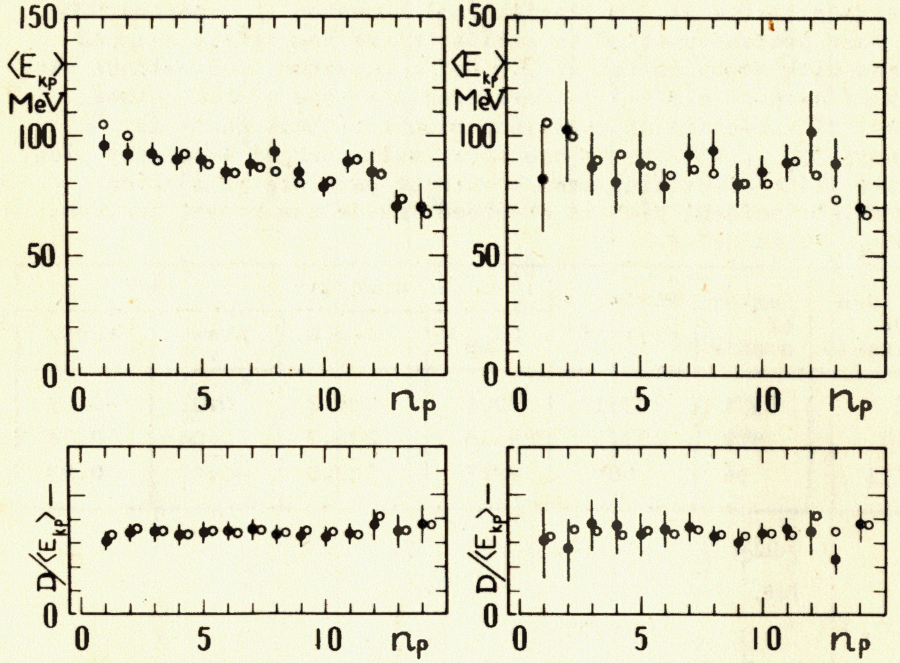


Fig.2. Dependences of the average kinetic energy $\langle E_{kp}\rangle$ of emitted fast protons and of corresponding normalized dispersion $D/\langle E_{kp}\rangle$ on fast proton multiplicity n_p, in pion-xenon nucleus collisions at 3.5 GeV/c momentum: empty circles - any type of collisions, class I; full circles, left - collisions without particle production in which incident pion is deflected or absorbed in passage through nuclear target; full circles, right - collisions without particle production in which incident pion is absorbed inside the target nucleus.

figs.3 and 4, tables 3 and 4; c) the data on proton transverse momentum spectra, figs.5 and 6, and tables 5 and 6. It is of interest to compare various spectra in subsamples of collision events with definite multiplicities n_p=1,2,3,...,8, ≥9 of emitted protons, tables 2,4,6.

Let us sum up the most important features of these spectra and distributions below.

2.1. Features of the Energy Spectra of the Emitted Fast Protons

The proton energy E_{kp} spectrum $N(E_{kp})$ in the class of events named I does not differ from the proton energy spectra in the

Table 3

Characteristics of the longitudinal momentum P_{Lp} spectra $N(P_{Lp})$ of fast protons emitted in collisions of negatively charged pions with xenon nuclei at 3.5 GeV/c momentum, for various classes of events: class I - containing any type of collisions; class II - containing collision events without particle production, with zero or one negatively charged secondary pion; class III - containing events without particle production in which incident pion is absorbed inside the target nucleus. $\langle P_{Lp} \rangle$ is in MeV/c.

Class of events	Number of events	Number of protons	Quantity			
			$\langle P_{Lp} \rangle$	r.m.s.	skew.	kurt.
I	6301	18351	110.4	256.2	0.07	-0.39
II	972	2973	96.0	236.7	0.04	0.04
III	96	682	89.7	242.0	-0.17	0.23

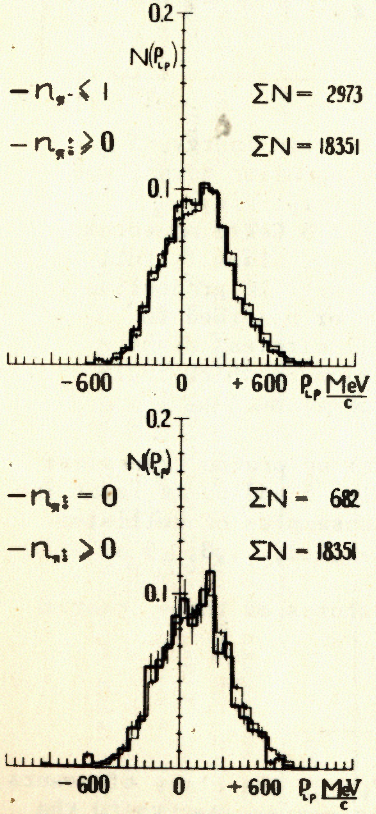


Fig.3. Fast proton longitudinal mentum P_{Lp} distributions $N(P_{Lp})$ in pion-xenon nucleus collisions at 3.5 GeV/c momentum: fine lines upper and lower - for any type collision events, class I; heavy line upper - for collisions without particle production in which incident pion is deflected or absorbed in passage through target nucleus, class II; heavy line lower- for collisions without particle production in which incident pion is absorbed inside the target nucleus. ΣN - numbers of protons in histograms, n_π number of secondary pion in events.

Table 4

Quantities describing distributions of the longitudinal momentum P_{Lp} of fast protons emitted in negatively charged pion-xenon nucleus collisions at 3.5 GeV/c momentum, in two classes of events: class I - containing any type collision events; class II - containing collision events without particle production, in which one secondary pion of negative charge is observed or no any pion is emitted. $\langle P_{Lp} \rangle$ is in MeV/c. Data are for samples of events with various multiplicities of emitted protons n_p.

Class	n_p	1	2	3	4	5	6	7	8	9
I	$\langle P_{Lp} \rangle$	164.6	146.1	109.3	112.8	101.3	96.1	106.7	98.9	90.4
	r.m.s.	256.2	260.3	241.6	242.3	238.7	237.9	236.7	235.4	231.2
	skewness	0.07	0.08	0.08	0.05	0.05	0.00	0.22	-0.08	-0.05
	kurtosis	-0.39	-0.08	-0.21	-0.25	-0.22	-0.09	-0.02	0.03	-0.12
II	$\langle P_{Lp} \rangle$	165.6	100.5	103.4	101.1	82.8	88.6	95.4	90.7	89.2
	r.m.s.	194.8	234.0	246.2	234.9	245.2	238.2	231.8	251.6	233.9
	skewness	0.26	0.09	0.08	0.22	0.27	0.17	0.26	-0.22	-0.05
	kurtosis	0.32	-0.26	-0.39	-0.14	-0.10	0.07	-0.28	0.69	-0.07

classes of events named II and III, fig.1 and table 1; in the class I, in about 90% of collisions, events with particle production occur.

The n_p -dependences of the average proton energy $<E_{kp}>$ and of the normalized dispersion $D/<E_{kp}>$ in events included to the class I are almost the same as in events included to the classes II and III, fig.2 and table 2. The n_p -dependences of the proton energy spectra are almost the same in samples of collision events included to the classes I and II, table 2.

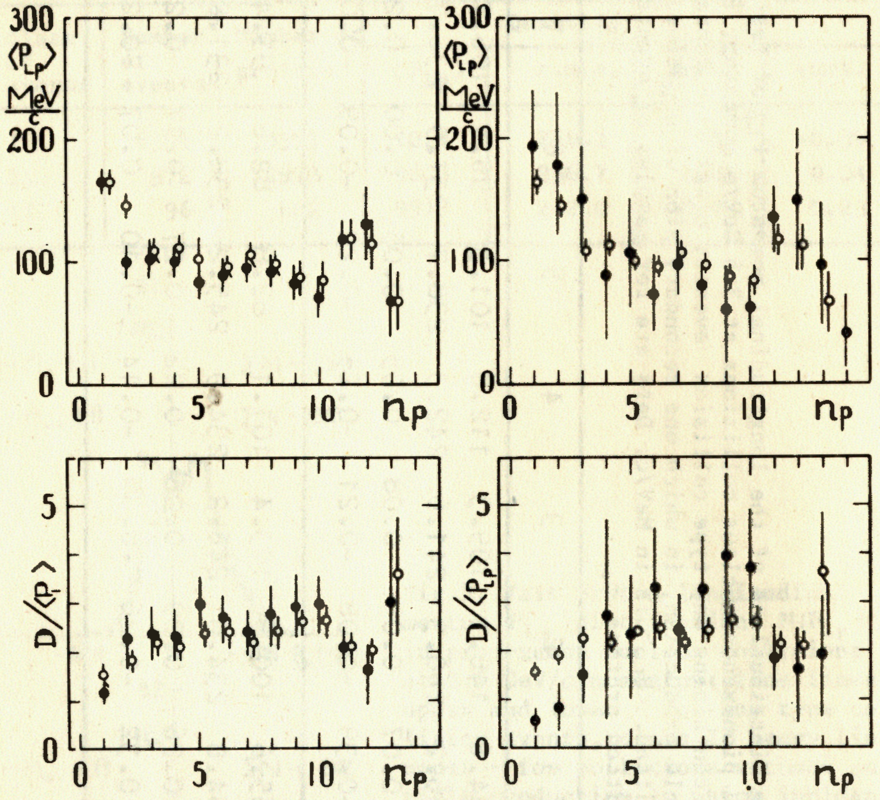


Fig.4. Dependences of the average longitudinal momentum $<P_{Lp}>$ of emitted fast protons and of corresponding normalized dispersion $D/<P_{Lp}>$ on fast proton multiplicity n_p, in pion-xenon nucleus collisions at 3.5 GeV/c momentum: empty circles - any type collisions, class I; full circles, left - collisions without particle production in which incident pion is deflected or absorbed inside target nucleus; full circles, right - collisions without particle production in which incident pion is absorbed inside target nucleus.

The energy spectra of protons emitted into forward hemisphere differ from the spectra of the protons emitted into backward hemisphere in all the classes I-III of collision events, table 1. But, the spectra of protons emitted into forward hemisphere are almost the same in all the classes and the spectra of protons emitted into backward hemisphere are almost the same in all the classes as well, table 1.

2.2. Features of the Longitudinal Momentum Spectra of the Emitted Protons

The longitudinal momentum spectra of emitted protons do not differ by much in the classes I-III of collision events, fig.3 and table 3.

The n_p -dependences of the average longitudinal momentum $<P_{Lp}>$ and corresponding normalized dispersion $D/<P_{Lp}>$ are almost the

Table 5

Characteristics of transverse momentum P_{Tp} spectra $N(P_{Tp})$ of fast protons emitted in negatively charged pion-xenon nucleus collisions at 3.5 GeV/c momentum, for various classes of collisions: class I - containing any type collisions; class II - containing collision events without particle production, with one secondary negatively charged pion or without secondary pions; class III- containing events without particle production in which incident pion is absorbed inside the target nucleus. $<P_{Tp}>$ is in MeV/c.

Class of events	Number of events	Number of protons	Quantity			
			$<P_{Tp}>$	r.m.s	skew.	kurt.
I	6301	18351	300.8	133.4	0.49	-0.21
I_F		12198	304.6	137.0	0.42	-0.32
I_B		6153	293.2	125.5	0.63	-0.07
II	972	2973	303.1	134.7	0.46	-0.24
II_F		1943	309.4	138.9	0.39	-0.40
II_B		1030	291.4	125.6	0.59	-0.10
III	96	682	299.0	132.6	0.54	-0.26
III_F		444	306.5	134.8	0.41	-0.49
III_B		238	285.2	127.2	0.78	0.36

same in the classes I-III of collision events, fig.4. The n_p-dependences of proton longitudinal momentum spectra $N(P_{Lp})$ are almost the same in the classes of events I and II, table 4.

2.3. Features of the Transverse Momentum Spectra of Emitted Protons

The transverse momentum P_{Tp} spectra $N(P_{Tp})$ of emitted protons in the samples of events included to the classes I-III do not differ practically, fig.5 and table 5.

The n_p-dependences of the proton transverse momentum average values $\langle P_{Tp} \rangle$ and of corresponding normalized dispersions $D/\langle P_{Tp} \rangle$ are identical in all the classes I-III of collision events, within total n_p values interval - from $n_p = 1$ to $n_p = 14$, fig.6. The n_p-dependences of the proton transverse momentum spectra are practically the same in the classes of collision events I and II, table 6.

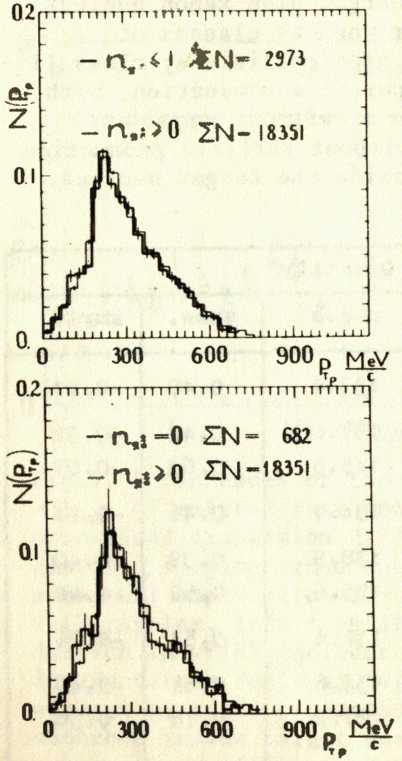


Fig.5. Fast proton transverse momentum P_{Tp} distributions $N(P_{Tp})$ in pion-xenon nucleus collisions at 3.5 GeV/c momentum: fine lines, upper and lower - for any type collision events, class I; heavy line, upper - for collisions without particle production in which incident pion is deflected or absorbed in passage through target nucleus, class II; heavy line, lower - for collisions without particle production in which incident pion is absorbed inside the target nucleus, class III, ΣN - number of protons in histograms, n_π - number of secondary pions in events.

Table 6

Quantities characterizing distributions $N(P_{Tp})$ of transverse momentum P_{Tp} of protons emitted in negatively charged pion-xenon nucleus collisions at 3.5 GeV/c momentum, in samples of events with various numbers n_p of protons, for two classes of events: class I - containing any type collisions; class II - containing collision events without particle production, in which one secondary negatively charged pion is observed or not any secondary pion is emerged. $\langle P_{Tp} \rangle$ is in MeV.

Class	n_p	1	2	3	4	5	6	7	8	9
I	$\langle P_{Tp} \rangle$	319.8	309.3	303.2	306.4	300.3	293.7	297.6	294.8	290.9
	r.m.s.	140.0	135.7	135.6	136.0	134.8	129.0	130.0	132.0	127.9
	skewness	0.28	0.36	0.55	0.46	0.48	0.55	0.54	0.53	0.55
	kurtosis	-0.55	-0.29	-0.25	-0.22	-0.19	-0.21	-0.15	0.03	-0.06
II	$\langle P_{Tp} \rangle$	335.1	311.8	308.4	312.3	305.3	295.0	304.2	315.3	291.1
	r.m.s.	122.8	141.0	131.2	129.5	139.9	131.9	144.2	138.4	130.6
	skewness	0.18	0.41	0.33	0.29	0.32	0.66	0.53	0.46	0.51
	kurtosis	-0.70	-0.54	-0.57	-0.41	-0.35	-0.08	-0.45	-0.16	-0.00

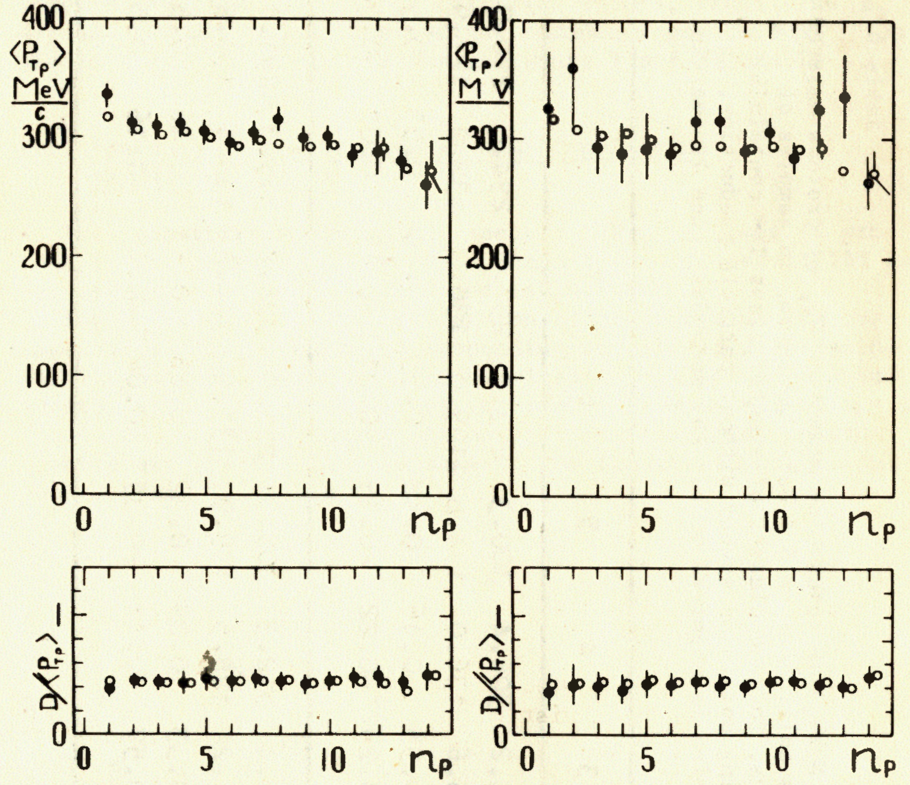


Fig.6. Dependences of the average transverse momentum $<P_{T_p}>$ of emitted fast protons and of corresponding notmalized dispersion $D/<P_{T_p}>$ on fast proton multiplicity n_p, in pion-xenon nucleus collisions at 3.5 GeV/c momentum: empty circles - for any type of collisions, class I; full circles, left - for collisions without particle production in which incident pion is deflected or absorbed in passage through the target nucleus, class II; full circles, right - for collisions without particle production in which incident pion is absorbed inside the target nucleus.

The proton transverse momentum spectra, for protons emitted into forward and into backward hemisphere, are different but, the differences are practically the same in all the classes I-III of collision events, table 5. The differences between the transverse momentum spectra for the protons emitted into forward and backward hemispheres, in any of the classes I-III, are small - the average values $<P_{T_p}>$ and the r.m.s. differ no more than about a few per cent, table 5.

It should be emphasized, in addition to the features presented in sections 2.1-2.3, that the ratio N_F/N_B between intensities N_F and N_B of fast protons emitted into forward "F" and into backward "B" hemispheres is practically the same in all the classes I-III of collision events: $(N_F/N_B)_I \approx (N_F/N_B)_{II} \approx (N_F/N_B)_{III} = (1.98 \pm 0.04)_I \approx (1.89 \pm 0.10)_{II} \approx (1.87 \pm 0.20)_{III}$. As the measure of the proton emission intensity the total number of protons emitted into a hemisphere is used.

3. EXTRAPOLATIONS

The data presented in foregoing section 2 were obtained in studying characteristics of emitted protons in pion-xenon nucleus collisions at 3.5 GeV/c momentum of the incident negatively charged pion. The questions arise therefore: Would apply to fast neutron emission what applies to the fast proton emission? Are the features of the fast proton emission, discovered in pion-nucleus collisions, proper to any hadron-nucleus collisions? Are the features of the proton emission process, known in pion-nucleus collisions at 3.5 GeV/c momentum, proper to the proton emission at higher and lower incident pion momenta?

All these questions must find appropriate answers primarily in experiments, although some reasonable predictions may be given now, on the basis of some additional experimental data available.

Firstly, the characteristic shapes of the $<n_p> - n_\pi$ and $<n_n> - n_\pi$ dependences, observed in our experiments, are almost identical; $<n_p>$ is the average proton multiplicity in events with $n_\pi = 0, 1, 2, \ldots$ secondary pions, $<n_n>$ is the average number of neutron-initiated stars in events with $n_\pi = 0, 1, 2, \ldots$ secondary pions. From this fact, it can be concluded that it is reasonable to think the fast neutrons to be emitted identically as the fast protons are.

Secondly, almost identical features of energy spectra and angular distributions of the "g"-particles, usually regarded to be fast protons, in proton-emulsion collisions at 4.5 GeV/c momentum/10/ and of the fast protons in pion-xenon nucleus collisions at 3.5 GeV/c momentum are observed. From this fact it can be concluded that it is reasonable to think the features of the fast proton emission in pion-nucleus collisions are proper to various different hadron-nucleus collisions as well, at least for pion-nucleus and proton-nucleus collisions.

Thirdly, the multiplicity n_g distributions of the "g" tracks in proton-AgBr collisions at 4.5, 67, 200, 400 GeV/c momentum of the incident proton are almost identical/10,11,12,13/. The same is observed in Pi-AgBr collisions at 17, 60, 200 GeV/c momentum of the incident pion/11/.Fast proton energy spectra in proton-AgBr collisions at 4.5 and 400 GeV/c momentum of incident proton[10,12] are the same; these spectra do not differ from the fast proton energy spectrum obtained in this work in pion-xenon nucleus collisions at 3.5 GeV/c momentum. From these facts, it is reasonable to conclude that the fast proton emission features observed in our experiment at 3.5 GeV/c momentum may be regarded as energy-independent, at projectile energies above pion production threshold.

We can conclude, therefore, that the features of the fast proton energy and momentum spectra presented in section 2 may be reasonably regarded as proper to fast nucleon energy and momentum spectra in any hadron-nucleus collisions at any high energy of the projectile hadron. But, it should be emphasized clearly again that the problems in question should find their final answers in future experiments.

4. CONCLUSIONS

The occurrence of events without particle production, in which energy and momentum spectra of emitted protons are practically the same as the spectra in events with particle production, leads to the conclusion that:

a) The nucleon emission process proceeds independently of the particle production process;

b) Fast nucleon emission may occur in some of hadron-nucleus collisions in advance of the particle production, like the ionization of atoms by energetic charged hadron in its passage through a material occurs in advance of the collision with an atomic nucleus leading to the particle production.

The n_p-independence of the energy and momentum spectra of emitted protons allows one to conclude the knocking-out mechanism of nucleon emission does not seem to play any important role in fast nucleon emission observed.

The independence of the energy and momentum spectra of emitted protons on the multiplicity n_π of produced pions indicates that the observed outcomes in hadron-nucleus collisions appear in result of decay outside the target nucleus of some intermediate objects created at first inside it.

5. REMARKS

The conclusions formulated above do not contradict the law of particle production in hadron-nucleus collisions, formulated in our previous work[14]: Various frequency distributions characterizing the particle production process in hadron-nucleus collisions at an energy E are the composition of some number m of corresponding statistically independent frequency distributions characterizing the particle production process in hadron-nucleon collisions at the average energy E/m.

The properties of the energy and momentum spectra incline us to expect the n_p- and n_π-independences of fast nucleon angular distributions as well.

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Энергетические и импульсные спектры нуклонов, испущенных в столкновениях адронов высоких энергий с ядрами

Исследуются энергетические и импульсные спектры "быстрых" протонов с кинетическими энергиями от ~20 до ~400 МэВ, в столкновениях пион-ксенон при 3,5 ГэВ/с, в двух классах событий: когда частицы рождаются и когда рождения частиц не происходит. Спектры практически одинаковы в обоих классах событий и в подклассах, в которых наблюдаются разные кратности испущенных протонов. Полученные результаты позволяют заключить, что: 1/ процесс испускания нуклонов происходит независимо от процесса рождения частиц; 2/ прямое выбивание нуклонов не играет какой-либо заметной роли; 3/ рождение частиц происходит через какие-то промежуточные объекты, рожденные сначала в ядре-мишени и распадающиеся после выхода из него.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1983

Strugalski Z. E1-83-155

Energy and Momentum Spectra of Nucleons Emitted in High Energy Hadron-Nucleus Collisions

Energy and momentum spectra of "fast" protons, of kinetic energy from about 20 to about 400 MeV, are studied in pion-xenon nucleus collisions at 3.5 GeV/c momentum, in two samples of events - when particles are produced and when particle production does not occur. The spectra are practically the same in both the samples of events and in corresponding subsamples of events - with various multiplicities of emitted protons. Results obtained allow one to conclude that: 1) The fast nucleon emission process proceeds independently of the particle production process; 2) The knocking-out mechanism of the fast nucleon emission does not play an important role in observed emission of protons; 3) Particle production proceeds via some intermediate objects created at first inside target nucleus and decaying after having left it.

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

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