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PASSAGES OF HIGH ENERGY HADRONS THROUGH ATOMIC NUCLEI

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INTRODUCTION

During past few years a great deal of our attention has been given to studies of the properties of intranuclear matter and interactions with it of accelerated hadronic projectiles.

The subject matter in this work is to describe the obtained unique experimental data from the point of view of their applicability for the new safe power engineering and chemical elements transformation technology. The data were obtained in observing the nuclear collisions of fast strongly interacting particles (hadrons) with atomic nuclei in the 180 litre xenon bubble chamber [1–3] of the ITEPh (Moscow Institute of Theoretical and Experimental Physics).

In this chamber, all electrically charged products of the collision reactions were registered with the efficiency similar to that in other track detectors [1]. Additionally, the neutral pions (π^0) are registered with the efficiency of about 100 %, if with energies equal to 0 or higher than 0. It provided a possibility of performing almost «total» experimental investigations of the collision processes at projectile momentum from about 2 up to about 9 GeV/c [4,5].

The nuclear (strong) interactions of the incident high energy hadrons with atomic nuclei give rise to a great variety of secondary phenomena observable in the chamber: *the ejection of fast (20–500 MeV) nucleons* from the target nucleus, the *«evaporation» of nucleons and light nuclear fragments (N, D, T, He)* from the target nuclei, *multiple hadron creation.* The emission (ejection) of the «fast» nucleons and the multiple hadron creation are the most frequently occurring and observed expressive phenomena.

At first sight on a xenon chamber photographs (and on photographs from other heavy liquid bubble chambers as well) the pictures registered are sometimes almost indecipherable, because many tracks of secondary particles cover themselves even if only one collision event is recorded on a photograph. But, special analysis, based on three stereophotographs for any event, allows one to obtain correct picture.

New experimental information obtained this way allowed one to analyse, from a new point of view, the wealth of experimental data on hadron–nucleus collisions at energies available — up to some thousands GeV — from cosmic rays as well, e.g.

The π^0 mesons in about 98 % of events decay after lifetime of about 10^{-17} s into two gamma quanta with energies as large as the half of the rest mass of π^0 mesons. The gammas of such energies are detectable effectively by creation of visible well (e^+e^-) pairs, by the method worked out [4].

And so, the chamber should be large enough. The development of the registered picture of some physical process must be totally expressed. The numbers of the photographs, obtained during the chamber exposition, must be statistically satisfactory. The numbers of the photographs were large enough — hundred thousands, up to millions. The chamber used may be accepted as the total geometry track detector, its dimensions were $103 \times 44 \times 40$ cm^3.

Firstly, the exposition of the chamber in beams of 3.5 GeV/c momentum negatively charged pions was realized for the investigations of the generation and decays of neutral bosons into neutral pions and gamma quanta. The main results of those works were published. Now, some part of those photographs, about 200,000, were used in this work as well — for investigations of the hadron–xenon nucleus nuclear collision processes at 3.5 GeV/c momentum. This part of photographs was analyzed in the Laboratory of High Energies at the Joint Institute for Nuclear Research in Dubna and at the Particle Physics Laboratory in the Faculty of Technical Physics and Applied Mathematics at Warsaw University of Technology. The data in this work were obtained at the Institute of Atomic Energy in Swierk, Poland. Of special interest was then the applicability of the results in new power engineering and elements transmutation technology — in order of working out methods for radioactive waste neutralization.

1. SCANNING AND EXPERIMANTAL MATERIAL ACCUMULATION

It was stated conclusively that in observing the hadron–nucleus collision events on the chamber stereophotographs, when the projectile hadrons are of high energies — over the pions creation threshold, one meets in fact two sorts of the hadron–nucleus collision processes: one is some *soft* collision, in which incident hadron does not cause the multiple creation of secondary hadrons. There are the passages of the projectile (incident hadron) through the target nucleus accompanied by the *ejection* of «fast» ($\sim$ 20–500 MeV) target nucleons and light nuclear fragments (N, D, T, α).The second one, *hard*, is the process, which happens on the background of the first one — the secondary hadron creation occurring sometimes on the «*pure passage*» of the incident hadron through intranuclear matter. The «fast» nucleon emission is a *general process*, which accompanies the hadron passage through layers of intranuclear matter. There are the «fast» nucleon emission in events when the particle creation does not occur, at all. The characteristics of the emitted protons (nucleons) — the energy and distributions mainly — are the same in both the cases.

1.1. Results of the Scanning

- The percentage of the stoppings of the projectile hadrons inside the xenon target nucleus depends on the projectile energy value. The photographs from the smaller 26 litre xenon bubble chamber of the LHE JINR (Laboratory of High Energies, Joint Institute for Nuclear Research) exposed in beams of pions at energies 2.34, 5 and 9 GeV allow one to prepare the table.

Table 1. The percentage (%) of the stopping events of the pionic projectile inside xenon target nucleus, in dependence on its momentum

P_π, GeV/c	2.34	3.50	5.00	9.00
%	15	10.6 ± 0.5	0.5 ± 0.5	0.0 ± 0.5

- The emission intensity of the nucleons from the nuclear targets does not depend on the particle creation process. The energy and angular spectra of the emitted «fast» nucleons are identical in events with creation of secondary hadrons and in the events without production of secondary hadrons. It may indicate that the produced hadrons are generated via some *intermediate objects*.
- Any hadron fast enough in passing through layers of the intranuclear matter causes the emission of the nucleons ($\sim$ 20–500 MeV). The intensity (multiplicity) of the emitted nucleons equals the number n_N of nucleons met by the projectile hadron at the distance not larger than the range of the strong interaction is. In other words, the incident hadron interacts locally within the target nucleus.

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

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

$$\pi^- + Xe \rightarrow \pi_0^- + R_e + n_p + f, \qquad (1b)$$

where π^- — pionic projectile and π_0^- — outcoming projectile pion, R_e — residuary xenon nucleus, f denotes nuclear «evaporated» fragments, n_p — intensity or number of emitted fast protons, which occur in the fiducial region of nearly $42 \times 10 \times 10$ cm^3 volume situated coaxially and centred inside the volume $103 \times 44 \times 40$ cm^3 of the chamber.

In total, about 200,000 photographs were scanned. The events selected in the scanning were analyzed.

2. EXPERIMENTAL DATA

In addition to former experimental data published in series of the papers [6–8], the new data are:

1. Additional argumentation is obtained in support of the existence of the physical process known as the *passage* of the high-energy hadron through layers of intranuclear matter. In this work, the observation of this process (the passage) emerges just during the chamber photographs scanning — in the sample of the *soft* collisions.

2. The new argumentation in support of the existence of the *intermediate objects in the hadron multiple creation process.* The objects called in former papers «generons», here emerge as well.

3. The hadron–nucleus collisions are local — the «track» of the hadron passage may be determined experimentally (at the impact of the projectile within the target nucleus).

4. The damage of the target nucleus in the collisions is strictly local. The damaged part of the target nucleus is evidently smaller than the diameter of the nucleus.

5. Some information on the energy and angular spectra of emitted «fast» protons is of impostance for applications for the power technology and for element

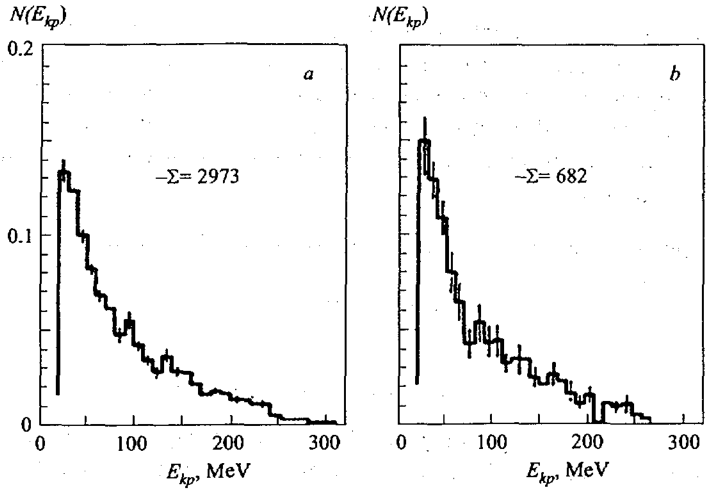

Fig. 1. Proton kinetic energy E_{kp} spectra $N(E_{kp})$ in samples of events of the type (1a) and of the type (1a) and (1b) together; Σ is the number of protons in the histogram. Pion–xenon nucleus collisions are without particle production at 3.5 GeV/c momentum

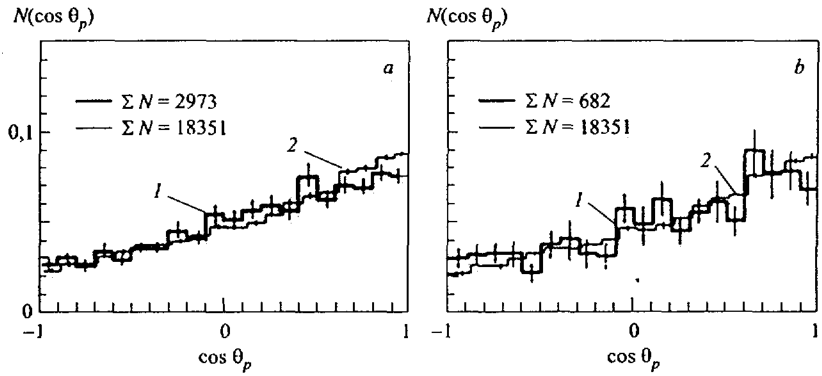

Fig. 2. Distributions N $(\cos\theta_p)$ of cosine of the emission angle θ_p of fast protons, of kinetic energy from about 20 to about 500 MeV, in various samples of pion–xenon nucleus collisions at 3.5 GeV/c momentum: *a*) in the sample containing collision events without particle production, when incident pion is absorbed inside the target nucleus or deflected in traversing it, histogram *1*, and in the sample of anytype collision events, histogram *2*; *b*) in the sample of collision events without particle production when incident pion is absorbed inside the target nucleus, histogram *1*, and in the sample of anytype collision events, histogram *2*. ΣN is the number of protons in the histogram

transmutations — for radioactive waste liquidation by beams of accelerated hadrons.

6. The kinetic energy E_{kp} of the emitted protons is identical in the events of the reactions of the type (1a) and (1b); Fig. 1.

7. The distributions $N(\cos\theta_p)$ of cosine of the emission angle θ_p of fast protons, of kinetic energy from about 20 to about 500 MeV, in various samples of pion–xenon nucleus collisions at 3.5 GeV/c momentum are almost identical; Fig. 2.

3. CONCLUSIONS AND REMARKS

1. Conclusive information has been obtained experimentally on the existence of observable subnuclear phenomenon — the hadron passage through nuclei (through layers of intranuclear matter) at hadron energies higher than pion creation threshold.

2. The laws of fast (~20–500 MeV) protons (nucleons) emission accompanying the passages described by us formerly are supported in new investigations as quite correct.

Table 2. Characteristics of the emitted protons kinetic energy $\langle E_{kp} \rangle$ in dependence on n_p in $\pi^- + Xe$ nuclear collisions without hadron production at 3.5 GeV/c momentum in the sample of events of the type (1a) and (1b) reactions, together; n_p — intensity or number of emitted fast protons. Energy is in MeV

Quantity	n_p									
	≥ 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

Table 3. Characteristics of the emitted protons kinetic energy $\langle E_{kp} \rangle$ in the sample of events of the type (1a) reaction without any secondary pion, $n_\pi = 0$, and in the sample of events of the type (1a) and (1b) reactions, together — with one negatively charged secondary pion, $n_\pi \leq 1$, for protons emitted in any direction and for protons emitted into forward «F» or into «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

3. Pure hadron passages through target nuclei can be simply selected during a chamber photographs scanning.

4. The general law of the hadron passage is: Any hadron of kinetic energy higher than the pion production threshold causes the fast nucleon emission from the target nuclei in traversing them — along a path λ [fm]; after the nucleon emission light nuclear fragments (N, D, T, He) «evaporation» starts.

5. The number n_N of the emitted nucleons equals the number of nucleons contained within the cylindrical volume $v = \pi D_0^2 \lambda$ [fm^3] centred on λ within the target nucleus:

$$n_N = \pi D_0^2 \lambda \langle \rho \rangle,$$

Table 4. Characteristics of the proton longitudinal momentum $\langle P_{Lp} \rangle$ distributions in π+Xe nuclear collisions without particle production at 3.5 GeV/c momentum in the sample of events of the type (1a) and (1b) reactions, together, $n_\pi \leq 1$, and in the sample of events of the type (1a), $n_\pi = 0$; n_p — intensity or number of emitted fast protons. Momentum P_{Lp} is in MeV/c units

	n_p										
	$n_\pi \leq 1$										$n_\pi = 0$
Quantity	≥ 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

Table 5. Characteristics of the proton transverse momentum $\langle P_{Tp} \rangle$ distributions in π = Xe nuclear collisions without particle production at 3.5 GeV/c momentum in the sample of events of the type (1a) and (1b) reactions, together, with various numbers of n_p of emitted protons. Momentum P_{Tp} is expressed in MeV/c units

	n_p									
Quantity	≥ 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

where D_0 [fm] is the diameter of nucleon and $\langle \rho \rangle$ is the mean density of nucleons inside the volume v in [nucleons/fm^3]. The D_0, λ, $\langle \rho \rangle$ are estimated experimentally — from the works of Hofstadter [8] and of E. Strugalska-Gola, Z. Strugalski [9].

6. Many aspects about the intranuclear matter distribution and the hadron passages through it are now so firmly established that it has been possible to use them in order to investigate other quantities.

7. The experimental results obtained in investigations of the «hadron passages» may be considered as a new step for experimental investigations of the nuclear forces.

8. The experimental data presented here in the tables should be very helpful in investigation of the possibilities how to use hadron–nucleus and nucleus–nucleus collisions at high energy for nuclear energy extractions. In our opinion it is possible to do it [7,6,10].

Table 6. Characteristics of angular distributions $\langle\theta_p\rangle$ of the emitted protons in $\pi + Xe$ nuclear collisions at 3.5 GeV/c momentum with $n_p \geq 1$, $n_p = 1, 2, \ldots, 8 \geq 9$, for two samples of events: sample (1a) of events in which particle production does not occur, but incident pion is absorbed inside the target nucleus or deflected in the passage through it; sample (1b) containing any-type collision events. θ — proton emission angle in degrees; Σn_p —number of events at a given n_p

n_p	Σn_p		$\langle\theta_p\rangle$		r.m.s.		Skewness		Kurtosis	
	a)	b)	a)	b)	a)	b)	a)	b)	a)	b)
≥ 1	2973	18351	76.7	74.7	37.3	37.5	0.32	0.36	-0.51	-0.59
1	165	1120	67.0	68.6	27.1	36.5	0.51	0.53	0.15	-0.28
2	180	1804	76.6	70.4	37.2	37.0	0.37	0.42	-0.53	-0.50
3	150	2193	77.8	74.6	37.8	37.1	0.42	0.31	-0.53	-0.70
4	208	2392	76.4	74.9	35.5	37.5	0.32	0.37	-0.31	-0.55
5	240	2689	79.2	76.0	38.6	37.8	0.13	0.35	-0.62	-0.59
6	342	2502	77.4	76.3	37.4	37.8	0.23	0.33	-0.72	-0.64
7	308	1890	76.3	74.6	36.8	36.8	0.18	0.29	-0.77	-0.64
8	360	1600	77.4	75.5	37.5	37.8	0.30	0.35	-0.44	-0.59
≥ 9	1020	2161	77.4	77.1	38.5	37.7	0.35	0.34	-0.51	-0.62

9. Important property of the obtained data is its applicability in physics and technology. The new, what is of a creative character, is the experimental information that the collision processes and the damage of the target nuclei are local; it is not the model but the experimental fact.

10. It may be stated conclusively that in observing hadron–nucleus collision in any track detector at high energies, one may observe in fact two collision processes — superimposed and independently occurred: 1. The first one — soft pure nuclear collision process; 2. The second one — the hadron–nucleon head-on hard collision process, as proceeding on the background of the first one. In the pure nuclear collision process, on the background of the passage of the incident hadron through intranuclear matter, the creation (production) of secondary hadrons may occur sometimes (in projectile hadron collision with one of downstream nucleons on the course of the projectile inside the intranuclear matter).

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