сообщения
объединенного
института
ядерных
исследований
дубна

E1-88-211

Z.Strugalski[1], T.Pawlak[1], W.Peryt[1], M.Alrohiah[1],
M.Mousa[1], S.El-Sharkawy[1], B.Sredniawa[2], K.Miller,
J.Pluta[1]

EXPERIMENTAL STUDY OF HADRON PASSAGE THROUGH INTRANUCLEAR MATTER

[1] Institute of Physics of the Warsaw Technical University,
Warsaw, Poland.
[2] Institute of Physics of the Jagiellonian University,
Cracow, Poland

1988

1. INTRODUCTION

The interaction of high energy hadrons with atomic nuclei gives rise to a great variety of phenomena; the nucleon emission, particle generation, and nuclear fragment evaporation are the most frequently occurring and observed. In analysing pion-nucleus collisions on photographs of the xenon bubble chamber, where practically all the produced particles including neutral pions of kinetic energy equal 0 or larger than 0 are detected and recorded effectively enough, events have been observed at energies of the projectiles from about 2 up to about 9 GeV in which no any of particles which could be produced emerge, but intensive emission of nucleons occurs /1/; the emitted nucleons are "fast" — of kinetic energy from about 20 up to about 400 MeV, as is known from the measurements of energies of the emitted protons. At the lower energies, at 2-3.5 GeV, one charged pion is observed among the collision reaction products in some part of the events only; we are inclined to assume it to be the projectile pion which traversed the target nucleus. In other part of events at these energies no any pion is emerged, and we assume them to be such events in which the incident pion stopped inside the target nucleus. At higher energies, over about 4 GeV, "stoppings" do not occur at all, only the "passages" are observed plentifully.

The passages of hadrons through atomic nuclei, and through nuclear matter in general, may be an analogy to the penetration of fast charged particles through materials, and the nucleon emission occurring in association with the passages may be a secondary effect caused by a process in nuclear matter which corresponds in its rough similarity to the charged particle energy loss process in materials. The observations of the passages should be expected as well, by reason of: the mean free paths of hadrons in nuclear matter corresponding to the total hadron-nucleon collision cross-sections are in many cases of the order of the nuclear matter layer thicknesses involved in collisions of hadrons with massive target nuclei, or larger than these thicknesses. But, such events could not be observed in experiments in which all the pions including neutral ones are not registered with efficiencies high enough — near to 100%.

The finding of the passages and understanding them shall be of a great value for application of the target nuclei as fine detectors of properties of the particle production process at its initial stage — in statu nascendi — in hadron-nucleon collisions. Studies of the process may throw as well a light ral particles produced were not observed effectively enough. In fig. 1 one of such "passages" registered in the chamber is presented.

In fig. 2, the proton multiplicity distributions are shown in the classes of events of the type (1) and (2), and in the sample of any-type collisions.

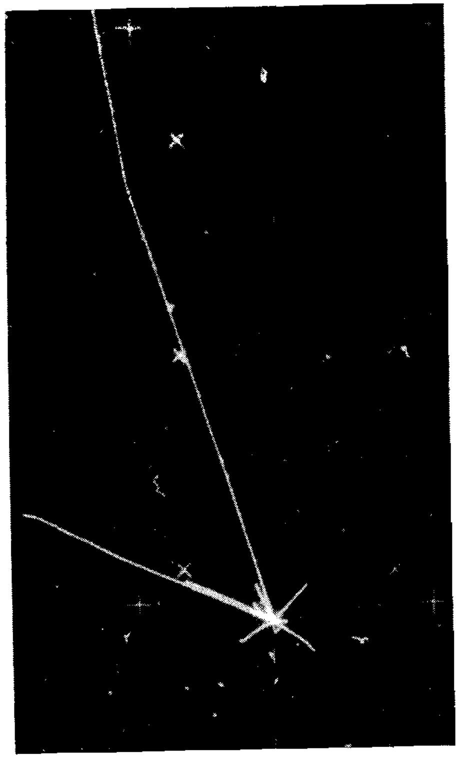

Fig. 1. The passage of the incident pion through xenon nucleus. The pion traversed the target nucleus, left it and escaped the chamber (the longest track); shorter tracks are left by the fast protons emitted in the collision.

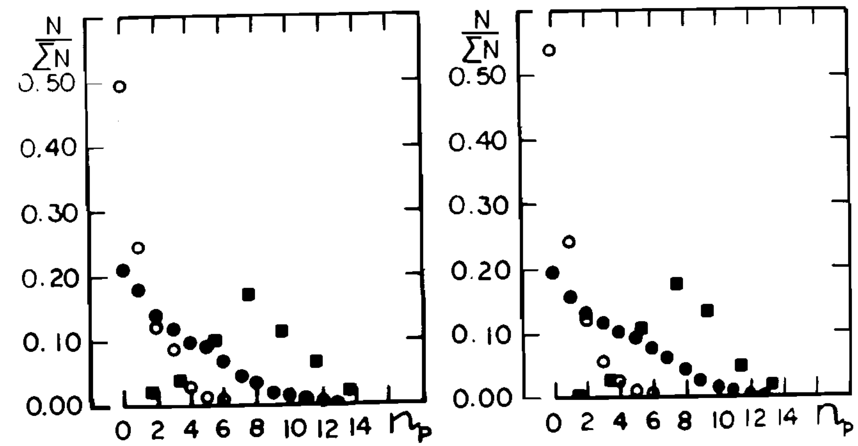

Fig. 2. Proton multiplicity n_p distributions $N(n_p) = N/\Sigma N$ in pion-xenon nucleus collisions at 3.5 GeV/c momentum: O – the passages, ■ – the stoppings, ● – any-type collisions. Left side – experimental data, right side – predictions given by corresponding formulas presented in section 4. N – number of events at a given proton multiplicity.

The distributions of the events of the type (1) and (2) are different, and they differ from the distribution for any-type events; the mean proton multiplicity in the any-type events is $< n_p > = 3.20 \pm 0.01$, that in the stoppings is $< n_p > = 7.4 \pm 0.3$, and that in the events without particle production — in the passages and stoppings together — is $< n_p > = 3.31 \pm 0.26$.

The distribution for the stoppings is almost symmetrical relatively to the mean proton multiplicity $< n_p >$. It is reasonable to consider the events to be such in which the projectiles fell on the target nucleus parallelly to its diameter at the impact parameter short enough, at $b \approx 0$, when the nuclear matter layer thickness is sufficiently large; at 3.5 GeV/c stoppings occur in about 2% of the any-type collisions, the passages occur when collisions happen at larger impact parameters — when the nuclear matter layer thicknesses are smaller. Then, the stoppings and passages are the events of the same character, but in the stoppings the hadron path ends off within the target nucleus, because the hadron energy is too low for covering the nuclear matter layer involved in the collision.

The occurrence of the stoppings depends on the incident pion energy, therefore. In scanning of photographs of the 26 litre chamber, we obtained that at 2.34 GeV/c momentum stoppings are in about 12% of the any-type collision events; at 3.5 GeV/c, in about 2%, at 5 and 9 GeV/c the percentage is practically 0. It leads to the conclusion that some range-energy relation exists for hadrons in nuclear matter; at 3.5 GeV/c this range for the incident pions is as large approximately as the xenon nucleus diameter is.

In both the cases under discussion — in the stoppings and passages — intensive emission of fast protons is observed; such protons are known as the g-track leaving particles [3]. Identical emission occurs in the any-type collisions, when at 3.5 GeV/c particles are produced in more than about 90% of the events. The transverse and the longitudinal momentum spectra, and the angular distributions of the emitted protons in various classes of events are practically the same [2]. It is reasonable to extrapolate this result on the neutron emission as well, or on all the nucleons as a whole.

4. DATA ANALYSIS

Suppose to be true our conclusion, formulated in section 3, that stoppings here correspond to the passages of the incident pions through nuclear matter layer as thick as the maximum thickness λ_{max} of the target nucleus is. Let, for convenience, express this thickness in nucleons per some area S units, in (nucl/S). The thickness can be expressed in protons per S units as well, in (prot/S), because in average the proton-nucleon ratio is almost as large as Z/A, where Z and A are the charge and mass numbers of the target nucleus[4,5]. The thickness of the nucleus can be determined using the known nucleon density distribution in it, for example — the Fermi distribution[4]. Similarly, the mean thickness $<\lambda>$ of the target nucleus, and the thicknesses $\lambda(b)$ at various distances b from the center of a nucleus in (nucl/S) or in (prot/S), can be determined. The distribution $W[\lambda(b)]$ of the thicknesses $\lambda(b)$ of nuclear matter layers in a nucleus can be calculated this way, as well. As the S quantity it is reasonably to apply $S = \pi D_0^2 = 10 \cdot 3$ fm^2, where D_0 is the nucleon diameter. For the xenon target nucleus, the calculations give. $\lambda_{max} = 18.66$ (nucl/S) or $\lambda_{max} = 7.69$ (prot/S); $<\lambda> = 8.52$ (nucl/S) or $<\lambda> = 3.51$ (prot/S). These values should be treated as experimentally obtained, in nuclear structure studies[4].

Comparisons of the values calculated with corresponding data obtained experimentally and presented in section 3 lead to the conclusion that: a) The mean multiplicity of the emitted protons $<n_p> = 7.4 \pm 0.3$ in the stoppings at 3.5 GeV/c momentum equals the calculated number of the protons $n_p = \lambda_{max} S = 7.7$ contained within the cylindrical volume $\lambda_{max} S = DS$ centered on the nucleus diameter D. b) The mean multiplicity of the emitted protons $<n_p> = 3.31 \pm 0.26$, in the sample of the events without particle production, is almost the same as the number of protons $<\lambda>S = 3.51$ contained within the volume $<\lambda>S$ centered on the mean path of the incident pions in nuclear matter; this mean path corresponds to the mean nuclear matter layer thickness $<\lambda>$ (prot/S) in the xenon nucleus.

The findings presented above lead obviously to simple relation between the mean multiplicity $<n_p>$ of the emitted fast protons and the nuclear matter layer mean thickness $<\lambda>$ (nucl/S) involved in the collisions:

$$<n_p> = \frac{Z}{A} <\lambda> S \left(1 - e^{-\frac{<\lambda>}{\lambda_t}}\right), \qquad (3)$$

where $\lambda_t = 1/\sigma_t$ is the hadron mean free path in (nucl/S), σ_t is the total hadron-nucleon cross-section in (S/nucl).

In searching for effects of the particle production process on the nucleon emission process, it has been found that the particle production does not effect on the nucleon emission intensity at any energy of the incident hadrons; at energies higher than a few GeV it is seen simply — the mean multiplicities of the emitted fast protons are almost energy-independent, for example. It leads to the conclusion that formula (3) may be applicable for any-type collisions. Simple comparison of predictions of this formula with corresponding experimental data shows that it is the case (the Table).

In attempts to describe the proton multiplicity distribution $N(n_p)$ in the stoppings, fig. 2, we found that the binomial distribution:

$$P(n_p) = C_{DS}^{n_p} \left(\frac{Z}{A}\right)^{n_p} \left(1 - \frac{Z}{A}\right)^{DS - n_p}, \qquad (4)$$

Table

Mean multiplicities of fast protons $<n_p>$ emitted in hadron-nucleus collisions at various energies: experimental data and predictions by formula (3).

Reaction	Energy, GeV	$<n_p>$ experiment & ref.		$<n_p>$ calc.
$\pi^- + Xe$	3.5	3.20 ± 0.01	/2/	3.19
$p + AgBr$	200	2.64 ± 0.10	/6/	2.99
$\pi^- + Em$	60	2.04 ± 0.12	/6/	1.90
$\pi^+ + Al$	250	1.2 ± 0.1	/7/	1.23
$\pi^+ + Au$	250	3.7 ± 0.3	/7/	3.71
$K^+ + Al$	250	1.2 ± 0.06	/7/	1.09
$K^+ + Au$	250	3.3 ± 0.2	/7/	3.54

expresses it quantitatively[2], where $D \equiv \lambda_{max}$ is in (nucl/S); for the xenon nucleus $D = 18.58$ (nucl/S); $C_{DS}^{n_p} = [n_N!]/[n_p!(n_N - n_p)!]$ and $DS = \lambda_{max} S = n_N$. χ^2-test shows that the distributions, the experimentally obtained $N(n_p)$ and the $P(n_p)$ given by formula (4), are practically the same[2]. Physically, it means that in traversing the target nucleus along its diameter D the hadron meets always $n_N = DS$ = const nucleons around its course and among the nucleons met the number n_p of the protons fluctuates, and all the protons met are emitted and observed as the fast protons.

Reasonably, therefore, to suppose that such charge fluctuations occur along any path of a hadron in a nucleus, and the number of the fast nucleons emitted equals the number n_N of the nucleons contained within cylindrical volume λS centered on the path and involved in interactions. Then, formula for the proton multiplicity distribution in any-type hadron-nucleus collisions will be obviously:

$$N(n_p) = \sum_{n_N = 1}^{n_N = DS} W_0(n_N) \left(1 - e^{-\frac{n_N}{n_t}}\right) C_{n_N}^{n_p} \left(\frac{Z}{A}\right)^{n_p} \left(1 - \frac{Z}{A}\right)^{n_N - n_p} \qquad (5)$$

for $n_p = 0, 1, 2, 3, \ldots, n_N$, where $W_0(n_N) = W_0(\lambda S)$ is the probability that incident hadrons hit on nuclear matter layers of the thicknesses λ (nucl/S) and meet $\lambda S = n_N$ nucleons around their paths in target nuclei; $n_t = \lambda_t S$ is the number of nucleons met by the incident hadron on the path in nuclear matter as long as the mean free path λ_t (nucl/S) is. $W_0(n_N)$ is determined by the Fermi distribution[4].

Formula (5) contains the A-dependence of $N(n_p)$, because $W_0(n_N) = W_0(\lambda S)$ depends on A; it contains the energy- and hadron identity-dependence as well, through the σ_t energy- and hadron identity-dependences. It can be applied without any limitations at energies over a few GeV, at lower energies energy loss of hadrons inside target nuclei should be taken into account in calculating the distribution $W_o(n_N) = W_o(\lambda S)$.

The proton multiplicity n_p distribution $N_w(n_p)$ in the class of the events without particle production, or in the passages, should be then $N_w(n_p) = N(n_p)e^{-n_N/n_i}$, where $\lambda_i = 1/\sigma_i$, and σ_i is the inelastic hadron collision cross-section in (S/nucl), $n_i = \lambda_i S$, $N(n_p)$ is defined by formula (5).

In fig. 2, comparison of the experimentally obtained proton multiplicity distributions in various classes of events with corresponding distributions given by the formulas presented above is shown. Formula (5) has been tested experimentally for pion-, kaon-, and proton-nucleus collisions at energies from about 3 up to about 400 GeV; as an example, in fig.3, the testing for the pion-xenon nucleus collisions at 3.5 GeV/c momentum is presented.

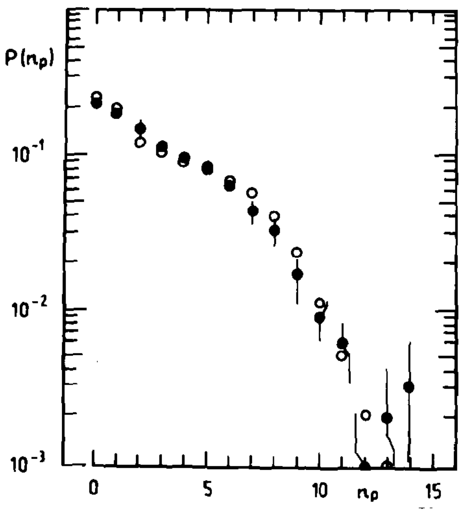

Fig. 3. Experimental testing of the formula (5); ● – experimental data on proton multiplicity n_p distribution $P(n_p)$ in pion-xenon nucleus collisions at 3.5 GeV/c momentum, O – predictions given by formula (5).

5. CONCLUSIONS

A short conclusion review may be useful and give a summary of this work. 1) High energy hadrons can pass through nuclei without causing the particle production; the passage is accompanied by fast nucleon emission in a strictly definite manner; the number n_N of the emitted nucleons is $n_N = \lambda S(1 - e^{-\lambda/\lambda_t})$, where λ in (nucl/S) is the nuclear matter layer thickness passed. 2) The nucleon emission in the collisions without particle production proceeds in the same manner as the emission in any-type hadron-nucleus collisions, when particles are produced. 3) The nucleon emission intensity, or multiplicity, in hadron-nucleus collisions is determined by the target nucleus geometry — by the target nucleus size and the nucleon density distribution in it. 4) Hadrons, in their passages through nuclear matter, see the nucleon density distribution in the target nuclei as stable in which the proton-nucleon ratio fluctuates in definite manner. 5) Hadrons lose their energy in passing through nuclear matter, the nucleon emission may be the observed phenomenon related to the energy loss; stoppings of hadrons in nuclear matter occur.

This work is performed with support in CPBP Programme 01.09 in Poland.

REFERENCES

1. *Strugalski Z., Pluta J. – Sov.Journ.of Nuclear Phys., 1974, 27, 504.*
2. *Strugalski Z., Pawlak T., Pluta J. JINR Communications, E1-82-718, E1-82-719, E1-82-841, E1-83-234, E1-85-888, Dubna.*
3. *Powell C.F., Fowler P.H., Perkins D.H. The Study of Elementary Particles by the Photographic Methods, Pergamon Press, London. 1959.*
4. *Elton L.R.B. Nuclear Sizes, Oxford University Press. 1961.*
5. *Strugalski Z. – Nuclear Phys., 1966, 87, 280;*
   Strugalski Z., Miller K. JINR Communications, E1-81-781, Dubna, 1981.
6. *Babecki J., Nowak G. – Acta Phys.Polonica, 1978, B9, 401.*
7. *Verbeure F. 1983 Lake Tabo Meeting; NA22 Collaboration, XV Symposium on Multiparticle Dynamics, Lund, 1984.*

Received by Publishing Department
on March 30, 1988.