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FORMULAS FOR DESCRIPTION OF NUCLEON EMISSION INTENSITY IN HADRON-NUCLEUS COLLISIONS

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1. INTRODUCTION

Among many processes which take place when atomic nuclei are bombarded by hadrons at high energies - at energies higher than the pion production threshold - the emission of "fast" nucleons from the target nuclei plays important role. The emitted nucleons are "fast" - with kinetic energies from about 20 up to about 400 MeV, and are known as the "g-track leaving particles", if protons are recognized in photonuclear emulsions.The presence of events in which intensive emission of nucleons appears without ejection of particles which could be produced[1,2], and experimental finding that the particle production process in hadron-nucleus collisions does not influence the nucleon emission process at any projectile energy[3], cause us to be inclined to conclude that the nucleon emission process proceeds independently of the particle production, and any collision of a hadron with an atomic nucleus can give rise to the nucleon emission. In most of experiments the emission of "fast" protons is observed only, the neutron emission leaves almost unobserved in the detectors in use now.

The nucleon emission may be characterized simply by the multiplicity n_N and by n_N-distribution of the emitted nucleons, by energy and momentum spectra, and angular distributions of the nucleons. The nucleon multiplicity n_N, or the proton multiplicity n_p only, may serve as a natural measure of the nucleon emission intensity.

We limit ourselves here to considerations about the nucleon emission intensity, or correctly, about the proton emission intensity mainly. We would like here to describe the nucleon emission intensity simply and quantitatively, on the basis of the picture of this process obtained experimentally in our studies[1-3], performed by means of the Dubna JINR 26 litre xenon bubble chamber exposed to 2.34 GeV/c momentum positively charged pions and to 5 and 9 GeV/c momentum negatively charged pions, and by means of the Moscow ITEPh 180 litre xenon bubble chamber exposed to negatively charged pions at 3.5 GeV/c momentum. In forming our viewpoint, results obtained in various other experiments[4-15] and our data on energy and momentum spectra[16], and angular distributions[17] of the emitted fast protons at various incident hagrons played important role.

What does it mean "To describe a physical process quantitatively?". A number of examples from the history of physics

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teach the general procedure by which we acquire physical understanding, creating finally a picture of the process and its quantitative representation by a formula. There are three elements prerequisite to an understanding a physical phenomenon: a) Qualitative picture of the phenomenon; b) Precise knowledge of the behaviour of the variables characterizing the phenomenon; c) Boundary conditions.

The purpose of the present paper is to put on record results of our efforts, to express by formulas the characteristics of the intensity of emission of nucleons in hadron-nucleus collisions at high energies. The formulas are not simple fittings of the experimental data, they are based on physical motivations only, and do not contain free parameters.

2. EMPIRICAL BASIS

The empirical basis which is to be presented now was found in experimental studies of hadron-nucleus collisions at incident hadron energy from about 2 up to about 9 GeV, and in the analysis of appropriate data available /4-15/ up to about 3500 GeV. Results were presented in one of our earlier works /18/ and in the works cited in it.

2.1. Appropriate Facts Stated Experimentally

Here, the experimental facts are listed only which will underlie in deducing the formulas characterizing the nucleon emission intensity:

I. Hadron-nucleus collision events occur in which the projectile with kinetic energy much larger than the pion production threshold passes through massive target nucleus without causing ejection of particles which could be produced; the passages are accompanied by emission of fast nucleons; at projectile energies from about 1 up to about a few GeV stoppings of hadrons inside the target nucleus occur as well, the percentage of occurrence of stoppings decreases with projectile energy increase - at above a few GeV they do not occur at all, only passages happen relatively plentifully.

II. The nucleon emission proceeds in a strictly definite manner: a) The number of emitted nucleons n_N equals the number of nucleons met by the hadron around its course

$$n_N = \pi D_0^2 \lambda (1 - e^{\frac{\lambda}{\lambda_t}}), \qquad (1)$$

where D_0 is the nucleon diameter; here D_0 is the radius of the cylindrical region, centered on the hadron path λ, within which the nucleons are met, λ is in nucleons/S units and $S = \pi D_0^2 \approx 10.3\ \mathrm{fm}^2$; λ_t in nucl/S is the mean free path of the hadron in nuclear matter for the total hadron-nucleon interaction, connected with the elementary hadron-nucleon total cross section σ_t in S/nucleon as $\lambda_t = 1/\sigma_t$. b) The energy and momentum spectra, and the angular distributions of the emitted protons do not depend on the projectile energy and identity; the spectra and distributions are independent of the number n_p of emitted protons and of the number n_π of produced pions as well. c) Incident hadron, in passing through atomic nucleus along its diameter D, sees always the same number $n_N(D)$ = const of the nucleons around it within the $\pi D_0^2 D$ region, but the number n_p of the protons met among the n_N nucleons fluctuates as:

$$n_N = C_{n_N}^{n_p} \left(\frac{Z}{A}\right)^{n_p} \left(1 - \frac{Z}{A}\right)^{n_N - n_p}, \qquad (2)$$

where $C_{n_N}^{n_p} = n_N!/[n_p!(n_N - n_p)!]$, Z and A are the atomic and mass numbers of the target nucleus. d) Any high energy hadron loses its kinetic energy in traversing atomic nucleus; the energy ΔE_h MeV of the hadron lost on its path λ nucl/S in nuclear matter is:

$$\Delta E_h = \epsilon_h \lambda, \qquad (3)$$

where ϵ_h in MeV/(nucl/S) is the measurable coefficient - for pions /19/ $\epsilon_h = \epsilon_\pi \approx 180$ MeV/nucl/S, for protons /19/ $\epsilon_h = \epsilon_p \approx 360$ MeV/nucl/S.

III. The particle production process in hadron-nucleus collisions does not influence the nucleon emission process at any projectile energy.

IV. The distribution $W[b(\lambda S)] = W[b(n_N)]$ of the nuclear matter layer thicknesses λ nucl/S, at various impact parameters $b(\lambda S)$, $\lambda[b(n_N)]$, for a given target nucleus can be determined simply from the experimentally given nucleon density distribution in nuclei /20/ , from the Fermi distribution, for example /20/.

2.2. Qualitative Picture of the Passage of a Hadron through Nuclear Matter Accompanied by Fast Nucleon Emission

The facts presented above incline us to start with very simple picture of the passage of a hadron through nuclear matter: Any high energy hadron gives rise to fast nucleon emission from the target nucleus, in passing through it; reactions leading to the emission proceed monotonically along the hadron path. On the background of the passage and the nucleon emission associated with it, other processes may occur, for example interactions of the hadron leading to the particle production, to high energy nucleon recoils, to charge exchange processes, etc. In most of the cases when particles are produced the passage of the incident hadron goes through some distance in nuclear matter in advance of the reaction leading to the particle creation.

The number of nucleons in the target nucleus involved in the emission process is as large as the number of nucleons contained within the volume $\pi D_0^2 \lambda = S\lambda$ centered on the hadron path λ.

Within the frames of the picture presented above, various types of hadron-nucleus collisions may occur: the passages, stoppings, and events in which passages are accompanied by the particle production reactions.

3. DESCRIPTION PROCEDURE

As the measure of the nucleon emission intensity we employ the multiplicity n_N of the emitted nucleons - it is simply the observed number n_N of fast nucleons emitted in any of the collision events. Nucleon intensity distribution is expressed then naturally by the nucleon multiplicity n_N distribution $N(n_N)$ as well.

Following parameters describing the multiplicity distributions are usually of interest: a) The mean nucleon multiplicity $\langle n_N \rangle$; b) The width of the distribution defined by the square root of the second central moment, or the dispersion $D = (\langle n_N^2 \rangle - \langle n_N \rangle^2)^{1/2}$; c) The asymmetry of the distribution, as measured by the skewness $\gamma_1 = \langle (n_N - \langle n_N \rangle)^3 \rangle / D^3$; d) The kurtosis of the distribution $\gamma_2 = \langle (n_N - \langle n_N \rangle)^4 \rangle / D^4$.

In most of experiments, corresponding characteristics are obtained only for the usually observed proton multiplicities n_p; they are expressed by the same above written formulas, when the nucleon multiplicities n_N are replaced by the proton multiplicities n_p in them.

4. FORMULAS

The nucleon multiplicity n_N distribution $N(n_N)$ and the mean nucleon multiplicity $\langle n_N \rangle$ will be determined here explicitely; the quantities D, γ_1, and γ_2 may be obtained from the $N(n_N)$ and $\langle n_N \rangle$ as well.

The nucleon multiplicity distribution $N(n_N)$ is determined by the $W[b(n_N)] = W[b(\lambda S)]$ distribution of the probability for incident hadron to fall on the target nucleus at such impact parameter $b = b(n_N) = b(\lambda S)$ to which the nuclear matter layer corresponds, thickness nucl/S of which is such that $\lambda S = n_N$ nucleons are contained around the hadron course in nuclear matter λ.

The distribution $W[b(n_N)]$ is:

$$W[b(n_N)] = W[b(\lambda S)] = \int_{b(n_N+1/2)}^{b(n_N-1/2)} \frac{2b}{R_c^2} db = \begin{cases} \dfrac{[b(1.5) + 2D_0]^2 - b^2(1.5)}{R_c^2} & \text{for } n_N = 1 \\[2ex] \dfrac{b^2(n_N - 1/2) - b^2(n_N + 1/2)}{R_c^2} & \text{for } n_N = 2, 3, 4, \ldots\ldots, DS \end{cases} \qquad (4)$$

where $R_c = b(1.5) + 2D_0$. D and D_0 are the diameters of the target nucleus and of the nucleon correspondingly. With the addition of $2D_0$ the range of the hadron-nucleon interaction at the nucleus periphery is included; $b(n_N) = b(\lambda S)$ can be determined from the nucleon density distribution /20/ $\rho(r)$ in nuclei:

$$n_N(b) = \int_V \rho(r) dv, \qquad (5)$$

where $V = 2(R_c^2 - b^2)^{1/2} \cdot \pi \cdot D_0^2$ - the cylindrical interaction region centered on the hadron path $\lambda = 2(R_c^2 - b^2)^{1/2}$ in nuclear matter. Because $n_N(b)$ is strictly decreasing function of b, the reciprocal function $b(n_N)$ can be obtained from formula (5).

The mean thickness $\langle \lambda \rangle$ nucl/S of the target nucleus can be obtained from the relation:

$$S \langle \lambda \rangle = \sum_{\lambda S = 1}^{\lambda S = DS} S\lambda \cdot W(n_N) = \sum_{n_N = 1}^{n_N = DS} n_N W(n_N), \qquad (6)$$

where D is the target nucleus diameter.

Now, we are ready for writting formulas for $N(n_N)$, $\langle n_N \rangle$, and $N(n_p)$, $\langle n_p \rangle$, and then - for corresponding dispersions, skewnesses, and kurtosises as well.

4.1. Nucleon Emission Intensity n_N Distribution $N(n_N)$

Naturally, formula (4) allows one to obtain formula for $N(n_N)$:

$$N(n_N) = k W(n_N)\left(1 - e^{-\frac{\lambda(n_N) \cdot S}{\lambda_t \cdot S}}\right) = k W(n_N)\left(1 - e^{-\frac{n_N}{n_t}}\right), \qquad (7)$$

where $n_t = \lambda_t \cdot S$ and λ_t in nucl/S is the "total" mean free path of the hadron in nuclear matter related to the total hadron-nucleon cross-section σ_t in S/nucleon as $\lambda_t = 1/\sigma_t$, k - the normalization coefficient defined explicitly below.

The mean value of the nucleon emission intensity n_N is:

$$\langle n_N \rangle = \langle \lambda \rangle (1 - e^{-\frac{\langle \lambda \rangle}{\lambda_t}}), \qquad (8)$$

where $\langle \lambda \rangle$ nucl/S is given by formula (6).

4.2. Proton Emission Intensity n_p Distribution $N(n_p)$

On the empirical basis presented above, the proton multiplicity n_p distribution $N(n_p)$ may be simply written as:

$$N(n_p) = k \sum_{n_N=1}^{n_N=DS} W(n_N)\cdot(1 - e^{-\frac{n_N}{n_t}}) C_{n_N}^{n_p} (\frac{Z}{A})^{n_p} (1 - \frac{Z}{A})^{n_N - n_p}, \qquad (9)$$

where $W(n_N)$ is given by formula (4) from the nucleon density distribution in nuclei; the second factor takes into account the efficiency of hadron interaction in nuclear matter; the binomial factor accounts for the fluctuations of the electric charge in nuclear matter, which are seen by the incident hadron around its path λ ; the normalization coefficient

$$k = \sum_{n_N=1}^{n_N=SD} 1/(1 - \exp[-n_N/n_t]); \; n_N = 1, 2, \ldots, SD, \text{ but } n_N \geq n_p.$$

The mean intensity of the fast proton emission is:

$$\langle n_p \rangle = \frac{Z}{A} S \langle \lambda \rangle (1 - e^{-\frac{\langle \lambda \rangle}{\lambda_t}}). \qquad (10)$$

Formula (9) describes the nucleon emission intensity distribution in the sample of any-type collision events - when passages and particle production occur. This formula, if multiplied by the factor e^{-n_N/n_i}, describes the proton emission intensity distribution $N_{pass}(n_p)$ in the sample of the passages of the incident hadron through target nuclei without causing particle production as well, then:

$$N_{pas}(n_p) = N(n_p)\cdot e^{-\frac{n_N}{n_i}}, \qquad (11)$$

where $n_i = \lambda_i S$, and λ_i is the mean free path of the incident hadron in nuclear matter for an inelastic reaction, in nucl/S unit; λ_i is related to the inelastic hadron-nucleon cross section σ_i S/nucleon as $\lambda_i = 1/\sigma_i$.

If passages could be selected which occur along the target nucleus diameter D, we would have for corresponding distribution $N_{pasD}(n_p)$ of the emitted proton multiplicity n_p :

$$N_{pasD}(n_p) = W(n_N)(1 - e^{-\frac{n_N}{n_t}}) C_{n_N}^{n_p} (\frac{Z}{A})^{n_p} (1 - \frac{Z}{A})^{n_N - n_p}. \qquad (12)$$

When the mass number of the target nucleus is large enough, $A \geq 100$, the second factor is practically equal to one, and the normalization coefficient k, not written in formula (12), is almost one; n_N in formula (12) is definite and equal to DS, then $W(n_N)$ can be taken as equal to one, for normalization. Then, formula (12) can be rewritten, for the heavy nuclei, as:

$$N_{pas\,D}(n_p) = C_{n_N}^{n_p} (\frac{Z}{A})^{n_p} (1 - \frac{Z}{A})^{n_N - n_p}. \qquad (12')$$

Formula (12') describes as well the events when stoppings in nuclear matter occur on path lengths as large as the diameter D of the target nucleus is; such a case we observe in the xenon bubble chamber exposed to negatively charged pions at 3.5 GeV/c momentum /2/.

5. SHORT DISCUSSION AND REMARKS

In section 4, a complete set of formulas for description of the nucleon emission intensity has been given. The formulas, as deduced from empirical facts, should be regarded as found experimentally. Among the formulas, only those for characterizing the proton emission intensity are testable experimentally now, for various hadrons colliding with various nuclei, because information about neutron emission in hadron-nucleus collisions at high energies does not exist practically.

The formulas for the proton emission characteristics are applicable for the neutron emission characteristics as well, if the proton multiplicity n_p is replaced by the neutron multiplicity n_n and the ratio Z/A is replaced by the ratio (A-Z)/Z in them.

The quantities: dispersion, skewness, and kurtosis can be obtained from the formulas for the mean values of the nucleon, proton, and neutron multiplicities n_N, n_p, n_n, correspondingly, without difficulty.

A-dependences of the characteristics of the nucleon, proton, and neutron emission intensities are through the function $W(n_N)$ and the lengths $\lambda(n_N)$; the energy-dependences of the characteristics in question are through the energy-dependent mean free paths λ_t and λ_i ; the hadron identity-dependence is through the quantities λ_t and λ_i as well.

Formulas are valid without corrections at incident hadron energies above a few GeV, for the nuclei with $A \geq 12$; the same formulas are valid at lower energies as well, but in the case the dependence of hadron paths in nuclear matter on the hadron energy should be taken into account, due to the hadron energy losses in nuclear matter. Corrections may be done as it has been used to do in one of my earlier works /21/. The account for the interacting periphery of the nucleus may be performed in a different way, not as in formula (4), as well.

Some of formulas presented were tested in collisions of various hadrons with various nuclei at energies from about 1 up to about 3500 GeV.

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Стругальский З. E1-86-578
Формулы, описывающие интенсивности испускания нуклонов в столкновениях адронов с ядрами

На базе существующих экспериментальных данных выведены формулы, описывающие интенсивности испускания нуклонов в столкновениях адрон-ядро в терминах размеров ядра мишени и плотности распределения нуклонов в ядрах. Формулы не являются просто подгонкой под экспериментальные данные, их вывод базируется на глубокой физической мотивации, они не содержат свободных параметров. В формулах содержатся A- и энергетические зависимости и зависимость от того,какой налетающий адрон используется в столкновении с ядром. Формулы применимы при энергиях выше порога рождения пионов.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1986

Strugalski Z. E1-86-578
Formulas for Description of Nucleon Emission Intensity in Hadron-Nucleus Collisions

Formulas for description of the nucleon emission intensity in hadron-nucleus collisions, in terms of the data on the target nucleus size and nucleon dinsity distribution in atomic nuclei, are obtained on the basis of experimental data available. The formulas presented are not simple fittings of the data, they are based on physical motivation only, and do not contain free parameters. Formulas contain A-, energy-, and hadron identity-dependences, and are valid at incident hadron energy over the pion production threshold.

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

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