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DETERMINATION OF THE SHAPES AND SIZES OF THE REGIONS IN WHICH IN HADRON-NUCLEUS COLLISIONS REACTIONS LEADING TO THE NUCLEON EMISSION, PARTICLE PRODUCTION, AND FRAGMENT EVAPORATION OCCUR

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1. INTRODUCTION

In experimental studies of hadron-nucleus collisions, by means of the 26 and 180 litre xenon bubble chambers [1,2], results have been obtained which incline us to conclude that only a definite part of the target nucleus is involved in any of the collisions [3-5]. Three main processes occur when a hadron collides with an atomic nucleus massive enough: the emission of nucleons, the particle production, the target fragment evaporation. The question arises therefore: "What are the shapes and sizes of the regions of the nucleon emission, the particle production, and the fragment evaporation in hadron-nucleus collision?" The answer to this question should be found primarily in experiments.

Now, some newly obtained experimental information about the outcomes in the collisions may be used as the basis for a method of determination of the shapes and sizes in question.

In this paper we describe our method and we put on record results obtained by it.

2. METHOD

The method is based on the following experimental findings: a) Collision events are observed in which the incident hadron traverses the target nucleus or it is stopped in it completely without particle production; in any of such cases intensive emission of "fast" nucleons - with kinetic energy from about 20 up to about 400 MeV accompanies the collision [6,7]. b) The nucleons are emitted in a strongly definite manner - the number n_N of nucleons ejected in a hadron-nucleus collision equals the number of nucleons contained within the volume $v = \pi D_0^2 \cdot \ell$ fm^3 centered on the path ℓ of this hadron in nuclear matter:

$$n_N = \pi D_0^2 \ell \langle \rho \rangle, \qquad (1)$$

where D_0 is the nucleon diameter, $\langle \rho \rangle$ nucleons/fm^3 is the mean nucleon density inside the volume v; relation (1) may be expressed simpler

$$n_N = \lambda S, \qquad (2)$$

when $\lambda = \ell\langle\rho\rangle$ is expressed in units of nucleons/S and $S = \pi D_0^2 \approx 10\ fm^2$; instead of n_N in formula (2) the usually observed number n_p of emitted protons $n_p = \frac{Z}{A} n_N$ may be used [5], and then instead of λ in nucl/S λ in protons/S should be used. c) The particle production process does not exert any effect on the nucleon emission process [8]. d) The mean number $\langle n_b \rangle$ of charged fragments evaporated from the target nucleus in a collision depends simply on the number $n_N = \lambda S$ of the emitted nucleons:

$$\langle n_b \rangle = 1.25(n_N \frac{Z}{A} + \frac{A-Z}{Z}) = 1.25(\lambda S \frac{Z}{A} + \frac{A-Z}{Z}), \quad (3)$$

where λ is in nucleons/S, A and Z are the mass and charge numbers of the target nucleus; a physical meaning of formula (3) is that the target fragments are evaporated from a thin surface layer of the part of the target nucleus damaged in nucleon emission process [4].

Derivation of relations (1) and (2) is described in our previous works [4,5]. Formulas (2) and (3) were tested experimentally [4,5] using appropriate experimental data [9-11] at incident hadron momenta from a few up to few thousands GeV/c; quantitative agreement has been stated [12-15].

From formula (1), on the basis of experimental finding labelled by c), crucial relation between the mean number $\langle n_p \rangle = \langle n_N \rangle \frac{Z}{A}$ of the emitted and usually observed protons and the mean thickness $\langle \lambda \rangle$ of the target nucleus expressed in protons/S can be obtained [5]:

$$\langle n_p \rangle = \langle \lambda \rangle S(1 - e^{-t}), \quad (4)$$

where $t = \langle \lambda \rangle / \langle \lambda_t \rangle$ and $\langle \lambda_t \rangle$ in protons/S is the mean free path for any-type reaction of the incident hadron in the target nucleus connected with corresponding total hadron-nucleon cross-section σ_t as $\langle \lambda_t \rangle = \frac{Z}{A \sigma_t}$ and σ_t is in S/nucleon. Because $t \gg 1$, at incident hadron energies above a few GeV for target nuclei massive enough, $(1 - e^{-t}) \approx 1$ and relation (4) may be rewritten simply as:

$$\langle n_p \rangle \approx \langle \lambda \rangle S. \quad (5)$$

One can prove straight off that the mean multiplicity of the emitted protons $\langle n_p \rangle$ obeys relations (4) and (5) within the incident hadron energy region above a few GeV.

From the facts stated experimentally, labelled by a), b), and c), it is possible to deduce naturally the method for determination of the shape and size of the nucleon emission region. From the fact labelled by c), together with the facts labelled

by a) and b), it should be possible to determine the size of the region in which interactions of the incident hadron in the target nucleus occur leading to the particle production. From the fact labelled by d), together with facts a)-c), the shape and size of the region the target fragment evaporation is going on from can be determined.

3. RESULTS

In this section, results obtained will be presented shortly, as it is concerned to the nucleon emission, particle production, and target fragment evaporation processes.

3.1. Shape and Size of the Nucleon Emission Region

The shape S_N and size G_N of the nucleon emission region in a hadron-nucleus collision is determined by formula (1). The region is of cylindrical shape S_N inside the target nucleus, centered on the hadron path ℓ fm inside it; the size of this region is:

$$G_N = \pi D_0^2 \ell, \quad (6)$$

where D_0 in fm is the diameter of the nucleon.

In average, for a sample of hadron-nucleus collision events, the size of this region is:

$$\langle G_N \rangle = \pi D_0^2 \langle \ell \rangle, \quad (7)$$

where $\langle \ell \rangle$ in fm is the mean thickness of the target nucleus.

The shape and sizes (6) and (7) are independent of the incident hadron energy at energies higher than a few GeV; at lower energies, the size and the mean size decrease with the incident hadron energy decrease, because of the shortening of the thickness ℓ of nuclear matter layer involved in the collisions; the shortening is due to the monotonic hadron energy loss in nuclear matter [12], first of all.

The reactions leading to the nucleon emission happen along the incident hadron course in the target nucleus, the shape S_N of the region for these reactions is simply the hadron course ℓ in nuclear matter.

3.2. Shape and Size of the Particle-Producing Reaction Region in Target Nuclei

Particle-producing reactions of the incident hadron inside the target nucleus do not exert an influence on the nucleon emission process, it has been discovered experimentally[3-5,8]; particles are generated via some intermediate objects following predominantly the incident hadron course and decaying into observed "produced" resonances and particles after having left the parent nucleus[3]. But, any hadron traversing nuclear matter causes emission of the nucleons in a definite manner, according to formula (1), and the nucleon emission process is not disturbed by the particle-producing process. Consequently, the particle-producing reactions occur predominantly along the incident hadron course ℓ. It should be stated, from formulas (6) and (7), therefore: The region in the target nucleus where particle-producing reactions occur is linear one - predominantly along incident hadron course; the length of this region is as large as

$$G_S = \ell, \qquad (8)$$

where ℓ in fm is the thickness of the nuclear matter layer the incident hadron caused reaction with; the mean-size of the region is

$$\langle G_S \rangle = \langle \ell \rangle, \qquad (9)$$

where $\langle \ell \rangle$ in fm is the mean thickness of the nuclear matter layer involved in the collisions.

The lengths G_S and $\langle G_S \rangle$ are energy-dependent when the incident hadron energy is smaller than a few GeV, at higher energies these quantities are energy-independent.

3.3. Shape and Size of the Nuclear Fragment Evaporation Region

Geometrical and physical meaning of formula (3) is that fragments are emitted from the surface layer of the damaged, in the nucleon emission process, part of the target nucleus[4]; the shape S_b of this layer is determined by the shape S_N of the nucleon emission region; it is a tube-like region in the target nucleus, centered on the incident hadron course ℓ in nuclear matter, with the wall thickness as large as a half of the nucleon diameter D_0. The mean size of this region is:

$$\langle G_b \rangle = \pi\,[(1.5D_0)^2 - D_0^2]\cdot \ell, \qquad (10)$$

where D_0 and ℓ are in fm.

The size $\langle G_b \rangle$ is energy-independent when the incident hadron energy is higher than a few GeV.

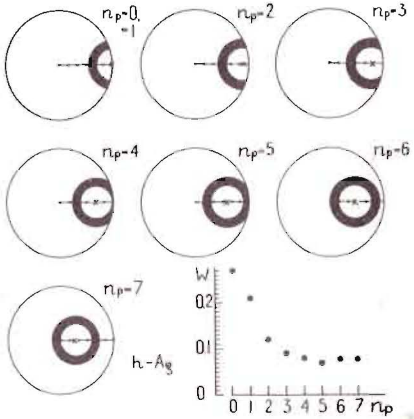
3.4. Location of the Regions in Target Nuclei

According to formula (1) and (2), for the emission of $n_p = \frac{Z}{A} n_N = 1,2,3,\ldots$ protons, the thicknesses of the nuclear matter layers $\lambda_i = \frac{n_p}{S} = \frac{1}{S}, \frac{2}{S}, \frac{3}{S}, \ldots \frac{i}{S}$ protons/S are involved in collisions correspondingly, at definite impact parameters $d_1, d_2, d_3, \ldots, d_i$. The cylindrical volumes $V_{pi} = \pi D_0^2 \lambda_i = \pi D_0^2 \frac{1}{S}, \pi D_0^2 \frac{2}{S}, \pi D_0^2 \frac{3}{S}, \ldots, \pi D_0^2 \frac{i}{S}$ centered on the incident hadron courses $\lambda_i = \lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_i$ in the target nucleus at distances $d_i = d_1, d_2, d_3, \ldots, d_i$ from its center are the regions the nucleons are emitted from; $i = 1,2,3,\ldots, n_p(D)$, where $n_p(D)$ is the number of protons contained within the volume $\pi D_0^2 D$ centered on the target nucleus diameter D.

The volumes $V_{bi} = \pi[(1.5D_0)^2 - D_0^2]\lambda_i = 1.25\pi D_0^2 \frac{1}{S}, 1.25\pi D_0^2 \frac{2}{S}, 1.25\pi D_0^2 \frac{3}{S}, \ldots, 1.25\pi D_0^2 \frac{i}{S}$, centered on λ_i are that the target fragments are evaporated from.

The particle-producing reactions in the target nuclei proceed along the lengths λ_i of the incident hadrons in the target nuclei.

In the figure the locations of the regions in question are presented schematically.



Scheme of location of the nucleon emission (empty circles), particle production (crosses), and target fragment evaporation (black rings) regions in hadron-nucleus collisions; the incident hadron h *is the proton, the target nucleus is the nucleus of the* **Ag** *atom. The incident protons fall on the target nuclei perpendicularly to the picture, from your side at points marked by the crosses. To various multiplicities $n_p = 0,1,2,\ldots,7$ correspond various thicknesses $\lambda = 1/S, 2/S, 3/S\ldots, 7/S$ of the nuclear matter layers involved in the collisions, where $S = \pi D_0^2 \approx 10$ fm² and D_0 is the nucleon diameter; at $n_p = 0$, (A/Z) -1 neutrons should be taken into account. The distances between points on the radius of the target nucleus are of $D_0/2$ fm. W is the percentage of events with $n_p = 0,1,2,\ldots,7$ emitted protons, occurring in a sample of collisions.*

4. CONCLUSIONS AND REMARKS

Precise analysis of the nucleon emission process[3-8] provided the above presented fine method for determination of the shapes and sizes of the regions inside the target nuclei where reactions leading to the nucleon emission, particle production, and target fragment evaporation occur.

The regions in question are always determined by the thicknesses λ of nuclear matter layers involved in hadron-nucleus collisions; the values of λ cannot be larger than the diameters D of the target nuclei, $\lambda \le D$. At incident hadron energies large enough - larger than $\epsilon_h D$, where ϵ_h in MeV/(nucleon/S) is energy loss[12] of a hadron h on its path length λ = 1 nucleon/S and D in nucleons/S is the diameter of the target nucleus, the mean values of the thicknesses involved $\langle\lambda\rangle$ are as large as the mean thicknesses $\langle\lambda_A\rangle$ of the target nuclei. It follows, from what has been said above, that the sizes $\langle G_N\rangle$, $\langle G_S\rangle$, $\langle G_b\rangle$ are clearly A-dependent, at incident hadron energies high enough; practically $\epsilon_h D$ is of a few GeV for incident pions and protons[12].

The values of λ may change due to disturbation of the monotonic energy loss of hadrons in nuclear matter, but it happens in about 15% of all collision events, as it can be concluded from the analysis of the multiplicity distributions of the emitted protons. The values λ may fluctuate as well. It is reasonable to state the existence of fluctuations of $\langle G_N\rangle$, $\langle G_S\rangle$, and $\langle G_b\rangle$, therefore.

Crucial and clearly interpretable experimental support for the correctness of formulas for S_N, G_N and $\langle G_N\rangle$ can be obtained straight off: the mean multiplicity $\langle n_p\rangle$ of the emitted protons in hadron-nucleus collisions at energies high enough equals $\langle\lambda_A\rangle S$, where $\langle\lambda_A\rangle$ in proton/S is the mean thickness of the target nucleus.

The relation between the mean number $\langle n_b\rangle$ of the charged fragments evaporated in a collision and the multiplicity n_p of the emitted protons exists and it is proved experimentally[4]. Formula for $\langle G_b\rangle$ is simple consequence of this relation. So, crucial support for formulas for S_N, G_N, and $\langle G_N\rangle$ is crucial support for formulas for S_b and $\langle G_b\rangle$ as well.

From the observed independence of the nucleon emission process of the particle production process, one can conclude that above crucial support for formulas for S_N, G_N, $\langle G_N\rangle$, S_b, and $\langle G_b\rangle$ is mediately a support for formulas for S_S, G_S, and $\langle G_S\rangle$ as well.

Many authors attempted to determine sizes of the nucleon emission and particle production regions in hadron-nucleus collisions[16-20]. Corresponding interference method has been worked out[16-18,21]. The method provides information about the region of emission, not about the region where the reactions leading to the emission occur. But, in my view, results obtained using this method[22,23] do not contradict our results.

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Определение форм и размеров областей, в которых в столкновениях адрон-ядро происходят реакции, приводящие к испусканию нуклонов, рождению частиц и испарению фрагментов

Определены формы и размеры областей в ядрах-мишенях, в которых происходят реакции, приводящие к испусканию нуклонов, рождению частиц и испарению фрагментов в адрон-ядерных столкновениях. Область испускания нуклонов цилиндрическая, с диаметром равным двум диаметрам нуклона, центрирована по направлению движения налетающего адрона в ядерной материи. Реакции, приводящие к рождению частиц, происходят в основном вдоль пути налетающего адрона в ядре-мишени. Испарение фрагментов происходит с поверхностного слоя части ядра-мишени, поврежденной при испускании нуклонов.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Determination of the Shapes and Sizes of the Regions in which in Hadron-Nucleus Collisions Reactions Leading to the Nucleon Emission, Particle Production, and Fragment Evaporation Occur

Shapes and sizes of the regions in target nuclei in which reactions leading to the nucleon emission, particle production, and fragment evaporation occur are determined. The region of the nucleon emission is of cylindrical shape, with the diameter as large as two nucleon diameters, centered on the incident hadron course. The reactions leading to the particle production happen predominantly along the incident hadron course in nuclear matter. The fragment evaporation goes from the surface layer of the part of the target nucleus damaged in nucleon emission process.

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

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