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Z.Strugalski, M.Sadzińska[1], E.Strugalska-Gola[2],
Z.Zawisławski

IMPACT PARAMETER DETERMINATION IN HADRON-NUCLEUS COLLISIONS

[1]Institute of Physics, University of Lodz,
Lodz, Poland
[2]Space Research Center, Polish Academy of Sciences,
Warsaw, Poland

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1. INTRODUCTION

In interpreting results of the H.Geiger and E.Marsden experiments[1], E.Rutherford has introduced[2] the method for investigation of the structure and properties of the matter by means of the particle beams directed on matter layers. Its importance is not diminished today. It was used in R. Hofstadter's experiments - for investigations of structures of atomic nuclei and nucleons by means of electron beams[3], in works of J.I.Friedman, H.W.Kendall, R.E.Taylor - for investigations of the quark-parton structure of the nucleon using high energy electrons[4,5], and - in our experiments - for investigations of intranuclear matter properties by means of high energy hadrons[6-10] falling on slabs[11,12] of intranuclear matter.

Really, massive target nuclei may be used as disc-shaped slabs and spherical objects of intranuclear matter in high energy nuclear collisions[11,12]. This statement is based on the data on hadron passages through atomic nuclei[9]. On the other hand, a numerous sample of collision events of definite monoenergetic hadrons with definite target nucleus may be treated as the interaction of monoenergetic beam of hadrons with a set of intranuclear matter slabs with different thicknesses[12]; it is convenient to express the thicknesses in nucleons/S units, $S = \pi D_0^2 \approx 10$ fm^2, D_0 is the strong interaction range which is as large approximately as the nucleon diameter D_0. The thickness of the intranuclear matter layer involved in a collision depends on the collision impact parameter - on the distance b of the incident hadron course from the center of the target nucleus.

Obviously, the sample of the numerous hadron-nucleus collisions is equivalent to the collision of spatially homogeneous beam of hadrons with the set of slabs of intranuclear matter; in other words, the density of the beam hadrons at any distance from the beam axis is identical.

In fact, in any collision the target nucleus is destroyed, but in any of it identical hadronic particle collides with identical target nucleus.

In such a sample of collisions of hadrons with nuclei the thicknesses of the intranuclear matter slabs are determined by the impact parameters in the hadron-nucleus collision[12].

For any thickness λ, expressed in nucleons/S, definite impact parameter $b = b(\lambda)$ corresponds to a spherical target nucleus. In a numerous sample of collisions of monoenergetic hadrons with spatially unpolarized nuclei the target nucleus may be treated as a spherical object.

In this work, the hadron-nucleus impact parameter determination is proposed and the accuracy of the determination is discussed.

2. TOPIC

The topic is: 1. How is it possible to determine the thickness of the intranuclear matter layer involved in any of hadron-nucleus collisions? 2. How can one single out a subsample, from a numerous sample of hadron-nucleus collision events, in which incident hadron collides with the intranuclear matter slab with definite thickness?

As a physical basis for the operation principle of the method the newly observed[9,10] nuclear process - the hadron passage through layers of intranuclear matter, will be employed. This process may be regarded as a nuclear analogue of the well-known electromagnetic process - of the passage of charged particle through layers of materials.

3. HADRONS PASSAGE THROUGH LAYERS OF INTRANUCLEAR MATTER

At energies above the pion production threshold, the collisions of hadrons with massive atomic nuclei give rise to a great variety of phenomena: the nucleon emission from the target nucleus, particle generation, nuclear fragment evaporation are the most frequently occurring and observed. The expressive and rather complicated picture of the hadron-nucleus collisions can be recognized in detail in some total experiments only - when all the collision reaction products are recorded and identified. Now it is possible to investigate the hadron-nucleus collision processes under the conditions desired - it can be realized by means of heavy liquid bubble chambers, nuclear emulsions and 4π geometry electronic devices.

Such well nigh on the total experiments were performed by means of the 26 and 180 litre xenon bubble chambers exposed to beams of electrically charget pions with momenta 2.34, 3.5, 5, 9 GeV/c from the accelerators of the Joint Institute for Nuclear Research at Dubna and of the Institute of Theoretical

and Experimental Physics in Moscow. In the chambers almost all protons emitted from target nuclei and produced particles, including neutral pions with kinetic energies equal to 0 or larger than 0, are detected and recorded effectively enough - with efficiency near to 100%.

In analysing photographs of the pion-xenon collisions registered in the chambers, two general classes of collision events may be naturally distinguished: I. The class in which particles, mainly pions, are produced and in some of events nucleons are emitted; we call them particle-producing collisions. II. The class of events without particle production - in such events single hadron of the same kind as the projectile was ejected, the nucleons are emitted and nuclear fragments evaporated from the target nucleus. At lower energies - lower than about 4 GeV - in some percentage of the pion-xenon nucleus collisions the incident hadron is absorbed inside the target nucleus; the absorptions are accompanied by the emission of nucleons from the target nucleus.

More accurate analysis of the two classes I and II of events allows one to state that the passage of hadrons through layers of intranuclear matter is observed[13,14]. The hadron passage is a nuclear process which may be treated as an analogy of the well-known electromagnetic process - of the passage of electrically charged particle through layers of materials. The hadron passage through intranuclear matter is accompanied by the emission of nucleons from the target nucleus; the emitted nucleons are with kinetic energies from about 20÷400 MeV, and are known as the g-track leaving particles if in photonuclear emulsions.

The characteristics of the emitted nucleons are the same in both the two classes of events I and II. Energy and angular spectra are independent of the momentum and identity of the hadronic projectile, at momenta above a few GeV/c. The spectra do not depend either on the multiplicity of the emitted nucleons or on the multiplicity of the produced particles - of the produced pions.

But, the multiplicity of the emitted nucleons n_N depends on the intranuclear matter layer thickness covered by the hadron.

The hadron passage is fundamental one, on the background of it the particle production process occurs.

4. RELATIONS BETWEEN THE HADRON-NUCLEUS COLLISION IMPACT PARAMETER AND THE INTENSITY OF THE NUCLEON EMISSION

In a target nucleus treated as a spherical object of intranuclear matter with a radius R, the impact parameter b values are from $b = 0$ to $b = R + D_0$, where the strong interaction range is as large as the nucleon diameter D_0 and so:

$$o \leq b \leq B, \qquad (1)$$

where $B = R + D_0$. In such a spherical nucleus, to any value of the impact parameter b in fm a definite tickness $\lambda = \lambda(b)$ in nucleons/S of the intranuclear matter layer, which the incoming hadron has to cover, corresponds[12].

The values of $\lambda(b)$ at various b, for different nuclei (A, Z) are given in our previous work[11]. For the $^{12}C_6$ nuclei b values are up to 6 fm, the $\lambda(b) = 6$ nucl/S at $b = 0$ fm and $\lambda(b) = 1$ nucl/S at $b = 3.43$ fm; for $^{131}Xe_{54}$ nuclei b values are up to $b = 9.5$ fm, the $\lambda(b) = 18$ nucl/S at $b = 0$ fm and $\lambda(b) = 1$ nucl/S at $b = 7$ fm; for $^{238}U_{92}$ nuclei b values are up to $b = 11$ fm, the $\lambda(b) = 23$ nucl/S at $b = 0$ fm and $\lambda(b)=1$ nucl/S at $b = 9.5$ fm.

For any hadronic projectile, the relation between the number n_N of the emitted nucleons and the thickness λ nucl/S covered by the projectile exists:

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

where $S = \pi D_0^2 = 10.3\ fm^2$, $\lambda_t = \frac{1}{\sigma_t}$ nucl/S, σ_t the total cross section for the hadron-nucleon collisions; λ_t is measurable quantity[8]. Formula (2) was tested experimentally[13,14] for various hadron-nucleus collisions at energies up to about 3500 GeV, for the incident protons.

In relation (2), the number n_N of the emitted nucleons, or the nucleon emission intensity, is determined experimentally[11].

It can be concluded, for the case when all the emitted nucleons are registered, that the thickness λ in nucl/S of the intranuclear matter layer involved in the hadron-nucleus collision is a measurable quantity - it is determined simply from the relation (2); the impact parameter $b(\lambda)$ can be determined from relations between λ and b given in our previous work[11].

But, in most experiments not all of the emitted nucleons are registered - only the proton component is observed directly. Moreover, we have stated experimentally[14] that the simple relation $n_p = \frac{Z}{A} n_N$ does not hold for the amount of protons n_p in relation to the namber n_N of nucleons emitted in the collision[13,14]; the number n_p of the protons among the number n_N of the emitted nucleons in a collision event fluctuates, and in average n_p is equal to $\frac{Z}{A} n_N$. It has been shown that the probability $P(n_p)$ to meet any time n_p protons among n_N emitted nucleons is given by the formula[14]:

$$P(n_p) = \binom{n_N}{n_p} p^{n_p}(1 - p)^{n_N-n_p}, \qquad (3)$$

where $p = \frac{Z}{A}$.

And so, the relation between n_p and the $\lambda(n_p)$ nucl/S is not simple. It holds with an approximation only; for a given number n_p of the emitted protons in a collision event we can accept with about 80% probability that in fact $n_p \pm 1$ protons are emitted or, in other words, $\frac{A}{Z}(n_p \pm 1)$ nucleons.

It can be concluded, therefore, that in about 80% of the hadron-nucleus collision events the thickness of the intranuclear matter layer involved in the reaction may be determined from the relation

$$n_p = \frac{Z}{A} \lambda\ S(1 - e^{-\frac{\lambda}{\lambda_t}}), \qquad (2')$$

where λ is in nucl/S; in these 80% of events the accurary of the thickness determination is about ±1 nucleon/S. But, it is not possible to single out the events in which the number n_N of the emitted nucleons is determined with such accuracy, they are contained in the total sample of events. In the rest of the events, in about 20% of the events, the number of the emitted nucleons, or of the emitted protons fluctuates according to the binomial law (3).

It can be concluded, therefore, that in a first approximation, when the multiplicity n_p of the emitted protons is used for determination of the intranuclear matter layer thickness involved in the collisions, the information obtained is true only for about 80% of events in the rest of the events the information is wrong; moreover we do not know which of the events are determined wrongly.

5. CONCLUSIONS AND REMARKS

It can be stated, therefore: in order to determine correctly the thickness of the intranuclear matter layer involved in a hadron-nucleus collision, the number of the emitted nucleons n_N should be determined as correctly as possible; from the relation (2) the thickness $\lambda(n_N)$ in nucl/S may be obtained. To any of the thickness $\lambda(n_N)$ for a given target nucleus (A,Z) the impact parameter $b(\lambda)$ corresponds.

From the data on the numbers of the emitted protons, it is not possible to determine the thickness λ of the intranuclear matter layer involved in any of the hadron-nucleus collision. From the data on the multiplicity n_p distribution $N(n_p)$ of the emitted protons, the distribution $N(\lambda[n_p])$ of the thickness of the intranuclear matter layers involved in the hadron-nucleus collisions may be obtained only; at any n_p of the distribution $N(n_p)$ in only about 80% of events the multiplicity of the emitted nucleons n_N may be determined from the relation $n_N = \frac{A}{Z} n_p$, with the accuracy of about ±1.

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Стругальски З. и др. E1-91-145
Определение параметра столкновения
в адрон-ядерных взаимодействиях

Рассматриваются проблемы: 1. Каким образом можно определить толщину слоя внутриядерной материи, вовлекаемой в любое из адрон-нуклонных столкновений? 2. Каким образом можно выделить, из численного набора адрон-ядерных столкновений, меньший набор событий с определенным параметром столкновения? Соотношение между числом испущенных нуклонов в столкновении и толщиной слоя внутриядерной материи, вовлеченной в столкновение, предоставляет возможность решения сформулированных выше проблем.

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Impact Parameter Determination
in Hadron-Nucleus Collisions

The topics in this paper are:1.How is it possible to determine the thickness of the intranuclear matter layer involved in any of a hadron-nucleus collision? 2.How can one single out a subsample, from a numerous sample of hadron-nucleus collision events, in which incident hadron collides with the intranuclear matter slab with definite thickness? Relation between the namber of the nucleons emitted in the collision and the thickness of the intranuclear matter layer involved in it provides a possibility of solving the topics in questions.

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

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