СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E1-97-177

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THE MECHANISMS OF THE HADRON-NUCLEUS COLLISION PROCESSES AND OF THE HADRON-NUCLEUS COLLISION INDUCED NUCLEAR REACTIONS — IN THE LIGHT OF EXPERIMENTAL DATA

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1997

1. INTRODUCTION

In the series of our recent works [1–14, 16–26], conclusive and experimentally based information has been obtained about the mechanism of the hadron-nucleus collision processes and on the nuclear reactions initiated by the collisions — we call them «the hadron-nucleus collision nuclear reactions», latter on.

It appeared that a nuclear reaction caused by the incident hadron consists of a sequence of complicated, depending one on other, processes and lasts in total no less than from about 10^{-24} up to about 10^{-16} seconds [11]. But, the hadron-nucleus collision process only which lasts about 10^{-24}—10^{-22} s may be treated as a fast initial stage of the nuclear collision reaction. The collision, in its exact meaning, ends with the ending of the first stage — after having left the target nucleus by the incident hadron and/or its successors.

In this paper, the subject matter is to describe the hadron-nucleus nuclear collision process only, and to present shortly but clearly and conclusively its characteristics — as experimentally based.

Let us start with a formulation of an adequate definition of the hadron-nucleus collision process in order to distinguish it from the «hadron-nucleus collision nuclear reaction».

2. THE HADRON-NUCLEUS NUCLEAR COLLISION PROCESS AND THE HADRON-NUCLEUS COLLISION INDUCED NUCLEAR REACTION

Let us start this section with definitions of both the processes: firstly of HADRON-NUCLEUS COLLISION PROCESS; secondly, of the hadron-nucleus collision induced nuclear reaction process or shortly, of THE HADRON-NUCLEUS COLLISION NUCLEAR REACTION.

2.1. The Hadron-Nucleus Collision Process

Hadron-nucleus collisions — as the acts of collidings or comings together with sudden, violent force of a hadron with an atomic nucleus under interest here — are the nuclear collisions when the distance d between both the bodies is not larger than the strong interaction range R_S is: $D+R_S \geq d \geq 0$, where D is the «diameter» of the nucleus and $R_S \approx D_0$ is the nucleon diameter defined in the work of Elton [15], for example.

It is known experimentally that the main process in such nuclear collisions is the passage of the incident hadron through the target nucleus [16,17] — or through the intranuclear matter. The particle production occurs on the background of this passage. The nuclear collision process is passing gradually in time through various stages [11,18], and it is localized in the cylindrical volume around the incident hadron course with the diameter as $2R_S$ is (or as $2D_0$ is), and lasts about 10^{-24}—10^{-22} s [11,18]. During such interval determined by the target nucleus size and the collision impact parameter, the projectile hadron is having left the target-nucleus and the collision process ends up [11,18].

In result of the incident hadron passage, the target nucleus is pierced through at a given impact parameter and damaged locally — the fast protons, with kinetic energy from about 20 MeV up to about 500 MeV, are emitted in such a number as it was the number of nucleons contained within the damaged cylindrical volume before the collision.

In the collision process, the incident hadron energy lost is strongly defined — only a definite part of the energy may be used [19].
The energy loss ΔE_h is [20]:

$$\Delta E_h = \varepsilon_h \lambda, \tag{1}$$

where ε_h is the hadron energy loss in GeV/(nucleon/S). For pions $\varepsilon_h = \varepsilon_\pi = 0.180$ GeV/(nucl/S), for protons $\varepsilon_h = \varepsilon_p = 0.360$ GeV/(nucl/S), $S \approx 10$ fm^2, λ is in nucleons/S [19]. For the mean thickness $\langle \lambda \rangle$ in nucleons/S of the target nucleus, the mean energy loss $\langle \Delta E_h \rangle$ GeV is:

$$\langle \Delta E_h \rangle = \varepsilon_h \langle \lambda \rangle. \tag{2}$$

The quantity $S \approx 10$ fm^2, λ is in nucleons/S.

The maximum energy loss is:

$$\Delta E_{h\,\max} = \varepsilon_h \lambda_{\max} = \varepsilon_h D(A), \tag{3}$$

where $D(A)$ is the target nucleus diameter for the nucleus with the mass number A.

The observed effect which the hadron energy loss in intranuclear matter is accompanied by is the emission of fast nucleons. The emission is determined for a given hadronic projectile by the target nucleus size and nucleon density distribution in it.

The mean number of the emitted protons equals:

$$\langle n_p \rangle = (Z/A)\langle \lambda \rangle S(1 - e^{(-\langle \lambda \rangle / \langle \lambda_t \rangle)}); \tag{4}$$

where $\langle \lambda \rangle$ in (nucleons/S) is the mean thickness of the target nucleons, $\langle \lambda_t \rangle$ in (nucleons/S) equals $\langle \lambda_t \rangle = 1/\sigma_t$ and σ_t is the total hadron-nucleon cross section in S per nucleon; $S \approx 10$ fm^2.

The nucleons from the cylindrical volume, with energies 20—500 MeV, are ejected probably during the time interval τ from about 10^{-23} up to about 10^{-22} s. The intermediate objects through which particles are produced by [23] are ejected from the target nucleus as well — like the fast nucleons [22].

In result, due to the collision process, the damaged target nucleus appeared — some (to a definite impact collision parameter for a given target nucleus with the mass number A and the charge number Z) definite number N of fast nucleons $N = n_n + n_p$ were emitted, where n_n and n_p are numbers of the emitted neutrons and protons; the damaged residual target nucleus is then with the new mass number $A-(n_n+n_p)$ and the charge number $Z-n_p$. The nucleons in it are in an unstable configuration, because the ejected fast nucleons are from the local region from the target nucleus involved in the collision [13,22], and the hadron-nucleus collision reaction mechanism is memorized by fast nucleons emitted from the target nuclei [6] during relatively long time interval [11,18].

And so, according to the definition of nuclear reactions: «A high energy nuclear collision reaction is a process in which nucleons are added to, removed from, or rearranged within a target nucleus under bombardment by hadrons or by a group of hadrons» [7]. The hadron-nucleus collision is accompanied by the collision induced nuclear reaction. This reaction does not stop with the collision process is extinguished; at that time a new stage of the collision induced nuclear reaction is intensively continued.

Let describe that reaction more clearly now, in the next section. The finishing of the hadron-nucleus collision process, in which the incident hadron was involved as an active element and the target nucleus participated as a spectator, is in fact the begining of a new stage of the collision induced nuclear reaction, in which the residual target-nucleus plays an active role.

The hadron-nucleus collision process lasts from about 10^{-24} up to about 10^{-22} s. Experimental indications are — the emission of fast nucleons from the definite local region of the target nucleus which the projectile passage through the nucleus is accompanied by that the first stage of the collision induced nuclear reaction starts almost together with the collision process starting. This stage of the nuclear reaction may be named the «fast» one.

It has been shown [5,7] that the damaged residual target nucleus memorizes shapes and volume of its local damage during relatively long time — from about 10^{-22} up about 10^{-16} s. The experimental indications about it are from the depend-

$$\langle n_p \rangle = (Z/A)\langle \lambda \rangle S(1 - e^{(-\langle \lambda \rangle / \langle \lambda_t \rangle)}), \qquad (4)$$

where $\langle \lambda \rangle$ in (nucleons/S) is the mean thickness of the target nucleons, $\langle \lambda_t \rangle$ in (nucleons/S) equals $\langle \lambda_t \rangle = 1/\sigma_t$ and σ_t is the total hadron-nucleon cross section in S per nucleon; $S \approx 10$ fm^2.

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ences of the number n_{ev} of the evaporated light fragments on the number n_p of the fast nucleons (protons) emitted [2,5,7]. This stage of the nuclear reaction proceeds due to the internal energy of the residual target nucleus.

2.2. The Nuclear Reactions Induced in Hadron-Nucleus Collisions

In the light of many experimental investigations of the hadron-nucleus collision process described widely in series of our publications [1—14], [16—24], the nuclear reaction induced by hadron-nucleus collision consists of two stages: the fast stage starting at the moment of impact of the colliding bodies and the slow stage starting practically a long time after the collision ending — when the incident hadron and its successors left the target nucleus.

As it has been known experimentally [13], in hadron-nucleus collisions the interaction of the incident hadron is localized in relatively small cylindrical volume with the radius as large as the strong interaction range R_S is, centered around the hadron course within the target nucleus. Two processes are usually occurring almost simultaneously when hadrons collide with atomic nuclei: a) The passage of the incident hadron through intranuclear matter, accompanied by the emission of nucleons with kinetic energy from about 20 up to about 500 MeV from the interaction region, we called them the «fast» nucleons emitted from the target nuclei; the emission of such nucleons is induced by the incident hadron in its passage through intranuclear matter. It is a general process occurring any time in all of the hadron-nucleus nuclear collisions. b) The production of hadrons [23] on the background of the projectile passage through layers of intranuclear matter; this process occurs sometimes in particle-producing collisions with downstream nucleons in the target nucleus [23,24].

Other processes, registered simply in nuclear emulsions or in bubble chambers, occurring after the collision process ending, are: the light nuclear fragments evaporation and the disintegration of the damaged residual target nuclei into smaller parts. They last from about 10^{-22} up to about no less than 10^{-16} s [11,25].

It can be concluded therefore, that the first stage of the hadron-nucleus collision induced nuclear reaction, starting just at the colliding particles impact and lasting during the hadron-nucleus interaction — during about 10^{-24} up to about 10^{-22} s — goes due to the incident hadron energy loss and it ends when the incident hadron and (or) its successors left the target nucleus.

In result of the fast stage of the collision induced nuclear reaction, the target nucleus is damaged locally, and it becomes to be in an instable nucleon configuration. It leads to starting the second stage of the collision induced nuclear reaction — the slow one. This stage of the nuclear reaction occurs due to the unequilibrium configuration of the nucleons inside the locally damaged residual target nucleus and is realised through the intranuclear energy changes. The resiences of the number n_{ev} of the evaporated light fragments on the number n_p of the fast nucleons (protons) emitted [2,5,7]. This stage of the nuclear reaction proceeds due to the internal energy of the residual target nucleus.

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The number of the light charged fragments evaporated from the damaged residual target depends definitely on the number n_p of the emitted fast protons, it was shown experimentally [27,28] and deduced quantitatively — from some geometrical considerations [26].

3. THE PHYSICAL MEANING OF THE NUCLEAR REACTIONS INDUCED IN HADRON-NUCLEUS COLLISIONS

The two stages of the nuclear reaction induced in hadron-nucleus collisions are observed experimentally — without doubt. It becomes apparent additionally in existence of two stages of the nuclear reactions induced in hadron-nucleus collisions.

In a broad outline, the slow stage of the reaction may be treated as an analog of the nuclear reaction induced by a neutron in its collision with a massive uranium nucleus. Hahn and Strassmann demonstrated in 1938 that neutron bombardment can produce the hadron induced nuclear reaction — fission of uranium nucleus. The accurate analysis of the hadron-nucleus collision reactions indicates that the bombardment of almost all atomic nuclei by hadrons leads to nuclear fission of the residual target nuclei. In other words, the bombardment of atomic nuclei by energetic hadrons leads to the nuclear fission of atomic nuclei; it becomes to be evident when the nuclei are massive enough, for the nuclear collision registered in nuclear emulsion, e.g.

It may happen that some energy overcompensated nuclear reactions will occur. The reactions induced by hadron-nucleus collisions are defined here as such in which a fraction of the incident hadron energy ΔE_d used for the target nucleus damage is smaller than the fraction of the intranuclear energy ΔE_r released, when the nucleons in the locally damaged residual target nucleus suffer an rearrangement and the nuclear fission occurs:

$$\Delta E_d << \Delta E_r, \qquad (5)$$

In fact, the hadron-nucleus collision reaction with the accelerated hadrons should be an analog of the neutron-uranium nuclear collision reaction observed by Hahn and Strassmann.

It would be unnatural when the fission of atomic nuclei, induced in bombardment of them by the high energy hadrons, would be not occurring in adequate experiments. In some cases, the total disintegration of the damaged residual target nucleus may occur, as well. The transmutations and disintegration of atomic nuclei by fast hadrons and nuclei was discussed more in some of our previous works [3,5,26].

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4. CONCLUSIONS AND REMARKS

In this work, the mechanisms of the hadron-nucleus collision processes and of the hadron-nucleus collision initiated nuclear reactions are described. The pictures of the processes are experimentally based.

It follows from the nuclear reaction mechanism (as the reaction initiated by a projectile hadron) that the target-nucleus damaged in a hadron-nucleus collision becomes to be in an unstable stage — the nucleon configuration in it is seriously disturbed and it must be transited into some new, stable configuration, due to intranuclear interactions. After such transition, the total energy of the new, stable, nuclear fragments may be smaller than the energy of the initial damaged residual target-nucleus, and this portion of the energy will be released.

It is known that the amount ΔE of this energy equals the difference of the intranuclear energy E_i of the residual target nucleus and the total final internal energy E_f of the stable nuclei obtained after the transition:

$$\Delta E = E_i - E_f. \tag{6}$$

In some of transitions the value of ΔE may be larger than 0, $\Delta E > 0$, and the energy ΔE will be released. According to the energy conservation principle, the value corresponds to the difference between the initial internal energy of the damaged target-nucleus and the final internal energy of all the nuclear transition reaction products.

How large are or may be the energies released? It may be determined in experiments. First estimations may be realized using the photographs of the fast hadron-initiated nuclear reactions; more accurate data should be obtained by nuclear spectroscopy methods.

We are in the position now to state: *In order to obtain the energy overcompensating collision-initiated nuclear reactions, the beams of pions with kinetic energies about 700 MeV may be used; or, the ion beams of kinetic energies about 700—1400 MeV per nucleon may be used successfully as well — when thrown on the nuclei with a middle charge numbers.* It should be tested experimentally and the optimal values of the beam particle energies and target-nuclei charge number values must be selected.

Maybe, as the nuclear fuel any of the target nuclei may be applied which satisfy the above desiderata concerning the projectile energies and target nuclei mass numbers or charge numbers.

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Received by Publishing Department
on June 4, 1997.

Стругальски З., Стругальска-Голя Э. E1-97-177
Механизмы процессов столкновения адрон-ядро
и ядерных реакций, возбуждаемых в этих столкновениях,
в свете экспериментальных данных

Механизмы процессов столкновений адрон-ядро и ядерных реакций, возбужденных в этих столкновениях, описываются как возникающие из экспериментальных данных. Ядра-мишени разрушаются локально определенным образом вследствие столкновений, конфигурация внутриядерных нуклонов становится неустойчивой. Эта неравновесная конфигурация должна перейти в стабильные состояния продуктов ядерных реакций. Разница между внутренней энергией поврежденного ядра-мишени и энергией стабильных продуктов реакции перехода в конечное состояние может быть выделяемой в некоторых случаях.

Работа выполнена в Лаборатории высоких энергий ОИЯИ; в Институте атомной энергии в Отвоцк-Сверке, Польша; в Институте физики Варшавского технологического университета, Варшава, Польша.

Сообщение Объединенного института ядерных исследований. Дубна, 1997

Strugalski Z., Strugalska-Gola E. E1-97-177
The Mechanisms of the Hadron-Nucleus Collision Processes
and of the Hadron-Nucleus Collision Induced Nuclear Reactions —
in the Light of Experimental Data

The mechanisms of the hadron-nucleus collision processes and of the hadron-nucleus collision induced nuclear reactions are described — as experimentally based. The target nuclei are damaged definitely and locally in the collisions and the configurations of the nucleons in them became instable. The configuration must transit into stable stages of the nuclear transition reaction products. The difference between the initial internal energy of the unstable residual nucleus and the total final energy of the stable products of the nuclear transition reaction may be released in some cases.

The investigation has been performed at the Laboratory of High Energies, JINR; at the Institute of Atomic Energy, Otwock-Swierk, Poland; at the Institute of Physics, Warsaw University of Technology, Warsaw, Poland.

Communication of the Joint Institute for Nuclear Research. Dubna, 1997