СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

96-332

E1-96-332

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# SPALLATION-MECHANISM AND CHARACTERISTICS

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1996

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Механизм и характеристики инициированного быстрыми адронами раскола атомных ядер

Механизм раскола ядра (спаллации) раскрывается на опыте. Раскол ядра-мишени является сложной ядерной реакцией, инициированной быстрыми адронами, в которой можно различить три стадии: а) первая — быстрая стадия, когда ядро-мишень повреждается локально, она длится от $\sim 10^{-24}$ до $10^{-22}$ секунды; б) вторая — медленная стадия, которая длится от $\sim 10^{-22}$ секунды до $\sim 10^{-17}$ секунды, на этой стадии испаряются медленные нуклоны из поврежденного ядра; в) третья — конечная стадия, когда поврежденное ядро-мишень раскалывается на две или больше частей.

Приводятся количественные характеристики этих стадий.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна, 1996

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Strugalski Z., Strugalska-Gola E., Wojciechowski A. E1-96-332
Spallation-Mechanism and Characteristics

Mechanism of spallation is revealed experimentally. Spallation is a complicated nuclear reaction initiated by fast hadron in which three stages may be distinguished: a) the first fast stage which the target nucleus is locally damaged in, it lasts $\sim 10^{-24} + 10^{-22}$ s; b) the slow stage which lasts $\sim 10^{-22} + 10^{-17}$ s after the collision started, the damaged and excited nucleus uses to emit the black track leaving particles; c) the final third stage in which residual target nucleus uses to split into two or more fragments.

Quantitative characteristics of each of the stages are presented.

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

Communication of the Joint Institute for Nuclear Research. Dubna, 1995

## 1. INTRODUCTION

Spallation is usually defined as a nuclear reaction initiated by high energy projectiles in which two or more fragments or particles, as protons and neutrons, e.g., are ejected from the target nucleus.

A mechanism of the spallation may be revealed on the basis of experimental information about the projectile-nucleus collision process. The projectile should be a known hadron, the target nucleus should be known and massive enough. The picture of the collision process mechanism and its characteristics must be obtained in experiments only — as prompted experimentally.

In many of our experimental investigations of the hadron-nucleus collision processes, the collision mechanism has been revealed and its characteristics are known conclusively. Experiments were performed with 26 and 180 litre xenon bubble chambers exposed to 2.34, 3.5, 5 and 9 GeV/c momentum of electrically charged $\pi$ mesons, mainly the negatively charged $\pi^-$ mesons have been used [1–29].

The subject matter in this paper is primarily to discover some mechanism of the spallation adequately to the hadron-nucleus collision process mechanism revealed in experiments. Secondly, attempts are made to characterize the spallation as widely as it is possible now.

## 2. THE HADRON-NUCLEUS COLLISION PROCESS [24]

In hadron-nucleus collisions, the interaction of the incident hadron (nucleon) is localized in relatively small cylindrical volume with the radius as large as the strong interaction range is, centered on the hadron course within the target nucleus.

Four main phenomena are usually observed 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 call them the «fast» nucleons latter; the emission of the nucleons is induced by the incident hadron in its passage through intranuclear matter.

b) The production of hadrons. On the background of the projectile passage-through layers of intranuclear matter, the particle-producing head-on collisions of the projectile with one of the downstream nucleons occurs; particles are produced through intermediate objects in 2 → 2 type endoergic reactions of the hadron and its successors with downstream nucleons. The intermediate objects as the hadron successors may use to collide with the next of the downstream nucleons and create new intermediate objects; the linear intranuclear cascade of the objects may develop along the incident hadron course in intranuclear matter, this way.

c) The evaporation of the target nuclear fragments, including the target nucleons of kinetic energy smaller than about 10—20 MeV.

d) The fission of the residual target nucleus into nuclear fragments.

In any case, whether the particles are produced or not, any projectile hadron causes the emission of nucleons in passing through atomic nucleus. This nucleon emission should not be confused with the nucleon evaporation with clearly different energy and angular distributions. The number $n_N$ of the emitted «fast» nucleons equals the number of nucleons contained within the volume $V = \pi R_s^2 \lambda \approx \pi D_0^2 \lambda$ centered on the hadron path $\lambda$ in intranuclear matter, where $D_0$ is the diameter of the nucleon, as large approximately as the strong interacting range is $R_s \approx D_0$. The particle production process does not effect an influence on the nucleon emission. In particular, the mean multiplicity $n_p$ of the emitted protons is: $\langle n_p \rangle \approx \langle \lambda_A \rangle S$, where $\langle \lambda_A \rangle$ is the mean thickness of the target nucleons in protons/S units, and $S = \pi D_0^2 \approx 10\ \mathrm{fm}^2$.

The evaporation process was studied experimentally in nuclear photoemulsions mainly; the evaporation products leave characteristic black tracks in the emulsion — the tracks of nuclei with the charge number $Z = 1$ to $Z = 2$ predominantly. It was obtained that:

1. The black track leaving particles exhibit an almost isotropic distribution.
2. The mean number of the black track leaving particles is not related to the number of generated pions, at energies of the incident hadron over a few GeV; this number $\langle n_b \rangle$ is weakly energy dependent at smaller energies.
3. Mean kinetic energy of the emitted black track leaving particles is about 20 MeV and stays with incident hadron energy change; it is independent as well of the identity of the impinging particle.
4. The ratio $N_F/N_B$ between the number $N_F$ of the black track leaving particles directed into backward hemisphere amounts about $1.1 \pm 0.1$; it does not depend on $n_b$ and it is the same for pion-nucleus collisions at about 60 and 200 GeV; it is reasonable to accept that $N_F/N_B$ is practically independent of the energy and identity of the impinging hadron.

In experiments performed by means of photonuclear emulsions, the relations between characteristics of the black track leaving and gray track leaving particles emission characteristics were investigated; among the gray track leaving particles the fast protons are predominantly with energies of about 20 to 500 MeV. Experimental relations in question allow one to conclude that:

1. Large difference between mean energies of the fast protons, $\langle E_g \rangle$, and of the black track leaving particles, $\langle E_b \rangle$, is independent of energy and mass of the projectile and of the target mass as well.
2. A large difference between angular distributions of the b- and g-track leaving particles is independent of the energy and identity of the impinging hadron, and of the target nucleus mass number as well.
3. The range and angular distributions of the gray track producing particles do not change with hadron energy change, as it has been proved at larger energies their number $n_b$ is proportional to $n_g$.
4. The dependence of the mean number of the black tracks $\langle n_b \rangle$ on the number $n_g$ of the gray tracks has the same behavior through the energy range 6.2 GeV to 400 GeV, one linear function describes it well. This linear function for proton-AgBr nuclei collisions passes near the dirigin $n_b = 1.21 n_g + 1.49$; this correlation is completely independent of the number of produced pions. Even if the shower particle multiplicity increases from 2.8 to 16.8 no change is observed in mean black and gray track multiplicities.
5. The multiplicities $n_g$ and $n_h = n_g + n_b$ obey the relation $\langle n_g/n_b \rangle = \langle n_g \rangle / \langle n_h \rangle \approx \mathrm{const} = 0.39$. It indicates proportionality between $\langle n_g \rangle$ and $\langle n_h \rangle$, and hence between $n_b$ and $n_g$; this relation is energy independent.

In the light of the mechanism of hadron-nucleus collision process described shortly above, the spallation appears as some complicated process in which three stages may be distinguished:

1. The first — fast stage in which the target nucleus is pierced along the projectile course and the fast nucleons are emitted in the numbers which are equal to the numbers of nucleons inside the cylindrical channel with the diameter $R_s$ centered on the incident hadron course, and nucleus becomes to be destroyed and unstable. When particle producing collisions intra the target nucleus occurred on the background of the projectile passage, the produced intermediate objects (generons) use to decay into the so-called produced particles — after having left the parent nucleus.
2. The second — slow stage, when the destroyed hadron should be transited from the unstable state — after first-stage passed to some more stable state in

which the wounded residual target nucleus is transiting itself in evaporating the low energy nucleons and fragments, mainly with an electrical charge 1.

3. The third — final stage is such in which the residual target nucleus uses to decay into two or more fragments, probably due electrical repulsive forces.

So after each of the stage definite products of the spallation appear: In the first stage — fast nucleons (protons) are ejected. In the second stage — some light fragments of the target known as black track leaving particles are ejected, mainly from the surfaces on the wounded or destroyed regions of the target nucleus. In the third stage, the final one, the residual target nucleus is transiting itself into two or more stable nuclei.

Detailed characteristic of the yields in each of the stages 1, 2 and 3 are presented as obtained experimentally, in references [1–35]. But it is of some importance to describe these characteristics once more here, and this description opens the next section 3. The characteristics will be mainly: on the fast nucleon emission, on the pion production intensity, on the other products of reactions.

## 3. CHARACTERISTICS OF THE SPALLATION

At the first stage — when the target nucleus is pierced.

It is known experimentally [20,21] that two general classes of hadron-nucleus nuclear collision events, I and II, are observed clearly and conclusively: I — is the class where the hadron-nucleus collisions in which hadrons are produced are accounted for; II — is the class where the collision events without hadron production are accounted for — pure passage of the projectile through the target nucleus is visiable; at kinetic energies less than a few GeV, the incident hadron is absorbed inside the nucleus of an average mass number.

In colliding with a target nucleus the projectile hadron starts to pass through the atomic nucleus. In the passage a definite part of the hit nucleus is involved only — the cylinder $\pi R_s^2 \lambda$ with the diameter $2R_s$ determined by the strong interaction range $R_s$ centered on the hadron path $\lambda$ in intranuclear matter.

Any hadron with kinetic energy higher than the pion production threshold causes fast nucleon emission from the target nucleus with kinetic energies from 20 up to 500 MeV. The number $n_N$ of the nucleons equals the number of nucleons contained within the cylindrical volume $v = \pi R_s^2 \lambda$ fm$^3$ centered on $\lambda$ in the target nucleus:

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

where $D_0$ (fm) is the diameter of the nucleon, $D_0 \approx R_s$; the relation (1) can be expressed simpler:

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

when $\lambda$ is expressed in (nucleons/S) units and $S = \pi D_0^2 \approx 10.3$ [fm$^2$].

The passage of the incident hadron through layers of intranuclear matter accompanied by the nucleon (proton) emission from the nucleus is a fundamental process in the hadron-nucleus collisions, on the background of it other processes occur at the first stage; the observable effect of the process is the emission of fast nucleons (protons) with kinetic energies from about 20 up to about 500 MeV. This process is memorized by the target nucleus during relatively long period [26] — from about $10^{-24}$ up to about $10^{-17}$ s, what can be concluded from definite relation between fast nucleon (or proton only) emission intensity (or multiplicity) $n_N$ (or $n_p$) and the mean intensity or multiplicity $\langle n_b \rangle$ of the black track leaving particles in emulsion [27]; the hadronic projectile leaves «a track» in intranuclear matter memorized relatively long in it — from about $10^{-24}$ up to about $10^{-16}$ s.

The emitted fast nucleons (fast protons) or gray track leaving particles in emulsions exhibit a differential energy spectrum:

$$N(E)\, dE \sim E^{\gamma} dE, \qquad (3)$$

where $N(E)$ is the number of protons per events and unit energy (MeV); $\gamma$ has the value $1.09 \pm 0.02$ [31]. The energy spectrum is identical in both the classes I and II of the collision events.

In $p$- and Pi-nucleus collisions at about 2 to about 400 GeV, the differential energy spectrum (3) is the same, as is stated experimentally [5,30–32]. The angular distribution is close to the form [5,30,31,33]:

$$\frac{1}{\sigma} \frac{d\sigma}{d(\cos\theta)} \sim \exp(0.96 \cos\theta), \qquad (4)$$

and stays constant in the projectiles energy range 2–400 GeV.

The particle creation process goes on the background of the incident hadron passage through intranuclear matter and it is localized along the projectile course in intranuclear matter within the tube of the radius $R_s$ as large as the strong interaction range is centered on the hadron course. Hadrons are created through some intermediate objects formed inside the tube within the target nucleus which use to decay after heaving left this nucleus, after about lifetime $\tau_g \approx 10^{-22}$ s, into commonly known «produced» particles and resonances.

In collision with nuclei massive enough at energies high enough, the intermediate objects may use to collide in ones turn with the downstream nucleons in the particle-creating collisions — the intranuclear cascade may develop of the intermediate objects along the hadron course through the volume $v = \pi R_s^2\lambda$. The multiplicity $n$ distribution $f(n, A, E_n)$ of the particles produced in a collision of a hadron $h$ with an atomic nucleus $A$ at the incident hadron energy $E_h$ is [15,34]:

$$f(n, A, E_h) = \exp\left(-\frac{\langle\lambda\rangle}{\langle\lambda_0\rangle}\right)\sum\left[1 - \exp\left(-\frac{\langle\lambda\rangle}{\langle\lambda_0\rangle}\right)\right]^{m-1} P_m(n), \qquad (5)$$

where $P_m$ is the composition of the $m$ statistically independent distributions of the particle multiplicities $n$ [15,31]. The relation (5) represents the composition of some number $m = 1, 2, 3\ldots$ of statistically independent outcomes which could be observed separately in elementary hadron-nucleon collisions at incident hadron energy $E_n/m$.

The first stage of the collision process ends after the incident hadron passage through the target nucleus, it plays a role during about $10^{-24} \div 10^{-22}$ s.

As the result of experimental investigation of the projectile energy transfer to target nucleus, the following mostly important facts have been states for the nucleus at rest in the laboratory [22].

In the hadron-nucleus collisions the projectile energy is transferred into the target nucleus in its passage through layers of the intranuclear matter anyhow; this energy transfer depends on the path length covered by the projectile and its successors; in the passage definite tube-shaped relatively small volume $v$ of the target nucleus is involved only. The energy transfer realized this way is limited and independent of the projectile energy, at energy high enough and amounts no more than about 8 GeV for the proton projectile colliding with middle heavy nuclei.

Often, on the background of the projectile passage, the energy is transferred to the downstream nucleons in some particle-producing collisions. As a result of these collisions intermediate objects or generons — as we have called them, are created in 2 → 2 type endoergic reaction. If the target nucleus is massive enough, the generons may collide with the downstream nucleons and produce new — secondary generons in ones turn; it is not excluded that in the generon-nucleon collision the newly created generon is glued to the primary one and some system of one, two, three, ... generons may be created. This energy transfer from the projectile to the generons is practically unlimited as depending on the projectile energy only. But this part of projectile energy is not transferred to the target nucleus — the intermediate objects (generons) are leaving the parent nucleus and they use to decay into observed «generated» hadrons after having left the parent nucleus.

In one of our works [22] mean and maximum energies of pions and protons lost in their passages through intranuclear matter have been estimated, e.g., the values of the mean energy and the maximum energy transfer $\Delta E_{\text{mean}}$ and $\Delta E_{\text{max}}$ are correspondingly 0.5 GeV and 1.5 GeV for pions with kinetic energy $E \geq 1.5$ GeV colliding with the $^{12}C_6$ nucleus. The values for the proton — $^{12}C_6$ collisions are correspondingly 1 and 0.1 GeV in the collisions at energies higher than 2.1 GeV.

Corresponding values for pion and proton collisions with Pb nuclei at energies higher than 4 GeV are: 1.9 and 4 GeV for pion-Pb; for $p +$ Pb reactions at the incident energies higher than 8 GeV the mean and maximum energies lost are 3.7 and 7.9 GeV, respectively.

It should be remembered although that the projectile energy lost for the generon production is not transferred to the target nucleus, because generons escape the parent nucleus and use to decay into resonances and particles after about $10^{-22}$ s.

In this, the first stage, the target nucleus is pierced only at some distance from the target diameter and the «fast» nucleons are emitted from the target nucleus. The hadron nucleus interaction is ended at the moment when incident hadron and its successors escaped the nucleus. The first stage of the collisions lasts $10^{-24} \div 10^{-22}$ seconds.

At the second stage — when the target nucleus is destroyed in the first stage of the collision — it should be transited into some stable state or states. The transition is realized through emission of the so-called black track particles — such particles which leave black tracks in photoemulsion, they are low-energy singly and multiply charged fragments of the nucleus ($p$, $d$, $t$ with kinetic energy $E$ less than about 30 MeV/nucleon and $^3$He, $^4$He with energy less than about 300 MeV/nucleon). Black track particles exhibit an almost isotropic angular distribution [31], and are treated mainly as evaporation particles, therefore.

The evaporation of the light nuclear fragments is determined by the surface layers of the damage in the target nucleus [25]. The damaged target nuclues memorized an information about the collision during relatively long period — not smaller than from $10^{-23}$ s up to about $10^{-16}$ s — from the starting of collision up to the starting of the residual damaged (pierced) target nucleus transition into stable fragments.

The dependence of the mean number $\langle n_b\rangle$ on the multiplicity $n_p$ of the emitted fast protons $n_p$ has been derived [25]:

$$\langle n_b\rangle = 1.25 n_p + 1.61; \qquad (6)$$

this formula is representative as well for $\langle n_b \rangle - n_g$ dependence, where $n_g$ is instead of $n_p$, because in fact $n_p \equiv n_g$.

Simultaneously, the formula

$$\langle n_g / n_b \rangle = \langle n_g \rangle / \langle n_h \rangle \approx \text{const} = 0.39 \qquad (7)$$

has been derived. Relations (6) and (7) are tested experimentally [25]. The correlations (6) and (7) are tested experimentally, on the emulsion data [35]. Correlations (6) and (7) are completely independent of the number of produced pions; they do not depend on the nature of the incident hadron, i.e., only the number of the emitted fast protons $n_p$ (nucleons $n_N$) in the hit nucleus determines the average number $\langle n_b \rangle$ of the black track leaving particles, emitted from the damaged target nucleus.

At the third, final stage residual target nucleus uses to decay into two or more stable parts (fragments).

After emission of the fast nucleons in the first stage and evaporation of the light target fragments, the residual target nucleus may be in an unstable state and than it must decay into stable lighter nuclei — nuclear fragments.

## 4. CONCLUSION AND REMARKS

The spallation revealed experimentally appears as a complicated nuclear process or reaction consisting of at least three closely related or connected parts which last about $10^{-24} \div 10^{-17}$ s after the collision starting.

At the first stage, which lasts about $10^{-24} \div 10^{-22}$ s, the target nucleus is locally damaged. At the second stage, lasting about $10^{-22} \div 10^{-17}$ s, the damaged target nucleus uses to evaporate the black track leaving particles — mainly protons. At the final stage, the residual target nucleus uses to split into two or more fragments.

In applying the subnuclear detector, the spallation may be successfully investigated experimentally.

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Received by Publishing Department
on September 11, 1996.