СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E1-98-166

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NUCLEI TRANSMUTATION BY COLLISIONS WITH HADRONS AND NUCLEI

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1998

1. INTRODUCTION

Atomic nuclei change their mass- and charge-numbers, A and Z, in collisions with energetic nuclei and hadrons at kinetic energies high enough. In other words, a transmutation of the colliding nuclei occurs — from one nucleus with definite A and Z to other nucleus — with some numbers A' and Z'. It is an old problem: medieval alchemists attempted to transmute base metals into gold. In general, «to transmute» means to change from one of species, condition, nature or substance into another. The transmutations or conversion of atoms of a given element into atoms of various isotopes or of a different elements occur in spontaneous disintegrations. They occur in artificially induced transmutation processes — in hadron and nuclei collisions with nuclei, as well.

The target nuclei transmutations in their bombardment with hadrons and nuclei proceed in a definite way. It is a consequence of the local damage of the target nuclei by the hadronic and nuclear projectiles strucking them at various impact parameters [1—9].

A hadron, in passing through an atomic nucleus [l-6], causes emission of definite number of protons (and of neutrons — evidently, as well) from it. The number of the emitted nucleons equals the number of the nucleons involved into interaction with the projectile, contained within the cylindrical volume

$$v = \pi R_h^2 \lambda = \pi D_0 \lambda \tag{1}$$

centered on the projectile course; R_h is the strong interaction range ($R_h = D_0$), and D_0 is the nucleon diameter.

When the projectile is a nucleus, it may be treated as a beam of fast monochromatic nucleons. Such a beam behaves itself similarly as the hadronic projectile does it; the number of the target nucleons involved in the collision depends on the collision impact parameter and it is the measurable quantity. The hadron-nucleus and nucleus-nucleus collision processes were discussed in our former works [7—10].

So, as the physical basis for the transmutation process, the properties of the hadron passage through layers of intranuclear matter should be used. Our considerations about the problem in question — the transmutations of the nuclei by hadron-nucleus collisions are starting with some compendium of the knowlegde about this basical process.

2. PHYSICAL BASIS FOR THE TRANSMUTATION OF NUCLEI BY HADRON-NUCLEUS COLLISIONS

The physical phenomenon, revealed experimentally and described in our early works, basical for understanding the observed picture and characteristics of the transmutation of nuclei produced by the impact of the fast hadrons (protons, pions, e.g.) and nuclei, is the passage of a hadron through a layer of intranuclear matter; the passage is accompanied by the emission of fast nucleons (~20–500 MeV) from the target nucleus [1—6].

2.1. The Hadron Passage through Layers of Intranuclear Matter [10,11].

Simple relations have been revealed experimentally [3—5].

1. The number n_N or the intensity n_N of the nucleons emitted from a target nucleus, when a fast hadron collided with it, depends simply on the thickness λ of the intranuclear matter layer involved in the collision:

$$n_N = \lambda S(1 - e^{-\lambda/\lambda_t}), \tag{2}$$

where λ in nucleons/S, $S = \pi D_0^2 \approx \pi R_h^2 \approx 10\ \text{fm}^2$, $D_0 \approx R_h$ is the nucleon diameter as large approximately as the strong interaction range R_h is, $\lambda_t = 1/\sigma_t$ is the hadron mean free path in intranuclear matter in nucleons/S, σ_t is the hadron-nucleon total cross-section in S/nucleon.

Formula (2) was tested experimentally to be valid for momenta of hadronic probes larger than about 2 GeV. The hadron passage through layers of intranuclear matter is a nuclear analogue of the electromagnetic process — of the passage of an electrically charged particle through layers of usual (atomic) matter. This phenomenon has been revealed in our experimental investigations [1,4,5,6,12].

Approximately appropriate simple relations:

$$n_N \approx \lambda S, \tag{3}$$

where λ is in nucleons/S, and

$$n_p \approx \lambda S, \tag{4}$$

where λ is in protons/S, are valid to.

2. Various intranuclear matter layers λ in [nucleons/S] in any of nuclei, practically at any distance from its center, may be estimated [13] using data on the proton (and nucleon at all) distributions in them determined by Hofstadter [14—16], and on the proton/neutron ratio at the nucleus periphery [17]. The emitted fast nucleons (protons — especially) are registered and recognizable well enough in many track detectors.

3. In confronting the data on the thiknesses of the intranuclear matter layers at any distance from the nuclei center with corresponding intensities of the emitted fast nucleons in a collision, one is in a position to conclude about the emission of the fast nucleons which the hadron passage through intranuclear matter is accompanied by; the number of the protons n_p and the number of the neutrons n_n are under interest.

The time interval $\Delta\tau$ for the hadron passage through the target nucleus determines how long lasts the fast — first stage of the hadron-nucleus collision process. In the light of the above presented considerations, the nucleus transmutation in this stage is almost recognizable and definite. The charge number Z and the mass number A change in definite manner: $A \to A-(n_n+n_p)=A'$ and $Z \to Z-n_p=Z'$, where n_n and n_p are the neutron and proton multiplicities of the emitted fast nucleons, respectively.

2.2. The Target-Nucleus Transmutations. So, the target nucleus transmutation is a complicated process, it proceeds in at least three stages or phases — according to the phases of the nuclear reactions induced by projectile hadrons in hadron-nucleus collisions [8,9].

In the first — fast stage, lasting about $10^{-24}-10^{-22}$ s, there appeares the residual target nucleus damaged and instable therefore. This target nucleus may be characterized by new charge Z' and mass A' numbers.

After about 10^{-22} seconds, the next (second) stage of the residual target nucleus transmutation may start, it lasts till about 10^{-16}s. In this phase the damaged target nucleus transits itself into some number of «evaporated» lighter nuclear fragments and nucleons.

The information on this second phase of transmutation is not so conclusive as such in the first phase one. Although, some indications about the process in this slow phase exists — from the relation:

$$\langle n_f \rangle = 1.25(n_p+(A-Z)/Z), \qquad (5)$$

where $\langle n_f \rangle$ is the mean number of the light fragments «evaporated» in the transmutation process at this stage, when the number n_p of the emitted fast protons is as determined in the first — fast stage [18].

Just after the transmutations in this slow phase of the intranuclear reaction, the third stage of the transmutation process may start. In this phase or stage, the damaged and excited target nucleus, in the second — slow stage of the reaction, may be not stable yet, and it should transmute into some pieces — lighter nuclei. It is the third or last stage of the transmutation.

The information about the third stage is mostly pure (from the track sensitive detectors). This information should be obtained by other methods.

Maybe, this information is contained in the data which are from more adequate experiments — as that of R.Brandt et al. [19], e.g.

3. EXPERIMENTAL DATA

The experimental data on the target nucleus transmutation process, in the context of this work, should be used from the adequate track detectors — from heavy liquid bubble chambers and from photonuclear emulsions, first of all, exposed to fast hadrons and nuclei from accelerators. In the detectors, the emitted fast nucleons, the evaporated nucleons and light nuclear fragments from the target nucleus, and the generated hadrons in the hadron-nucleus collisions at energies high enough must be registered over total 4π solid angle with an efficiency near to 100%, and they should be recognizable, as well.

3.1. Experimental Material. In this work our experimental material from the 26 and 180 litre xenon bubble chambers exposed in beams of positively charged pions at about 2.34 GeV and negatively charged pions at about 3.5, 5 and 9 GeV of kinetic energy has been used. The first chamber was of the Joint Institute for Nuclear Research (JINR) at Dubna, the second one — of the Institute of Theoretical and Experimental Physics (ITEPh) at Moscow. The expositions of the 180 litre chamber at 3.5 GeV were performed at the Moscow ITEPh accelerator, those of the 26 litre chamber were realized at the Dubna JINR synchrophasotron. The photographs from the bubble chambers were obtained in our former experiments — for investigations of the particle decays into gammas and neutral pions [20]. In total, now about 10^4 pion-xenon nuclear collisions were measured and analysed for investigations of the hadron-nucleus collision mechanisms. About $7 \cdot 10^3$ events from this probe are for the pion-xenon nucleus collisions at 3.5 GeV of kinetic energy; this part of the experimental material is the mostly accurately measured and analysed.

Because the information about the evaporated products obtained from the bubble chambers is very pure, the experimental material from the photographic emulsions [21—25] was applied as complementary. This experimental material from the chambers and emulsions together is equivalent to a corresponding material from a total 4π solid angle track detector — for analysing almost all the hadron-nucleus collision reaction products; in addition, it is worth-while to remark that in the bubble chambers the gamma quanta and the neutral pions are detectable and identificable accurately with an efficiency of about 100%.

3.2. Experimental Facts. In analysing the experimental material [1,2,7,20, 26,32] from the bubble chambers, many experimental facts were revealed. Below, it will be mentioned about those facts which are in connection with the process of the target-nucleus transmutation initiated by a projectile hadron or nucleus. Such facts are [4-7,20-34]:

1. In any of the hadron collisions with a target-nucleus only definite part of the target is involved — a definite cylindrical volume (1) around the projectile course in intranuclear matter with the radius R as long as the strong interaction range R_h is, $R = R_h \approx D_0$, where D_0 is the nucleon diameter [14].

2. In passing through intranuclear matter a projectile hadron causes emission of fast nucleons — with kinetic energies about 20 up to 500 MeV. The number of the nucleons equals the number of the nucleons involed in the collision reaction; this number is determined by formulas (2), (3), and (4) — it equals the number of the nucleons contained within the volume (1), and it is determinable in experiments.

3. The mean number $\langle n_f \rangle$ of the evaporated light nuclear fragments (p, D, T, α) depends on the number n_p of the fast protons emitted from the target nucleus — according to formula (5) [18,23]. The formula is valid for $n_p \leq p_p(D)$, where $n_p(D)$ is the number n_p of the emitted protons when the projectile hadron passed through the target nucleus along its diameter D.

4. Four main phenomena are usually observed when hadrons collide with atomic nuclei [7]:

a. The passage of the incident hadron through intranuclear matter, accompanied by the emission of nucleons with kinetic energy from about 20 up to 500 MeV from the interaction region, we call them the «fast» nucleons later; the emission of the nucleons is induced by the incident hadron in its passage through intranuclear matter;

b. The production of hadrons;

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

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

5. The production of hadrons has no any influence on the characteristics of the emitted fast nucleons and on the evaporated nuclear fragments, at energies high enough — over a few GeV of the kinetic energy of projectile hadrons.

6. The changes of the target nucleus in a hadron-nucleus collision are very complicated and are passing in at least three stages or phases of the collision induced nuclear reaction: the first, fast stage lasting about $10^{-24} - 10^{-22}$ s; the second, slow stage lasting from about 10^{-22} up to about 10^{-16} s, the third, last stage lasting more than 10^{-16} s.

In the first stage, the projectile hadron passes through the target-nucleus and is leaving it — as locally damaged. In the second stage, the damaged and excited residual target nucleus transmutes into more stable phase — through evaporation of the slow nucleons and light nuclear fragments. In the third stage the residual target nucleus, if not stable as yet, decays probably into two or more heavier stable fragments.

7. For any of the stages, in the target nucleus transmutation process induced in a hadron-nucleus nuclear collision, it may be ascribed corresponding change of the nucleus; the changes in the first stage are estimated in experiments almost exactly, the changes in the second stage may be estimated with less accuracy in the track-detector experiments. The changes in the third stage may be estimated in experiments like that of the large groups of physicists [19,34], by means of complicated electronic arrangements and various samples of corresponding detectors.

4. RESULTS AND CONCLUSIONS

The purpose of this work has been to systematize the experimental data that bear upon the transmutation of nuclei with the help of fast hadrons and nuclei. Here, the transmutations of nuclei caused by hadron-nucleus and nucleus-nucleus collisions at high energies are discussed only. The nuclei with the mass- and charge-numbers A and Z are transmuted into other nuclei — with some new mass- and charge-numbers A and Z:

$$(A, Z) \rightarrow (A', Z'). \qquad (6)$$

The transmutation may occur as:

a. From one nucleus with (A, Z) into one new nucleus with (A', Z');

b. From one nucleus with (A, Z) into a few new nuclei with $(A', Z') + (A'', Z'') \ldots + (A^* Z^*)$, some of the new nuclei may be protons or deuterons, and tritons, e.g., as well.

If, instead of the projectile hadron an energetic appropriate heavy nucleus is used, the target nucleus (A, Z) may be transmuted into A nucleons — $(A-Z)$ neutrons and Z protons will be ejected [10], and will be observed instead of the residual target nucleus. The projectile nucleus will be disrupted [10] into nucleons, as well.

The transmutation of the target nucleus caused by a hadron-nucleus collision at energies high enough (higher than about a few hundreds of MeV) appears as a complicated process which is proceeding in a few stages or phases, corresponding to the hadron-nucleus collision and the collision induced intranuclear reactions [9,35].

In conclusion, from the above presented data, it can be written:

Some, total and accurate identification of any of the emitted and evaporated nucleons and charged light target fragments in any of the hadron-nucleus collision events provides a possibility of determining quantitatively the transmutation products at any of the stages or phases of the transmutation process.

The results are applicable in investigations for the environmental engineering and for radiative waste transmutations with the fast heavy ions. An application of the results to the civil and environmental engineering is a subject matter of special investigations of one of us (A.D.) [36].

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