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Z.Strugalski*

TRANSMUTATIONS AND DISINTEGRATIONS OF ATOMIC NUCLEI BY FAST HADRONS AND NUCLEI

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*Warsaw University of Technology, Institute of Physics
ul. Koszykowa 75, PL 00-662 Warzaw, Poland
and
Institute of Atomic Energy, PL 05-400 Otwock-Swierk, Poland

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1. INTRODUCTION

When one nucleus passes close enough to the second nucleus so that the two interact appreciable anyhow, the collision of the nuclei occurs. If the distance between the centers of the colliding nuclei — the impact parameter d — is larger than the sum of the radii R_1 and R_2 ,$d > R_1 + R_2$, then they interact gravitationally and electrically; if $d < R_1 + R_2$, the nuclear interaction is taking place and nuclear reaction may occur. A nuclear reaction is a process in which nucleons are added to, removed from, or rearranged within nuclei in the collisions. The gravitational interaction in the nuclear collisions may be not taken into account — as of comparatively small constant. This definition holds if one of the colliding nuclei is replaced by any of hadrons.

It is customary to use a shorthand notation for specifying nuclear reactions:

$$ {}^{n}X_{z}({}^{n}Y_{z}\,,\ N)^{n}Z_{z}\ ; \qquad (1)$$

the first quantity ${}^{n}X_{z}$ specifies on of the colliding nuclei ${}^{n}Z_{z}$, specifies the final or residual nuclei; within the parentheses, the first ${}^{n}Y_{z}$ is the second of colliding nuclei or a colliding hadron; the quantity N specifies the emitted nuclei — the emitted nucleons in particular.

In 1939, the German radio-chemist Otto Hahn in collaboration with Fritz Strassman in bombarding Uranium ($Z = 92$) with neutrons found that among the products of neutron absorption by uranium there was radioactive barium ($Z = 56$), an element much less massive than the original uranium. How could such a light element be formed from uranium [1], it was soon resolved by Lize Meither and Otto Fresch [2], who suggested that neutron absorption by uranium produced a break or fission of the nucleus into two light fragments:

$$\mathrm{U}(Z = 92) + n \rightarrow \mathrm{Ba}(Z = 56) + \mathrm{Kr}(Z = 36)\ . \qquad (2)$$

This was a starting new type of nuclear reactions studies. This discovery showed that it is possible to split a nucleus into two massive parts. The mechanism of the nuclear fission has been discussed at that time by N.Bohr and J.A.Wheeler [3].

The probability of the occurrence of spontaneous fission is extremely small, and therefore the corresponding half-life is extremely long, e.g., for U^{235} it is about 10^{17} years. If some additional energy is supplied to the nucleus in a hadron-nucleus collisions at energy high enough, the increase in intranuclear energy may produce a large nuclear deformation which will be sufficient to permit the relatively easy separation of the nucleus into fragments. The probability for the occurrence of the fission should increase with the nucleus deformation increasing; this probability may be extremely high — e.g., the capture of neutron by ^{235}U increases its half-life by a factor of about 10^{45} — from about 10^{17} years up to about 10^{-21} seconds, as is known.

The subject matter in this paper is a consideration about the target-nucleus fission induced by hadronic or nuclear projectile; the picture of the nucleus damage — of the nucleus destruction process initiated by hadronic projectile — is of first importance in this context; it will be presented in the next section of this paper — as prompted experimentally.

2. THE PICTURE OF THE TARGET NUCLEUS DISINTEGRATION PROCESS

Lately, in our experimental studies of hadron-nucleus colliding at projectile kinetic energy larger than the pion production threshold, especially at about 1 to about 10 GeV, a new physical motivation has been obtained for the induced breakup or induced fission of the colliding nuclei [4—6].

Shortly, the mechanism of the colliding nucleus splitting into some nuclear fragments is of a new and different nature and more simple — it is prompted experimentally; a nucleus involved in a hadron-nucleus collision at energy high enough is pierced by the hadronic projectile, along its course in intranuclear matter; in passing through the nucleus, the hadron involves the intranuclear matter into strong interactions within the channel with the diameter $D = 2R_s$ centered on the hadron course; $R_s \approx D_0$ is the strong interaction range as large approximately as the nucleon diameter D_0 is. The nucleons with kinetic energy of about 20 up to about 400 MeV are emitted in a definite manner from a nucleus involved in such a way into the collision process — in the number as large as the number of the nucleons contained within the channel in the intranuclear matter involved in the collision is. Obviously, the destroyed nucleus should decay into heavier nuclear fragments and nucleons, the evaporated nucleons may appear as well. The decay or evaporation process should be determined by the collision impact parameter — first of all, for a definite target-nucleus it may be expected.

The answer to the question «How is the disintegration of the colliding nuclei proceeding?» should be find in observations and experiments. Let us start the next subsection of this paper with the presentation of adequate experimental facts, therefore.

2.1.Some Experimental Facts

Relations, important for the subject in question, were collected in one of former works [7—11]. Here, some of them will be rewritten only:

1) The mean multiplicity $<n_p>$ or intensity of the emitted fast protons — with kinetic energy from about 20 up to about 400 MeV — is related to the intranuclear matter mean layer $<\lambda>$ covered by a hadron as

$$<n_p> = \frac{Z}{A}<\lambda> \cdot S(1 - e^{-<\lambda>/\lambda_t}) , \qquad (3)$$

where $\lambda_t = 1/\sigma_t$ in nucleons/S , σ_t in S/nucleon is the total hadron-nucleon cross-section, $S = \pi R_h^2 \approx \pi D_0^2 \approx 10.3\ \mathrm{fm}^2$, $R_h \approx D_0$ is the nuclear interaction range as large as the nucleon diameter D_0, $<\lambda>$ in nucleons/S is the mean thickness of the target-nucleus [4—8].

2) The angular distribution of the emitted fast protons is independent of energy and identity of impinging hadron [12—15].

3) The kinetic energy spectra of the emitted fast protons are practically independent of energy and identity of the impinging hadron [16].

4) The mean value of the kinetic energy of the emitted protons is almost as large as one half of the meson rest mass [16]; the kinetic energy of the fast protons emitted to the backward hemisphere is almost as large as one half of the meson rest mass [17].

5) The dependence of the mean number $<n_b>$ of the black track leaving particles (low-energy singly and multiply charged fragments — p, d, t, with kinetic energy $E \lesssim$ 30 MeV/nucleon and ^{3}He, ^{4}He with $E \lesssim$ 300 MeV/nucleon) on the number n_g of the gray tracks (of the fast protons predominantly, $n_g = n_p$) exhibits the same behaviour; through the energy range from 6.2 GeV to 400 GeV and practically one function describes it well [9, 12, 13]. This function for p + AgBr nuclear collisions is [12]:

$$<n_b> = 1.21 n_g + 1.49. \qquad (4)$$

6) The $<n_b> - n_g$ correlation is independent of energy and identity of the incident hadron [13]; gray track number n_g, or the multiplicity n_p, of the emitted

fast protons determines the mean number of the emitted b-track leaving fragments. The correlation is completely independent of the number of produced pions [13].

7) The multiplicities n_g and $n_h = n_g + n_b$ obey the relation [12]:

$$<n_g/n_h> = <n_g>/<n_h> \approx \text{const.} = 0.39 \qquad (5)$$

which indicates proportionality between n_g and n_h , and hence between n_b and n_g, or n_b and n_p ; this relation is energy-independent, because $<n_b>$ and $<n_g>$ are energy-independent.

2.2. Some Heuristic Consoderations

The discovery in experiments [7, 8] of the relation between the fast nucleon emission intensity or multiplicity n_N and the intranuclear matter layer thickness λ in nucleons/S involved in hadron-nucleus collisions, together with the experimentally obtained [12, 13] relationship (4) between the mean intensity or multiplicity $<n_b>$ of the low-energy target fragment emission and the fast nucleon emission intensity n_N, provided starting point for a deduction of some picture of the nucleon fragment emission mechanism in hadron-nucleus collisions. The electrically charged particles are registered usually in experiments, the emission of the fast protons and of the track leaving particles will be discussed later predominantly, therefore.

The low energy target fragments, with kinetic energies $E_b \lesssim 30$ MeV/nucleon — protons, deuterons, tritons are leaving the black tracks in nuclear photoemulsions. The emission intensity or multiplicity n_b is related to the fast proton emission multiplicity n_p by formula (4) [12]. The $<n_b> - n_p$, or $<n_b> - n_g$, correlation is completely independent of the number of pions produced in the interactions under studies [13]; even if the produced hadron multiplicity increases from 2.8 to 16.8 no change is observed in the mean number of the low energy nuclear fragments and the number of the fast protons. Other energy-independent relation has been discovered experimentally as well [12], expressed by formula (5).

The picture of the nucleon fragment emission follows from the experimental facts described above and, as such, it should be treated as prompted experimentally. If it is true, it should provide qualitative and quantitative explanations of the energy-independent relations (4) and (5) [5, 12, 13]. Let us try to present this picture.

The fast protons, or the particles leaving gray track in the emulsions, with kinetic energy of about 20 to 400 MeV, are emitted from the target nucleus during or shortly after the passage of the incident hadronic projectile and its successors through it. One should expect therefore them to memorize the history of the collision.

In the hadron-nucleus collision, only relatively small part of the target nucleus is involved in the nuclear reaction — the channel of the diameter $D = 2R_h$ as large as the strong interaction range R_h is; $R_h \approx D_0$— the diameter of the nucleon [5, 7].

In result of the emission of fast nucleons from the target nucleus a damage appears in it. On the walls of such damages the equilibrium of interactions acting on nucleons in the atomic nucleus is disturbed, and the nucleons from the walls should be evaporated first of all — just after the fast nucleon emission. The emission happens a long time after the passage of the incident hadron, after about 10^{-17} s, evaporation particles appear mainly; the passage is about 10^{-23} s after the collision starting. The evaporated particles exhibit an almost isotropic angular distribution [9, 12, 13].

The intensity of the target fragments evaporated from the walls of the damages should be defined by the surface layer of the intranuclear matter as thick approximately as the nucleon radius $D_0/2$ is.

In the works performed by means of the nuclear photoemulsions, the $n_g \approx n_p$ is used instead of n_p and $n_h = n_g + n_b$. The multiplicity [12] n_h denotes the intensity of the heavy particle tracks.

2.3. Quantitative Relations

According to the heuristic considerations, geometrical and physical meaning of formula (4) is that fragments are emitted from the surface layer of the target nucleus [5]; in this layer, damaged in the fast nucleon emission process, the translocation of the nucleons at the damage walls starts; a motivation for this statement is given in former work [5]. The shape S_b of the damaged region is determined by the shape S_N of the fast nucleon emission region; it is a tube-like region in the target-nucleus, centered on the incident hadron course λ in intranuclear matter, with the wall thickness as large as half of the nucleon diameter D_0. The mean size of this region is:

$$<G_b> = \pi[(1.5D_0)^2 - D_0^2] \cdot \lambda \,, \qquad (6)$$

where D_0 and λ are in fm. The size $<G_b>$ is energy-independent when the incident hadron energy is larger than a few GeV [5].

The size of the target nucleus damage, above a few GeV energy of the incident hadron is:

$$\langle G_p \rangle = \pi \cdot D_0^2 \cdot \lambda . \tag{7}$$

From the definition $n_h = n_g + n_b$ or $n_b = n_h - n_g$; it may be written $\langle n_b \rangle = \langle n_h \rangle - \langle n_g \rangle$ The ratio $\langle n_b \rangle / \langle n_g \rangle = \langle n_b \rangle / \langle n_p \rangle = \{\pi[(1.5D_0)^2 - D_0^2] \cdot \lambda\}/(\pi D_0^2 \lambda) = 1.25$, and $\langle n_b \rangle = 1.25 \langle n_p \rangle$. When $n_g \equiv n_p \equiv 0$, the incident hadron interacted with $(A - Z)/Z$ neutrons only, to which correspond $\langle n_b \rangle = 1.25(A - Z)/Z$ evaporated neutral fragments. In result, it can be written:

$$\langle n_b \rangle = 1.25\left(n_g + \frac{A - Z}{Z}\right). \tag{8}$$

For the Ag and Br target nuclei in emulsions, when $\langle A \rangle = 94$ and $\langle Z \rangle = 41$ may be used, the formula gives:

$$\langle n_b \rangle = 1.25 n_p + 1.61 . \tag{9}$$

Formula (8) may be represented by the dependence on n_p instead of n_g, where $n_p \cong n_g$ is the multiplicity or intensity of the emitted protons. It is:

$$\langle n_b \rangle = 1.25 n_p + \frac{A - Z}{Z} ; \tag{10}$$

this relation is valid for the incident hadron energy larger than $D \cdot \varepsilon_h$, where D is the diameter of the target nucleus in nucleons/S, ε_h is the energy loss by the hadron in its passage through intranuclear matter in GeV/(nucleon/S). The data on the nuclear diameters $D = \lambda_{\max}$ in nucleons/S are given in our former work [18]; $\varepsilon_h = \varepsilon_p \approx 0.360$ GeV for incident protons and $\varepsilon_h = \varepsilon_\pi \approx 0.180$ GeV for incident pions, $S \approx 10\ \mathrm{fm}^2$.

The formula for the $\langle n_g \rangle / \langle n_h \rangle = \langle n_p \rangle / \langle n_h \rangle$ ratio may be written simply as:

$$\langle n_p \rangle / \langle n_h \rangle = \langle G_p \rangle / (\langle G_b \rangle + \langle G_p \rangle) \tag{11}$$

or

$$\langle n_p \rangle / \langle n_h \rangle = (\pi D_0^2 \lambda)/(\pi (1.5 D_0)^2 \lambda) = 0.44 . \tag{12}$$

This relation is energy-independent at incident hadron energies over $E_h \approx \varepsilon_h D$, i.e, for energies over a few GeV.

The experimentally obtained value of $\langle n_g \rangle / \langle n_h \rangle$ ratio is [12]: $\langle n_g \rangle / \langle n_h \rangle = 0.39 \pm 0.01$, for the p — emulsion nuclear collisions at 6.2 and 22.5 GeV; at 3500 GeV this ratio is from experiment 0.38 ± 0.02 [12].

The next relation, for an experimental testing, is:

$$n_h = n_g + n_b = \pi D_0^2 \lambda + \pi[(1.5 D_0)^2 - D_0^2]\lambda = 7.07 D_0^2 \lambda . \tag{13}$$

This formula is valid at the incident hadron energy $E_h > \varepsilon_h D$, where ε_h is the energy lost by the hadron on the intranuclear matter layer as thick as 1 nucleon/S, $S \approx 10\ \mathrm{fm}^2$, D is the diameter of the target nucleus in nucleons/S [18].

3. DISCUSSION AND SUMMARY

In the picture presented in the preceding section, the g-track leaving particles are emitted from definite cylindrical volume $\pi D_0^2 \lambda$ and the b -track leaving particles are emitted from the $0.5 D_0$ thick wall of definite coaxial pipe $\pi \cdot [(1.5 D_0)^2 - D_0^2]\lambda$ centered on the incident hadron course along λ in intranuclear matter. The ratio between both the volumes v_1 and v_2 is independent of the collision impact parameter $d = (D^2/4 - \lambda^2/4)^{1/2}$ (where D is the diameter of the target nucleus) and of the energy E, and identity of the incident hadron. Because the number of the gray track leaving particles emitted in a hadron-nucleus collision is determined by the volume v_1 and that of the black track leaving particles by v_2, it is clear why an “astonishing” [12] insensitivity to primary energy and identity of the correlation between black and gray tracks occurs.

But, the intranuclear matter layer thickness λ involved to the incident hadron interaction in intranuclear matter is independent of the hadron energy E, when E is larger than a definite energy value E_{0h} for a given nucleus; E_{0h} amounts a few GeV for the heaviest nuclei [20]. When $E \lesssim E_{0h}$, the length λ of the incident hadron way in intranuclear matter is energy-dependent, because of the energy loss of the hadron, and increases from $\lambda = 1$ nucleons/S up to $\lambda = D$ nucleons/S with E increase from the pion production threshold $E = E_t$ up to $E = E_{0h}$. The ratio between v_1 and v_2 is energy-independent but the number n_N of nucleons emitted from the volume v_1 and the number n_f of nuclear fragments evaporated from the volume v_2 are energy-dependent, because of the energy-dependence of the length λ; the ratio $<n_N>/<n_f>$ is energy- independent as well. The energy dependences of both the intensities n_N and n_f can be simply determined, as it has been done for the intensity of the fast nucleon emission [21].

Black track leaving particles exhibit an almost isotropic angular distribution [22]. This is discovered for a sample of any-type hadron-nucleus collision events. But, according to the picture drawn above, some anisotropy in angular distribution of the black track leaving particles may be found in a sample of events in which incident hadron is deflected only in its passage through the target nucleus and *h*-track leaving particles are emitted without particle production (in particular without pion production); the anisotropy should be relative to the plane containing the incident hadron course and perpendicular to the deflection plane. Similar anisotropy in angular distribution of the *g*-track leaving particles intensity was found and discussed in detail in one of my works [23].

Let us sketch once again briefly how the emission process of the *h*-track leaving particles proceeds. From the investigations described above, it is clear that in any hadron-nucleus collision only an active part of the target nucleus is destroyed, this part is in average as large as the volume $\pi(1.5D_0)^2\lambda$. For various nuclei with the mass numbers of about 100, as for the Ag nucleus, in nearly 90% of collision events the active part is situated in such a way that only the cylindrical part of the residual nucleus, near its surface, is destroyed. The nucleons on the damaged part of the target nucleus surface are not in the equilibrium state as the nucleons on the rest of the nucleus surface and, therefore, evaporate simply. After the emission of the fast nucleons and the evaporation of the target fragments, the residual target nucleus may be in an unstable state and then it must decay into stable nuclear fragments. The decay process should proceed in expense of the inner nuclear energy of the residual unstable nucleus.

In collisions of hadrons with lighter nuclei, $A \lesssim 100$, in almost all cases the evaporation of the *b*-track leaving particles goes from the surface of the residual target nuclei. When *A* increases, being $A \gtrsim 100$, the percentage of the surface evaporation decreases slightly, but in almost all events the evaporation is practically from the surface of the destroyed part of the nucleus.

Ending this paper, I am in a position to state: The results presented in this article may form physical basis for new alchemy — the science concerned with ways to turn one element into other elements, to elements transmutations.

The yield from the hadron-nucleus collision reactions — the mass spectrum of the produced elements should be determined elecfronically, using mass-spectrometry methods. It should be expected that the resolving efficiency will be high enough. The dependences of the emitted nuclei mass-spectra on the multiplicity of the emitted fast nucleons, or on the fast protons only, will be of general importance for characteristics of the yields in question.

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