94-322

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исследований
дубна

E1-94-322

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ATOMIC NUCLEI UTTER DISINTEGRATION INTO NUCLEONS BY HIGH ENERGY NUCLEAR PROJECTILES

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1994

1. INTRODUCTION

In studying experimentally the mechanisms of hadron-nucleus and nucleus-nucleus collision processes [1,2], the passage of the projectile hadron through layers of the intranuclear matter, accompanied by intensive emission of nucleons with energies of about 20 to 400 MeV from the target nucleus have been studied as a phenomenon of special importance [2--5]. When recognized conclusively and quantitatively well enough, this phenomenon can serve as the basis for many applications of single massive nuclei, for example as the intranuclear detector [6,7] for detection and observation of processes in atomic nuclei within volumes of about 10^{-12} -- 10^{-13} cm in time intervals of about 10^{-24} — 10^{-22} s; as the source of highly collimated monoenergetic beams of high energy nucleons and of neutrons -- in particular -- with simply and fluently adjustable energies within wide diapason of energy values [8,9].

From detailed thorough analysis of the nucleon emission process, induced from atomic nuclei by hadronic projectiles, a new method of nuclei utter disintegration by means of high energy nuclear projectiles emerged. It is worth while to emphasize that this finding may be of wide application in working out methods of utter disintegration of some injurous to helth radioactive elements into single nucleons.

The subject matter in this work is to describe the physical phenomenon -- the utter disintegration of nuclei by means of high energy nuclear projectiles, and the method of realization of such disintegrations in practice.

This work is performed within frames of my contacts with the Institute of Atomic Energy at Swierk-Otwock in Poland.

2. PHYSICAL FOUNDATION OF THE METHOD

In result of observations and analysis of the collisions of high energy hadrons with massive nuclei in xenon bubble chambers it has been found [10,11] that intensive emission of fast -- from about 20 up to 400 MeV kinetic energy — nucleons from the target nuclei proceeds independently of the particle production process. The emission appears in events with particle production and in events without particle production; the angular and energy spectra of the protons do not depend neither on the multiplicity $n_h = 0,1,2,3, \ldots$ of the produced particles in the collision events nor on the multiplicity $n_p = 1,2,3,\ldots$ of the emitted protons (nucleons) in them. The conclusion was prompted experimentally that high energy hadrons, in passing through intranuclear matter, induce the nucleon emission in a definite manner; the passages in their pure form are observed plentifully at incident hadron energies from about 1 to about 10 GeV — hadron-nucleus collision events without particle production are often observed [5]. The energy and angular spectra of the emitted protons (nucleons) are identical correspondingly in samples of events with particle production and in that events without particle production.

The laws of the fast nucleon emission which the hadron passages through layers of intranuclear matter are accompanied by were formulated [12], the hadron passages were investigated accurately in experiments [13].

The crucial relation between the mean multiplicity $<n_p>$ of the emitted fast protons in a hadron-nucleus collisions and the intranuclear matter layer mean thickness $<\lambda>$ in nucleons/S unit, involved in the collision,

$$<n_p> = \frac{Z}{A} <\lambda> S \left(1 - e^{-\frac{<\lambda>}{<\lambda_t>}} \right) \quad (1)$$

has been verified experimentally [13]. In the relation (1) $S = \pi D_0^2 \approx \pi R_h^2 \approx 10.3 \text{ fm}^2$, where R_h is the strong interaction range which is as large approximatelly as the nucleon diameter D_0 is; $<\lambda_t> = 1/\sigma_t$ is the hadron mean free path in intranuclear matter in nucleons/S units, σ_t — the total hadron-nucleon cross section in S/nucleon units.

Formula (1) represents a special case of corresponding laws of the nucleon emission [12].

Law I: Any hadron of kinetic energy higher than pion production threshold induces nucleon emission from the target nuclei in traversing them along a path λ fm; the number n_N of the emitted nucleons equals the number of nucleons contained within the cylindrical volume $v = \pi R_h^2 \lambda \approx \pi D_0^2 \lambda \text{ fm}^3$ centered on λ in the target nucleus:

$$n_N = \pi R_h^2 \lambda <\rho> \approx \pi D_0^2 \lambda <\rho> , \quad (2)$$

where $R_h \approx D_0$ fm is the strong interaction range and the nucleon diameter correspondingly, $<\rho>$ in nucleons/fm^3 is the mean nucleon density inside the volume v.

When λ is expressed in nucleons/S units, the relation (2) becomes more simple

$$n_N = \lambda \cdot S , \tag{3}$$

$S = \pi D_0^2 \approx 10.3\ \mathrm{fm}^2$.

Law II: In passing through intranuclear matter, any of hadrons of kinetic energy larger than the pion production threshold loses fluently its energy: the energy ΔE_h MeV of the hadron lost on the path length $\Delta\lambda$ nucleons/S equals

$$\Delta E_h = \varepsilon_h \cdot \Delta\lambda , \tag{4}$$

where $\varepsilon_h = \varepsilon_\pi =$ 180 MeV/nucleons/S and $\varepsilon_h = \varepsilon_p =$ 360 MeV/(nucleons/S).

Law III: Energy and momentum spectra, and angular distributions of the nucleons appeared in the emission process are independent of the projectile energy and identity, in the target nucleus system of reference, and of the number n_N of the emitted nucleons, and of the number $<n_\pi>$ of produced pions in hadron-nucleus collisions.

In other words, the nucleon emission process is not effected by the particle production process.

Law IV: Any hadron of kinetic energy larger than the pion production threshold induces the nucleon emission from the target nucleus in any type collision with it; the emission is induced in any case fluently along the hadron course through the thickness (nucleons/S) of intranuclear matter layer the hadron interacted with, and its intensity is characterized by

$$n_N = \lambda \cdot S \tag{5}$$

and

$$<n_N> = <\lambda> S . \tag{6}$$

The above presented properties of the hadron passage through intranuclear matter are concerned to single hadron passage through layer of intranuclear matter.

When as the projectile a high energy atomic nucleus is employed, then it is equivalent to the interaction of collimated beam of weakly (about 8 MeV/nucleon) bound nucleons with the target nucleus — the collision of the nucleon beam with atomic nucleus occurs. Any of the beam nucleons will cause the emission of nucleons from the target nucleus, similarly as in the case when the projectile nucleon in its passing through the target nucleus do it. But, in the nucleon beam collision with the target nucleus the nucleon projectiles traverse it almost simultanously at various impact parameters.

The mostly expressive case can be observed when the collision of the nuclei is head on, and the colliding nuclei are of the same radii — all the nucleons in both the colliding nuclei become to be free. The collimated beam of the projectile nucleons appears in the target nucleus reference system, the target nucleus emits the nucleons almost isotropically in its own reference system — when it is at rest; the emission intensity from it is the composition of the emission intensities induced by single nucleon at various impact parameters.

And so, the utter disintegration of a nucleus by high energy nuclei of equal or larger radii may be realized simply. But, the utter disintegration will occur when the energy of the incident nucleus is high enough, it may be determined from the formula (4). In this case, the nucleon emission from the target nucleus is observed only, without heavier nuclear fragments; the produced particles can appear as well.

When the collisions are not central, the utter disintegration of the overlapping parts of the colliding nuclei takes place only.

Similar collimated beams of nucleons are observed on photographs from the bubble chambers, the streamer chambers and in nuclear emulsions, when nuclear collisions are registered in them.

It should be emphasized that in the hadron-nucleus collisions the small cylindrical volume $\nu = \lambda S$ is involved only; ν is in nucleons, λ in nucleons/S, $S \approx 10.3\ \mathrm{fm}^2$. The volume ν is centered on the projectile hadron course.

3. THE METHOD AND THE NUCLEI DISINTEGRATION PROCEDURE

The method of the nuclei utter disintegration is simple: The nucleus which has to be disintegrated must be bombarded by collimated beams of hadrons with energies high enough. Naturally, such collimated hadron beams with energies high enough are appropriate beams of correspondingly high energy nuclei. Any of the accelerated nuclei is in fact the highly collimated beam of weakly (about 8 MeV/nucleon) bound nucleons. The beam nuclei should be as massive as the target nucleus is or larger. The energy of the nuclei projectiles should be:

$$E_{proj} \geq \epsilon_N \cdot D_{targ}, \tag{7}$$

where $\epsilon_N \approx \epsilon_p \approx 360$ MeV/(nucleon/S), D_{targ} — the target nucleus diameter in nucleon/S; the data on nuclei diameters are given in our former works [14,15]. The values of D_{targ} are, for example, for $^{12}C_6$ $D_{targ} \approx 6$ nucleons/S, for $^{56}Fe_{20}$

$D_{targ} \approx 13$ nucleons/S, for $^{131}Xe_{54}$ $D_{targ} \approx 19$ nucleons/S, for $^{207}Pb_{82}$ $D_{targ} \approx 22$ nucleons/S, and for $^{238}U_{92}$ $D_{targ} \approx 23$ nucleons/S.

The above nuclei collision configuration has been used with the target nucleus at rest in the laboratory system. It may be mostly convenient for applications in technology, biology, materials sciences and in unhealthy radioactive materials annihilation, in environmental pollution elimination. But, the nuclei disintegration process goes on in any-type collisions of nuclei with energies high enough. In any collision both of the colliding nuclei are disintegrated at the overlaping parts utterly, the remnant parts do not participate in the collision process, they are spectators.

4. SOME QUANTITATIVE RELATIONS

It is worth-while to present here the mostly important quantitative characteristics of nuclei which could be used as projectiles for utter disintegration of definite nuclei.

4.1. *The mass and kinetic energies of nuclei used as projectiles for utter disintegration of definite nuclei*

In Table 1, corresponding values are presented, obtained on the basis of data from our former works [14,15].

4.2. *The kinetic energies of the emitted protons and neutrons*

The mean energy $<E_p>$ of the emitted protons (nucleons) from the target nucleus disintegrated at rest in the laboratory system is [16]

$$<E_p> \approxeq \frac{m_\pi}{2}. \tag{8}$$

The energy spectrum is [17—19] independent of the projectile energy and identity; formula [19]

$$N(E)\cdot dE = E^{\gamma} dE, \tag{9}$$

describes it with $\gamma = 1.09 \pm 0.02$.

4.3. *The angular spectra of the emitted protons (nucleons) [18—20]*

The angular distribution of the emitted protons (nucleons) is described in laboratory system of reference by the relation [18]:

$$\frac{1}{\sigma} \cdot \frac{d\sigma}{d(\cos\theta)} e^{0.96\cos\theta}; \tag{10}$$

it is independent of the incident hadron energy and identity.

Table 1. The minimal values $M_{A\,min}$ of the masses M_A and kinetic energy $E_{kA\,min}$ of the nuclear projectiles which should be employed for disintegration of the nuclei with the mass numbers A into nucleons in head on collisions; P — the probability of the head on projectile collision with the target nucleus

A	$M_{A\,min}$	$E_{kA\,min}$ GeV/nucleon	P % min	P % max
$^{12}C_8$	12	2.13	3	12
$^{16}O_8$	16	2.55	4	11
$^{32}S_{16}$	32	3.70	4	9
$^{60}Co_{27}$	60	4.87	5	10
$^{108}Ag_{47}$	108	6.22	4	9
$^{131}Xe_{54}$	131	6.69	5	9
$^{197}Au_{79}$	197	7.79	4	9
$^{207}Pb_{82}$	207	7.93	4	8
$^{238}U_{92}$	238	8.35	4	7

5. CONCLUSIONS AND REMARKS

It may be concluded, from the above presented experimental facts and characteristics in question of the hadron-nucleus and nucleus-nucleus collision processes that hadronic and nuclear projectiles with kinetic energies above a few GeV and a few GeV/nucleon correspondingly may serve as effective means for massive atomic nuclei disintegration; when nuclear projectiles are massive enough the utter disintegration happens in head on collisions.

In hadron-nucleus (nucleon-nucleus) collisions a partial disintegration of massive nuclei occurs only [21]. The percentage W of the emission of a given number n_p of the protons from the Ag target nucleus, if bombarded by proton projectiles of energy high enough, is given in Table 2.

The mean number $<n_N>$ of the nucleons emittedd in a hadron-A nuclear collision for various target nuclei A is presented in Table 3. After the collisions, the pierced target nuclei decay into stable fragments; it should be investigated how this transition is going on.

Table 2. The percentage W of p + Ag nuclear collision events with n_p = 0,1,2,3,...,8 protons emitted in the reaction; the number of the emitted nucleons $n_N = n_p \frac{A}{Z}$

n_p	0	1	2	3	4	5	6	7	8
W %	26	21	12	9	8	7	8	8	1

Table 3. The mean number $<n_N>$ of the emitted nucleons in hadron-nucleus collisions with various target nuclei; the incident hadron energies are high enough see table 1

Target nucleus	$^{12}C_6$	$^{16}O_8$	$^{32}S_{16}$	$^{60}Co_{27}$	$^{108}Ag_{47}$	$^{131}Xe_{54}$	$^{191}Au_{79}$	$^{207}Pb_{82}$	$^{238}U_{92}$
$<n_N>$	2.82	3.20	4.40	5.90	7.74	8.52	10.15	10.38	11.05

But, it should be emphasized that the disintegration (the utter disintegration as well) of atomic nuclei goes continuously in the Nature: The nuclear component in the primary cosmic rays is disintegrated in upper layers of the planet atmosphere; the cosmic-ray nuclei in outer space — in galactics and in intergalactic space use to collide rarely but continuously — during milliards years.

All what has been written above should be treated as the physical basis for working out methods of nuclei disintegration.

I would like to state, some more, that the disintegrations of nuclei into nucleons, including the utter disintegration, are natural consequence of the process general for all the nuclear collisions: the hadron passage through layers of intranuclear matter accompanied by the emission of nucleons with energies from about 20 to about 400 MeV. This physical phenomenon manifests itself expressively on all the pictures of the collision reactions.

The hadron passage is the nuclear analogy of the known well electromagnetic phenomenon — of the passage of electrically charged particle through layers of materials accompanied by electron and ion appearance. This is general process independent of the other processes met in nuclear collisions.

In the context of our investigations described in this paper, I would like to make the mention of the K.D.Tolstov work [22] in which the total disintegration of heavy nuclei is considered in collisions of 4.5 GeV/c protons and 4.5 GeV/c/nucleon ^{4}He and ^{12}C nuclei with Ag and Pb nuclei.

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Received by Publishing Department
on August 8, 1994.