СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E1-97-176

E.Strugalska-Gola[1], Z.Strugalski[1,2]

THE PICTURE OF THE NUCLEI DISINTEGRATION MECHANISM — FROM NUCLEUS-NUCLEUS COLLISION EXPERIMENTAL DATA AT HIGH ENERGIES

Addresses for correspondence:
[1]Institute of Atomic Energy, 05-400 Otwock-Swierk, Poland
[2]Institute of Physics, Warsaw University of Technology, ul.Koszykowa 75, PL 00-662 Warsaw, Poland

1997

1. INTRODUCTION

This work is a continuation of our previous one [1] in which the target nuclei disintegration mechanism in nuclear reactions initiated by high-energy hadrons colliding with nuclei was depicted clearly and conclusively — as based experimentally. In our previous publications [2,3], it was mentioned that the nucleus-nucleus collision process is a composition of the hadron-nucleus collisions — especially of the nucleon-nucleus collisions. It was rather our hypothetical conclusion on the basis of the hadron-nucleus collision observation data. Similar statements, rather hypothetical ones, can be met as well in various review publications.

In contrary to those publications the information on the problem in question presented here is based on our analysis of the data from the nucleus-nucleus collision processes registered in nuclear photoemulsions and analysed qualitatively and quantitatively in works of many physicists [4].

The data on the target nuclei disintegrations in nuclear collisions mostly informative for the analysis are from the collision studies by photographic methods. We decided to use firstly the expressive pictures of the nucleus-nucleus collision reactions obtained a long time ago — as unbiased ones, although many of them are from the cosmic ray experiments only. It was decided to use such a kind of the observation procedure because of almost exclusively accurate technical analysis of individual collision events in the cited publications and of the completeness of the pictures of such registered events obtained by photographic methods [4].

The subject matter in this paper is:

1. To collect some sample of experimental facts which characterize generally the colliding nuclei disintegration processes, as presented in some of many former publications;

2. To collect additional sample of such experimental facts which have been obtained in some of publications performed in about last 25 years [5—7] by various methods;

3. To discuss about the experimentally obtained properties of the nuclei disintegrations.

2. EXPERIMENTAL DATA FROM WORKS PERFORMED BY PHOTOGRAPHIC METHODS

From observations of the hadron-nucleus collisions at high energies — higher by much over the pion production threshold — registered in heavy liquid bubble chambers one can conclude that the interaction is localized within the cylindrical volume centered around the projectile course at a distance as large as the strong interaction range R_S is, and three main phenomena may be seen when a fast nucleon collides with a resting nucleus:

a) The passage of the incident hadron through the target nucleus; b) The particle production appearing sometimes at the background of the passage; c) The fragmentation of the residual target nuclei and nucleon evaporation, in particular, from it [3]. The passage of the nucleon through a nucleus in most of the cases should be accompanied by the emission of fast nucleons with energies from ~ 20 up to ~ 500 MeV.

In nucleus-nucleus collisions, the properties of the hadron-nucleus collision will manifest themselves as well. A fast nucleus projectile with the energy per nucleon high enough — higher by much than the pion production threshold — may be treated as a very collimated beam of nucleons, which interacts with a layer of intranuclear matter in the target nucleus at rest.

In such a collision and interaction of the collimated nucleon beam with intranuclear matter, it is reasonable to expect that only peripheral groups of nucleons of the interacting nuclei will be involved in the collisions. The main parts of the colliding nuclei (of the resting target-nucleus and of the projectile nucleus playing the role of the incident nucleon beam one) will collide peripherally; they will be not sufficiently disturbed to be disrupted, and the nuclear fragments emerging from the encounter will appear at the fast stage of the collision (during about 10^{-24}—10^{-22} s): one with the velocity little different from that of the incoming nucleus, and the second — the damaged residual target nucleus. The residual target nucleus will suffer a transmutation at rest into stable fragments — through evaporation of heavy nuclear fragments and a fission into lighter nuclei. The incident-projectile nucleus will suffer the same transmutation in its flight after having left the collision region.

The volumes of the colliding nuclei interaction parts involved in the collision induced nuclear reaction depend on the collision impact parameters — the distances between the centers of the colliding nuclei. When the impact parameter equals 0, the head-on collision occurs.

The parts of the colliding nuclei involved in the collision are completely disrupted. From the resting target nucleus all the nucleons are emitted as the so-called fast ones with kinetic energies from ~ 20 up to ~ 500 MeV in the lab. system. The nucleons from the disrupted part of the projectile nucleus form the collimated beam of losely bound nucleons which may be observed; among the beam nucleons, the spectator — undisrupted part of the incident nucleus — may be observed in some cases.

The above depicted scenario was presented as prompted on the basis of the experimental information about the hadron-nucleus collision and about the hadron-nucleus collision induced nuclear reactions. In presenting it, the working hypothesis has been used: the yield of the nucleus-nucleus collision process is a composition of hadron-nucleus collision processes as treated separately.

But, what is really the picture of the nucleus-nucleus collision process? The answer to this question should be found in observations and experiments.

The first observations and experiments concerning this question were performed by many physicists using fast nuclei from cosmic rays and the photographic emulsion method. The main results were collected in the work of Powell, Fowler and Perkins [4]. Let us review shortly those very interesting results in the light of the expectations described above.

The studies of the energetic heavy nuclei collisions are greatly stimulated by their bearing on the particles and their interaction problems [4]. By following the tracks of heavy primary nuclei from their points of entry into a photographic emulsion stack untill they either escape from it or interact with nuclei, the values of the «interaction length» were determined.

For energetic particles which interact strongly with intranuclear matter, the target-area presented by a nucleus is given with an error of about 10%, by the relation $\sigma = \pi(1.45 \cdot 10^{-13} A^{1/3})^2$, where A is the number of nucleons, and $1.45 \cdot 10^{-13}$ cm corresponds to the mean distance between neighbouring nucleons. Knowing the density and chemical composition of the emulsion, the total nuclear cross-section can be calculated [4]: $\sigma_t = \Sigma^i N_m \sigma_m$, where N_m, σ_m represent the number of atoms of the m-th element per cm^3, and its nuclear cross-section, respectively, the summation being made for all the elements present in the emulsion.

As a consequence of the nuclear cross-section, there is an attenuation in the intensity of a beam of fast particles passing through matter. If they interact strongly with nuclei, the number surviving after a thickness x is given by:

$$N = N_0 e^{-\sigma_t x}, \quad (1)$$

and the mean distance travelled by a particle is: $l = l/\sigma_t$. This distance is referred to as the «interaction length» [4]. For a normal nuclear emulsions its value is found to be about 25 cm, a result close to that obtained in experiments with fast protons and π-mesons [4].

The interaction cross-section for an incident nucleus of radius R_i, colliding with a target nucleus of radius R_t, may be expressed in terms of an empirical relation introduced by Bradt and Peters (1950) [8]:

$$\sigma = \pi(R_t + R_i - R)^2, \quad (2)$$

where $R_{t,i} = R_0 A_{t,i}^{1/3}$. Assuming $R_0 = 1.45 \cdot 10^{-13}$ cm, R may then be deduced by comparing the experimental results with those computed. With

$$R = 1.17 R_0 \quad (3)$$

it is found to be valid, within an error of about ± 15%, for all particles, provided that either the incident or a target nucleus, or both, have atomic numbers $A \geq 12$. In particular, the calculated interaction lengths in emulsion, for nuclei ranging from helium to iron, deduced from it, are in good agreement with those found experimentally. It is therefore reasonable to use Eq.(3) to estimate the relative frequency with which primary nuclei of varoius masses interact with the different atomic components of the emulsion. The interaction lengths in emulsions in cm, of heavy nuclei of different types as determined by different authors [9—12], are given in table 16-1, p.605 in the cited work [4]; calculated values from formula (3) are given there as well. The authors [9—12] also studied the characteristics of the disintegrations produced by the energetic nuclei.

It may be seen that apart from the increased frequency of collision with hydrogen, the relative proportions of the primary nuclei which interact with light and heavy elements change little in passing from $Z=3$ to $Z=30$.

2.1. Features of the Disintegrations of Nuclei Produced by Heavy Nuclei [4]

A very striking feature of the collisions involving primary heavy nuclei is the frequency with which a fast secondary heavy nucleus, or a number of α-particles, emerge from the encounter. Nuclei with $Z \geq 2$ are never emitted at relativistic velocities from disintegrations due to fast protons. It is therefore reasonable to assume that any fast heavy secondary particles formed a part of the incoming nucleus and that they are fragments of it; that they are produced in peripherical collisions between two nuclei, only a few of the nucleons of the primary fast particle, or of the target nucleus, being involved in the impact. In such a collision, it may happen that the nuclei groups of nucleons of the interacting nuclei are not sufficiently disturbed to be disrupted, a heavy nuclear fragment emerging from the encounter with a velocity little different from that of the incoming particle; whilst

a fragment of the struck nucleus is given little velocity and remains intact in the emulsion.

In the «head-on» collisions between two nuclei, however, both of them may be completely dispersed into their component nucleons. In such events and when the primary particle is moving with great energy, the number of secondary products of the impact — mesons and other particles — may be very great because of the large number of nucleon-nucleon collisions involved. It is therefore found that the largest «stars» recorded in emulsions exposed at ballon altitudes are produced by the heavy nuclei of the primary radiation.

Ending this overview of the old emulsion data, it will be worth while to present a very important statement from the cited book [4]: «The composition, energy and angular distribution of the secondary particles from the disintegrations due to nuclear collisions of protons and neutrons in emulsion, are well known; see Sec.13 [4 p.608]. In the collision of two heavy nuclei, it is reasonable to assume that the disintegration products of each in its own rest-frame will be similar to that produced by the impact of a number of protons of velocity equal to that of the moving primary particle. If so, the characteristics of disintegrations in emulsions due to individual protons may be used as a guide in interpreting those due to more massive nuclei» — it was many years before 1959!

2.2. The Picture of Some Disintegrations of Atomic Nuclei by Hadrons and Nuclei, Registered in Photoemulsions [4]

The picture of the disintegration process of atomic nuclei induced by collisions of hadrons with the nuclei has been described widely enough in the first part of this work [1]. We use to mention here about it in order to take in mind some properties of this process being in common relation with the main questions under interest in this part of the work — the nuclei disintegration in nucleus-nucleus collisions.

The data used here are from the emulsion experiments, as referred by Powell, Flower and Perkins in section 16 of their review book [4].

However, in the «head-on» collisions between two nuclei, both of the colliding nuclei may be completely dispersed into their component nucleons. In such collisions events, when the primary nucleus is moving with great velocity (energy), the number of products of the impact — of mesons and other hadrons — may be very great — due to the large number of nucleon-nucleon particle-producing collisions involved. It is reasonable to assume, as well, that disintegration products of each nucleus in its own rest-frame will be similar to that produced by the impact of a number of protons of velocity equal to that of the moving primary nucleon.

Many of the events observed in photoemulsions and analysed in the works reviewed by Powell, Fowler and Perkins [4] support the above formulated assumptions, which are in agreement with our predictions on the ground of the data obtained in our works [1—3] and from the review works [4—7].

Let us describe shortly some of the registered in photoemulsions events which may be used as supporting the assumptions and statements formulated above in this work. The examples will be from the review work [4].

On the photograph [4] (pl.8-16), the carbon nucleus, moving with a velocity close to that of light, in result of the collision is decomposed into 3 α-particles emerged with nearly the same velocities; the absence of the tracks which could be associated with the «evaporation» of the struck nucleus «makes it reasonable to attribute the event to collisions with a proton». «This proton is recoiled and produced the track diverging from the incident nucleus course». In our interpretation: the struck nucleus C smashed perypherally through a hydrogen nucleus what led to the breaking of the nuclear bounds between nucleons involved on the nuclear periphery and in ones turn to the disintegration of the projectile-nucleus into α-particles.

In other of events, a nucleus of the charge number 12 ± 2 makes a nuclear collision and fragments. The incident particle is almost completely dispersed into its parent nucleons and the struck nucleus is also shattered. Special analysis [4] indicated that the struck nucleus must have been with Z about $35e$ — it was bromine [4, p.610—611].

A sulphur nucleus, S_{16}, moving with the velocity in the relativistic region, suffers a nuclear collision which led to the production of a «jet» of about 25 mesons.

Several of the tracks in the main jet are not individually resolved. A florine nucleus, $Z=9$, appeared as one of the fragments of the parent particle, (Plate 15—16) [4].

A carbon nucleus with energy about 20000 BeV makes a nuclear collision as a result of which more than 100 charged mesons are created, about half of which are in central «jet» of secondary particles. The incoming particle was dispersed into its component nucleons as a result of the collision [4, plate 16-19].

In other example, an oxygen nucleus interacts in the emulsion giving rise to fifty four shower particles [4, plate 16-20]. Three slow particles are ejected from the target nucleus; by chance they are all in the «backward» direction. Eight of the shower particles are contained in a cone of semi-vertical angle $\approx 3 \cdot 10^{-3}$ degrees. It is certain that most of these «inner-core» particles are protons from the decomposition of the primary nucleus... «The event provided a homogeneous jet of protons, accompanied by a similar stream of neutrons, all with the same energy per nucleon within narrow limits» [4].

On many plates in the book cited intensively in this work of Powell, Fowler and Perkins [4] one may find interesting and valuable pictures of the hadron-nucleus and nucleus-nucleus collision events. These events contain conclusive information about nuclear collision processes. This information supports our statement formulated in this work.

3. CONCLUSIONS AND REMARKS

It can be concluded that:

1. All the facts revealed in the works by photoemulsion technique support our results and conclusions based on them concerning the hadron-nucleus and nucleus-nucleus collision.
2. The photoemulsion data are complementary well enough to that data from heavy liquid bubble chambers, referred in the first part of this work.
3. More information about nuclei disintegration in hadron-nucleus and nucleus-nucleus collision induced nuclear reactions may be obtained by radiochemical and spectroscopy methods.
4. It cannot be excluded that the energy-overcompensating [14] nuclear reactions may occur.

REFERENCES

1. Strugalska-Gola E., Strugalski Z., Chmielowski W. — The Picture of the Nuclei Disintegration Mechanism — from Hadron-Nucleus and Nucleus-Nucleus Experimental Investigations at High Energies. JINR, E1-97-129, Dubna, 1997; references in it.
2. Strugalski Z. — Mechanism of High Energy Hadron-Nucleus and Nucleus-Nucleus Collision Process. JINR, E1-94-295, Dubna, 1994; references in it.
3. Strugalski Z. —Physical Meaning of the Yields from Hadron-Nucleon, Hadron-Nucleus and Nucleus-Nucleus Collisions Observed in Experiments. JINR, E1-95-23, Dubna, 1995; references in it.
4. Powell C.F., Fowler P.H., Perkins D.H. — The Study of Elementary Particles by the Photographic Method. Pergamon Press, London—New York, et al., 1959; many references in this book.
5. Baldin A.M. — EChaYa — Particles and Nuclei, 1997, v.8, p.429.
6. Bartke J. — Inter. Journ. of Modern Phys. A, 1989, v.4, №6, p.1319; references in it.
7. Stock R. — Particle Production in High Energy Nucleus-Nucleus Collisions. Phys. Reports, 1986, v.135, p.259.
8. Bradt H.I., Peters B. — Phys. Rev., 1950, v.77, p.54.

9. Kaplon M.F., Noon J.H., Racette G.W. — Phys. Rev., 1954, v.96, p.1408.
10. Rajopadhye V.Y., Waddington C.J. — Phil. Mag., 1958, v.3, p.25.
11. Cester R., Debenedetti A., Garelli C.M., Quasiati B., Tallone L., Vigone M. — Nuovo Cim., 1958, v.7, p.371.
12. Fowler P.H., Waddington C.J. — Phil. Mag., 1956, v.1, p.637.
13. Strugalska-Gola E., Strugalski Z. — The Picture of the Nuclei Disintegration Mechanism — from Nucleus-Nucleus Collision. JINR, E1-97-177, Dubna, 1997; references in it.

Received by Publishing Department
on June 4, 1997.

Стругальска-Голя Э., Стругальски З. E1-97-176

Картина механизма дезинтеграции ядер —
из экспериментальных данных по столкновениям ядер
при высоких энергиях

Данные экспериментов по ядерным столкновениям при высоких энергиях анализируются с точки зрения картины механизма процесса ядерного столкновения, подсказанной на опыте.

Фактически, продукты дезинтеграции каждого из сталкивающихся ядер, в их собственной системе отсчета, похожи на продукты столкновений с ядром-мишенью многих нуклонов с такой скоростью, как у нуклонов в налетающем (первичном) ядре-снаряде.

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

Сообщение Объединенного института ядерных исследований. Дубна, 1997

Strugalska-Gola E., Strugalski Z. E1-97-176

The Picture of the Nuclei Disintegration Mechanism —
from Nucleus-Nucleus Collision Experimental Data at High Energies

Experimental data on nuclear collisions at high energies, mainly obtained from photographic emulsions, are considered from the point of view of the picture of the nuclear collision processes mechanisms prompted experimentally. In fact, the disintegration products of each nucleus involved in a nuclear collision, in its own rest-frame, are similar to that produced by the impact of a number of nucleons of velocity equal to that of the moving primary nucleus.

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 of the Warsaw University of Technology, Warsaw, Poland.

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