СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

96-1

E1-96-1

Z.Strugalski[1], H.Jedrzejec[2], E.Mulas[3], E.Strugalska-Gola[2]

FINAL STAGE OF HIGH ENERGY HADRON-NUCLEUS NUCLEAR COLLISION REACTIONS

---

[1] Warsaw University of Technology, Institute of Physics,
ul.Koszykowa 75, Warsaw, Poland
and
Institute of Atomic Energy, PL 05-400 Otwock-Swierk, Poland
[2] Institute of Atomic Energy, PL 05-400 Otwock-Swierk, Poland
[3] Warsaw University of Techmology, Branch of Plock, Poland

1996

1. INTRODUCTION

The mechanism of hadron-nucleus collision ractions was studied during relatively long period in our experiments [1] in which intranuclear detector [1—4] has been used.

In hadron-nucleus collisions the interaction of the incident hadron (nucleon, for example) is localized in relatively small cylindrical volume with the radius as large as the strong interaction range is, centered by the hadron course within the target nucleus. Four main phenomena are usually observed when hadrons collide with atomic nuclei [1]:

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 later.

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 collision reactions; the emission of fast protons is identical as in a).

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

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

The incident hadron passage a) and the particle production b) form the first, initial stage of the hadron-nucleus collision reaction, realized during about $10^{-23} + 10^{-22}$ seconds; the target nucleus is damaged in this stage. The phenomena c) and d) may be taken into account as one phenomenon — the disintegration of the target nucleus damaged in the first stage of the collision, named above as a) and b); this stage we call the second one. The first stage is the «fast» one, the second is the «slow» one.

In the first stage of the collision, the hadronic projectile energy is transferred partly to the target-nucleus and partly to the downstream nucleons involved in the particle-producing collision reactions with the projectile. The energy of the projectile transfer to the target nucleus is limited [5], and it is no larger than about a few GeV; the energy transfer from the hadronic projectile to a nucleon involved in particle production process seems to be practically unlimited [5].

The «fast» stage of hadron-nucleus collision reactions has been discussed widely on the basis of the experimental data from the xenon bubble chambers [1] and from appropriate electronic arrangements [1,6,7]. The «slow» stage of the hadron-nucleus nuclear collision reaction is the subject of the considerations in this work.

The discussion here is based on our experimental knowledge about the mechanism of the «fast» stage of the collision reactions and about the mechanism of the energy transfer from hadronic projectiles into target nuclei, in collisions at high energies.

This work may be considered as a second part or continuation of the former work [1].

2. THE TARGET NUCLEUS DAMAGED IN THE «FAST» STAGE OF A HADRON-NUCLEUS COLLISIONS REACTION

The produced intermediate objects, the «produced particles» are emitted by, and the fast nucleons accompanying the incident hadron and their successor in their passage through the target nucleus escape the parent nucleus very soon after the instant of impact, after 10^{-22} sec, and leave the nucleus as damaged and in a highly excited state. The meaning exists [8] that the excitation energy of the nucleus may sometimes be comparable with its total binding energy [8]. Our experimental investigations indicate that the damage is defined and limited to the channel inside the target nucleus with the diameter $D \approx 2R_h$ (where $R_h \approx D_0$ is the strong interaction range as large approximately as the nucleon diameter D_0) centered on the incident hadron course [9]. The incident hadron energy transferred into target nuclei in collisions at high energies is limited and defined, as well [5].

The hadron-nucleus collision reaction comes at this moment into the second stage — the «slow» stage one. In this stage, emission of particles from the residual target-nucleus in the high by excited state, however, takes place relatively slowly [8], possibly about 10^{-17} sec may be taken into account, after the instant of impact.

Three facts discovered in experiments indicate on a possible interpretation of the damages of the target nuclei in hadron-nucleus collision reactions; the facts are:

1. Relations between characteristics of nuclei (nuclear sizes and nucleon density distribution in them) and some characteristics of the nucleon emission process from the damaged nucleus (or of the proton emission process only) may be discovered and investigated experimentally [1—5].

2. The hadron-nucleus collision mechanism is memoried by fast nucleons emitted from target nuclei [9].

3. Definite relations have been find experimentally between the intensity n_p of the fast protons and the mean intensity $<n_b>$ of the electrically charged slow target fragments emitted from the nucleus in hadron-nucleus collisions [10].

It may be concluded from the statements 1.—3. that: The consequences of the existence of the two stages in hadron-nucleus collisions manifest themselves during relatively long time — from about 10^{-22} sec up to about 10^{-16} sec. It may mean that the damages of the target nuclei in the collision reactions determine the fragment evaporation. Consequently, the evaporation of the residual target fragments and their transmutation into stable state and stable fragments is due to the internal nuclear energy of the residual target nucleus, in its transmuting from the damaged state.

In some cases the nuclear energy of the damaged target may be relatively large and it may compensate the energy used for the target damage by the hadronic projectile.

It is with while to emphasize that the damages in about $(70 \div 90)\%$ of collision events are located at the peripheries of the target nuclei [11], where the energy of the incident hadron needed for the target peripheral damage is about $200 \div 500$ MeV for pions and about $400 \div 1000$ MeV for protons.

3. TRANSMUTATION OF THE DAMAGED TARGET-NUCLEUS INTO EVAPORATED NUCLEONS AND NUCLEAR FRAGMENTS

Let us start this section with a definition of a high energy nuclear collision reaction.

A high energy nuclear collision reaction is a process in which nucleons are added to, removed from, or rearranged within a target nucleus under bombardment by hadrons (protons or neutrons, or mesons — for example), or by a group of hadrons (deuterons or alpha-particles — for example); gamma quanta of energy high enough may induce the nuclear reactions as well.

The above defined nuclear reactions are the artificially induced nuclear processes of atomic nuclei transmutations.

Within a few years, starting from the O. Hahn and F.Strassman work [12] in 1939, a series of scientific and technological advances had shown the very promissing outlook for gaining useful energy from the atoms by artificial processes of target-nuclei transmutations. O.Hahn, in collaboration with F.Strassman, bombarded uranium nuclei with neutrons and performed careful chemical testing on the resulting radioactive material, they found that among the products of the neutron absorption by uranium $^{235}U_{92}$ there was radioactive barium Ba_{56} which is much less massive than the original uranium:

$$^{235}U_{92} + n \rightarrow Ba_{56} + Kr_{36}. \qquad (1)$$

It happened the question, how could such a light element be formed from uranium?

At that time, L.Meitner and O.Frisch suggested that neutron absorption by uranium produced a fission or breakup of the target uranium nucleus into two lighter fragments [13]. This way, new type of nuclear reactions was discovered; this discovery showed that it is possible to split a nucleus into two massive parts. For many of heavy nuclei, the probability for the occurrence of neutron-induced fission is high, the half-life of 10^{-21} sec.

In 1939, N.Bohr and J.Wheeler proposed a liquid-drop model of nuclear fission that was successful in explaining the general features of the fission process [14].

The analysis of the Hahn's reaction showed that a heavy nucleus can break up into light fragments with the release of a substantial amount of energy. The decrease in binding energy per nucleon with increasing mass number *A* means that a heavy nucleus can breakup into two lighter fragments.

In fact, this process is inhibited by the sharp attractive nuclear forces, and the probability of the occurrence of spontaneous fission is small, 10^{17} years for $^{235}U_{92}$. However, if some additional energy is supplied to the nucleus, the increase in binding energy may produce a large deformation of the nucleus which will be sufficient to the separation of the target nucleus into two or more parts; the fission may occur — the probability of the neutron-induced fission becomes to be very high — the half-life is about 10^{-21} sec.

The possibility of occurrence of the fission observed by Hahn and Strassman is suggested by the decrease in binding energy per nucleon with increasing mass number *A*, what means that a heavy nucleus can break up into two lighter fragments with the release of a substantial amount of energy.

From our experiments, it follows the mechanism of the hadron-nucleus collision process [4]. According to this mechanism the target-nucleus is damaged by much in the collision by incident hadron. High excitation of the damaged nucleus should correspond to the damage and the fission of the damaged target nuclei with the mass numbers $A = 200$ should occur frequently.

In the xenon bubble chambers and in emulsions, the events of the target nuclei fission do not occur frequently, because the target nuclei Xe, Ag, Br are with to small mass numbers: $^{131}Xe_{54}$, $^{108}Ag_{47}$, $^{80}Br_{35}$. The disintegrations of the target nuclei into nucleons and light fragments occur only — the evaporation of the target disintegration products occurs plantifully, and it is observable.

The evaporation of the fragments is determined by the fast proton emission [10]. Simple relations exist [10] between the mean intensity or multiplicity $<n_{b>}$ of the singly and multiple electrically charged slow target fragments evaporation and the intensity or multiplicity n_p of the fast proton emission in the hadron-nucleus collisions:

$$<n_{b>} = 1.25(n_p + \frac{A-Z}{Z}) \qquad (2)$$

and

$$\frac{<n_b>}{<n_h>} = \mathrm{const} = 0.44, \qquad (3)$$

where $n_h = n_p + n_b$.

4. CONCLUSIONS AND REMARKS

The information about the final stage of high energy hadron-nucleus collision reactions presented here should be enlarged by additional investigations of this hadron-nucleus collision stage by radiochemical methods.

Formulas (2) and (3) were derived simply in one of our former works [10], and tested experimentally.

REFERENCES

1. 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; and the publications cited in it.
2. Strugalski Z. — The Target Nucleus as an Indicator of Various Properties of the Hadron-Nucleus and Hadron-Nucleon Collision Processes. JINR E1-80-548, Dubna, 1980.
3. Strugalski Z. — Study of the Particle Production Process Using Nuclear Targets. JINR E1-81-576, E1-81-577, E1-82-287, Dubna.
4. Strugalski Z. — On Studies of the Hadron-Nucleus Collision Processes. JINR E1-92-56, Dubna, 1992; works cited in it.
5. Strugalski Z. — Mechanism of Energy Transfer from Hadronic and Nuclear Projectiles into Target Nuclei in Collisions at High Energies. JINR E1-94-321, Dubna, 1994.
6. Faessler M.A. et al. — Nuclear Physics, 1979, B157, p.1.
7. Strugalska-Gola E. — Emission of Protons and Mesons in Collisions of High Energy Hadrons with Atomic Nuclei. Warsaw University of Technology, PhD Thesis, 1995.
8. Powell C.F., Fowler P.H., Perkins D.H. — The Study of Elementary Particles by the Photographic Method. Pergamon, 1995, London (p.452).

9. Strugalska-Gola E., Mulas E., Sredniawa B., Strugalski Z. — The Hadron-Nucleus Collision Reaction Mechanism Memorized by Fast Nucleons Emitted from Target Nuclei. JINR E1-95-230, Dubna, 1995.
10. Strugalski Z. — The Evaporation of Singly and Multiply Electrically Charged Slow Target Fragments in Hadron-Nucleus Collision Reactions. JINR E1-95-231, Dubna, 1995.
11. Strugalski Z. — On the Emission of Target Fragments in Hadron-Nucleus Collisions. JINR E1-84-195, Dubna, 1984.
12. Hahn O., Strassman F. — Naturwiss., 1939, 27, p.11.
13. Meitner L., Frisch O.R. — Nature, 1939, 143, p.239.
14. Bohr N., Wheeler J.A. — Phys. Rev., 1939, 56, p.426; works cited in it.

Received by Publishing Department
on January 9, 1996.