СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E1-2000-122

E.Strugalska-Gola*, Z.Strugalski*

PHYSICAL BASIS FOR NUCLEAR ENERGY EXTRACTION

*Institute of Atomic Energy, 05-400 Otwock-Świerk, Poland
e-mail: elasg@hp2.cyf.gov.pl; zstrug@hp2.cyf.gov.pl

2000

1. INTRODUCTION

Two nuclear processes may be used now for the nuclear energy extraction: fission and fusion. For many years efforts were made to construct the nuclear reactor based on the thermonuclear fusion process but any of such type reactors does not work now. The nuclear reactions acting now are based on the nuclear fission process — exactly on the Hahn-Strassman nuclear fission process.

We would like to present shortly the status of the developments on both the main directions in nuclear energy extraction methods.

As the basis of my considerations, some argumentation about the «need for nuclear energy» as future main energy source will be used. It may be concluded from the investigations by Ian Fells that [1]: The current total world energy use is just under 10 Gtn o.e. (giga-tons oil equivalent). The most ecologically constrained scenarios give a figure of 14.2 Gtn o.e. by 2050, of which 5 Gtn o.e. would be renovable, which is 35 per cent; fossil fuels will continue to play a dominant role.

Energy supply will pose increasing problems through the next century as world population and life-style expectation rise. The replacements for fossil fuels will become imperative and both renovable energy (solar, wind, biomass and so on) and nuclear energy sources will play increasingly important roles past 2050. At that time, the renovables will take over the role that fossil fuels have played in the past, once these fuels are in short supply in the second half of the next country. The «new renovables» provide still only 2 per cent of the world's energy, although — despite over about 30 years of development; moreover, much of that remains expensive and has to be subsided.

Many expected that nuclear fusion could play a very important part in energy supply, provided that fusion power stations really can be constructed as based on the scientific demonstrations from ITER EDA and JET. ITER EDA — International Thermonuclear Experimental Reactor Engineering Design Activities was established in 1992 by the EU, Japan, Russia and USA; JET — the Joint European Torus, located at Abingdon in the UK, began operation in 1983 and has become the flagship of the whole EU fusion programme [2]. The European programme involves the work of about 2000 physicists and engineers, including around 250 PhD students in the associated laboratories of the JET and the JRC (Joint Research Centre). All the member states have institutions actively participating in the fusion programme. The Community's own Joint Research Centre (JRC), having institutes in various locations, also undertakes work for the programme. Most of the fusion devices have been built along the tokamak principle, but there are also stellarators. There are as well a number of facilities for technological development such as large superconducting-magnet-testing facilities.

Around at the same time the Next European Torus (NET) team was established and given the task of enhancing the programmes activities on safety and the environment, concentrating on the preparation, from the technological point of view, of the next-step experiment beyond JET.

The NET team has become the cardinal point for initiating and coordinating R&D in fusion technology, as well for Europe's contribution to the Engineering Design Activities of the International Thermonuclear Reactor (ITER EDA) which was established in 1992 by the EU, Japan, Russia and USA [2,3].

Now, it may be concluded: besides there has been a high rate of progress and a comprehensive engineering design work has been carried out under the ITER EDA programme, the further efforts may be taken to develop fusion as a practical energy source and it will be added to several decades [2]. During the past decade, there have been valuable works carried out under the ITER EDA programme, although.

In such situation with the longly and widely expected energy plants based on the fusion process, it was reasonable to start and carry out works on a more deep understanding of the spallation and energy release processes in nuclear collisions.

2. THE HADRON-NUCLEUS NUCLEAR COLLISIONS

In analysing hadron-nucleus nuclear collisions at high energies, at energies higher than the pion production threshold, it has been observed that the target nucleus is always damaged locally — within a small part of it, around the projectile course [4,5]. The damaged part is a tube with the radius as large as the nuclear interaction range, which is approximately equal to the nucleon diameter. As a result of this damage, the configuration of the nucleons inside the residual target-nucleus became unstable, and it must transit into stable one [4].

It has been evaluated that (depending on the kinetic energy of the projectile hadron) the interaction of the projectile lasts from about 10^{-24} up to 10^{-22} s and it is the first, «*fast stage*» of the hadron-nucleus collision reaction. After this stage, there is no more direct influence of the hadronic projectile on the residual target-nucleus. The damaged and therefore unstable nucleus must transit itself into some stable state or states of its fragments. This transition is realised only due to the intranuclear energy of the damaged target and proceeds with the «*evaporation*» of nucleons and light nuclear fragments This transition lasts from about 10^{-22} up to about 10^{-16} s, and it is the second, «*slow stage*» of the nuclear collision reaction or process. The projectile energy loss in the fast stage of the collision is always defined, and relatively small — depending on the collision impact parameter [5]. The energy loss in the second, «slow stage» is defined by the number of the «evaporated» slow nucleons and light nuclear fragments [6].

3. THE NUCLEAR ENERGY RELEASE IN HADRON-NUCLEUS COLLISIONS

The mechanism of the nuclear energy release under discussion here is a consequence of the mechanism of hadron-nucleus nuclear collision which has been depicted in our former work [6], as prompted experimentally.

Four main processes (phenomena) are usually observed when hadrons collide with atomic nuclei:

1. The passage of the hadron projectiles or their successors through layers of intranuclear matter, accompanied by the emission of «fast» nucleons with kinetic energy from about 20 up to about 500 MeV from the strong interaction region of the incident hadron. The energy spectrum of the emitted protons is [7]:

$$N(E)dE \sim E^{-\gamma}dE, \qquad (1)$$

where $\gamma \approx 1$.

There are some arguments that the neutrons are of the same properties [8]. It is the «fast» or first stage or phase of the collision process which lasts from about 10^{-24} to about 10^{-22} s.

2. The production of hadrons, on the background of the emission of fast nucleons. It goes through some intermediate objects (generons) which are decaying into observed secondary hadrons — after having left the parent nucleus.

3. The «evaporation» of the target fragments including the target nucleons of kinetic energy smaller than about 10–20 MeV; it lasts from about 10^{-22} up to about 10^{-16} s. It is the slow stage of the collision process.

4. The fission of residual target nucleus into nuclear fragments — in the *spallation* process.

The projectiles — pions, protons, kaons and other hadrons lose their kinetic energy in passing through layers of intranuclear matter due to electromagnetic and strong interaction with downstream nucleons. The range-energy relation in intranuclear matter for pions and protons was obtained experimentally [9].

In the first stage of the nuclear collision, the target damage is realised on an account of a definite portion of the incident hadron energy. The third and fourth stages of the hadron-nucleus collision process are on the account of internal nuclear energy — in transiting the excited residual nucleus into its stable stage.

The nuclear energy release is realised during the third and fourth processes. It is not excluded that the nuclear energy released from the damaged residual target nucleus may be overcompensating the energy of the projectile used for the target nucleus damage.

The hadron projectile energy ε_h lost for the damage of the target nucleus is estimated: it is $\varepsilon_\pi \approx 0.18$ GeV/nucleon/S for the pionic projectiles and $\varepsilon_p \approx 0.36$ GeV/nucleon/S for the proton projectiles, where $S = \Pi D_0^2$, D_0 is the nucleon diameter.

It cannot be stated a priori that the energy released in the «slow» stage of observed nuclear reactions is smaller than the energy of the projectile hadron lost inside the target nucleus in the «fast» stage.

The portion of the intranuclear energy released by the unstable residual target nucleus transition into its stable final state may be larger than the portion of the projectile energy lost inside the target nucleus — for its damage. In this case one has to do with a single-nucleus nuclear energy amplifier. It means that the portion ΔE_r of the energy released in the residual nucleus transition may be larger than the portion ΔE_h of the projectile hadron energy lost for the target nucleus damage

$$\Delta E_r > \Delta E_h . \tag{2}$$

Such nuclear reactions are the energy overcompensating ones. These reactions may form a basis for future accelerator-driven (accelerator controlled) nuclear energy plants.

The stage of the residual target nucleus, after the above-mentioned «slow» one — after having left by the evaporated light fragments is not stable as well, because of its deformed shape and it must transit itself in a fission process into two or more heavier nuclear fragments; additional portion of the intranuclear energy may be released, too. If the nuclear energy released in the «fast» stage is called ΔE_f, the energy released in the first and second «slow» stages are $\Delta_1 E_s$ and $\Delta_2 E_s$ correspondingly, the total intranuclear energy released in the hadron-nucleus collision reaction is:

$$\Delta E_{tr} = \Delta E_f + \Delta_1 E_s + \Delta_2 E_s . \tag{3}$$

If the total intranuclear energy released is larger than the portion ΔE_h of hadron energy lost in the target nucleus ΔE_{hl}:

$$\Delta E_{tr} \geq \Delta E_{hl} , \tag{4}$$

then the hadron-nucleus collision reaction is energy-overcompensating.

4. THE ENERGY BALANCE IN THE HADRON-NUCLEUS COLLISION PROCESSES

For studies of the nuclear energy release in nuclear collision processes, the simplest of haron-nucleus collision events has been analysed, namely, such collision event in which the incident hadrons in passing through the target nuclei are absorbed or stopped in them, or passed them without causing the particle production [7,8]. Possible effects of the particle production process on the nucleon emission and the target fragment evaporation in hadron-nucleus collisions were investigated. It was found that the particle production process does not influence the nucleon emission and the fragment evaporation processes [10]. The events under study were photographed in 180 litre xenon bubble chamber of the Institute of Theoretical and Experimental Physics at Moscow, exposed to 3.5 GeV/c negatively charged pion beam from the ITEPh accelerator. In such conditions, the incident pion is completely stopped in the central pion-xenon nucleus collisions.

4.1. Energy Balance in Events when the Incident Hadron Traversed the Target Nucleus Nearly to Its Diameter — the First, «Fast» Stage of the Collision. In the sample of such events, the energy of the incident pion lost in the target nucleus is $E_h = 3.2$ GeV, because a small portion ≈ 0.3 GeV of it is lost by ionization inside the bubble chamber. In result of such collision, in the average $\langle n_p \rangle = 7.4$ «fast» protons and $\langle n_n \rangle = [(A - Z / Z]\langle n_p \rangle$ «fast» neutrons, or simply $\langle n_N \rangle = (A - Z)\langle n_p \rangle$ «fast» nucleons are emitted. The mean number of nucleons $\langle n_N \rangle$ fluctuates in a known manner, but we do not take it into account here — for simplicity.

The mean kinetic energy of the emitted «fast» nucleons is $\langle E_{kN} \rangle \approx 90$ MeV, as is known from «fast» proton mean energy $\langle E_{kN} \rangle$ measurements.

The mean kinetic energy of the emitted k «fast» nucleons $\langle \Sigma E_{kNp} \rangle$ is then:

$$\langle \Sigma E_{kNp} \rangle = (A / Z)\langle n_p \rangle \langle E_{kp} \rangle, \tag{5}$$

where $\langle n_p \rangle$ and $\langle E_{kp} \rangle$ are measurable quantities; A and Z are the mass- and charge-numbers.

The total mean kinetic energy of the ejected «fast» nucleons (5) is one of parts of the incident hadron kinetic energy $\Delta_I E_h$ lost in its passage through the target nucleus. Another part of the incident hadron energy $\Delta_{II} E_h$ could be the energy lost for the particle creation process, through the intermediate objects (generons). But, only the events without particle production are analysed in this section (and $\Delta_{II} E_h = 0$), the mean kinetic energy of the emitted nucleons:

$$\langle \Sigma E_{kN} \rangle = \Delta_I E \leq E_h \tag{6}$$

is in fact equal to or smaller than the kinetic energy E_h of the incident hadron.

Then, all the hadron kinetic energy E_h is lost for the «fast» nucleon emission and for the target nucleus to damage (and to excite), therefore. This stage of the collision induced nuclear reaction lasts from about 10^{-24} to 10^{-22} s. The second stage of the collision process lasts from about 10^{-22} up to about 10^{-16} s., and this nuclear reaction taking place in this second (slow) stage is caused by the residual target spontaneous transition from its instable nucleon configuration into a stable one. The transition is due to the internal energy of the residual (damaged as well) nucleus. This energy release manifests itself in the nucleons and the residual light nucleus fragments emission («evaporation»).

4.2. Energy Balance in the Second Stage — when the Damaged Residual Target Nucleus Transits Itself into a Stable Stage, in Evaporating Slow Nucleons and Light Nuclear Fragments. The evaporated light target fragments leave «black» and dense tracks in photographic emulsions and in other track detectors — as bubble chambers, if electrically charged. The intensity of emission of such fragments is usually denoted by n_b (multiplicity of such tracks in an event under study). A simple relation between the average number of the black tracks $\langle n_b \rangle$ and the number n_h (multiplicity) of the «fast» protons in photoemulsions has been found experimentally [11]:

$$\langle n_b \rangle = 121 n_g + 1.49, \tag{7}$$

where $n_g = n_h$, according to the notation used in photoemulsion methods. This relation has been derived on the basis of an assumption that the light nuclear fragments are «evaporated» predominantly from the surface layer of the inner side wall of the «tunnel» left inside the target nucleus after the passage of the incident hadron through the target nucleus [10]:

$$\langle n_h \rangle = 125(n_g + [\{A - Z\} / Z]), \tag{8}$$

where $n_g = n_p = 0,1,2,3,\ldots$

For the heavy elements in the emulsions Ag and Br, this formula gives:

$$\langle n_h \rangle = 125 n_g + 161, \tag{9}$$

which is practically, within the frames of systematical errors, the same as the formula (5) from experimental estimations [II]. This formula is valid (it is tested) for any hadron-nucleus collision [11]; for hadrons with kinetic energies within the values 6.2 – 400 GeV — for protons and 2.34 – 4 GeV — for pions as the projectiles.

4.3. The Last («Third») Stage of the Hadron-Nucleus Collision Process — a Break-Up (or Fission) of the Highly Excited Residual Target Nucleus into Two Lighter Fragments. The residual target nucleus, after the evaporation of nucleons and lighter nuclear fragments (in the second stage) is deformed by much and highly excited still, therefore. It is mostly under interest when a break up may occur with the release of some portion, $\Delta_2 E_r$, of the target nucleus intranuclear energy — when and which nuclei will be employed; now it is known that the high A mass nuclei may be used successfully.

Special experimental investigations should be performed of many of heavy nuclei.

5. RESULTS AND DISCUSSION

The intranuclear mean energies released in all the stages are: $\langle \Delta_1 E \rangle$, $\langle \Delta_2 E \rangle$, $\langle \Delta_3 E \rangle$; the last quantity $\langle \Delta_3 E \rangle$ cannot be evaluated in this experiment.

The formula for the nuclear energy released is [12]:

$$\langle \Delta_r E \rangle = \langle \Delta_1 E \rangle + \langle \Delta_2 E \rangle + \langle \Delta_3 E \rangle. \tag{10}$$

Let us introduce the quantity Q:

$$Q = \langle \Delta_r E \rangle - E_h, \tag{11}$$

which can be treated as the energy balance; E_h is the kinetic energy of the incident hadron; it is defined as: $\langle \Delta_r E \rangle = \langle \Delta_1 E \rangle + \langle \Delta_2 E \rangle = 2370$ MeV; Q value is negative, it amounts $Q = \langle \Delta_1 E \rangle + \langle \Delta_2 E \rangle - E_h = -0.8$ GeV, for central collisions under discussion here. The value $\langle \Delta_3 E \rangle$ has not been evaluated.

It is not excluded that the energy released in some collisions is E_h-overcompensating — for different target nuclei and different projectiles. The portion $\langle \Delta_3 E \rangle$ may be released in collisions of hadrons with large A target nuclei.

In future investigations, for practical use:

1. Experiments should be performed in hadron-nucleus collisions; the target nuclei should be with possible large mass numbers.
2. The detection of the spallation products from the target nuclei may be identified and the energy of the nuclear fragments should be determinable.
3. The spallation of the residual target nucleus should be correctly recognized and quantitatively evaluated — with high efficiency.

References

1. Fells I. — The Need for Energy, Europhysics News, Nov/Dec 1998, v.29, No.6, p 193—196.
2. Bruhns H. — The EU Fusion Programme, Europhysics News, Nov/Dec 1998, v.29, No.6, p.206—209.
3. Fussion Special Issue, Europhysics News, Nov/Dec 1998, v.29, No 6, p.190—236
4. Strugalska-Gola E. — The Mechanisms of the Nuclear Energy Release in Hadron-Nucleus and Nucleus-Nucleus Collisions, Annual Report 1998 of the Institute of Atomic Energy, Otwock-Swierk, Poland, p.78—79, 1999.
5. Strugalski Z. — Experimental Studies of Mechanisms of Intranuclear Processes Induced by Hadron-Nucleus and Nucleus-Nucleus Collisions. Annual Report 1998 of the Institute of Atomic Energy, Otwock-Swierk, Poland, p.77—78, 1999.
6. Strugalski Z. — The Evaporation of Singly and Multiply Electrically Charged Slow Target Fragments in Hadron-Nucleus Collision Reactions. JINR, E1-95-231, Dubna, 1995.
7. Strugalski Z., Strugalska-Gola E. — The Mechanisms of the Hadron-Nucleus Collision Process and of the Hadron-Nucleus Collision Induced Nuclear Reactions — In the Light of Experimental Data. JINR, E1-97-177, Dubna, 1997; references in it
8. Strugalski Z. et al. — Experimental Study of the Pion-Xenon Nucleus Collisions without Particle Production at 3.5 GeV/c Momentum. JINR, E1-82-719, E1-82-841, Dubna, 1982; JINR, E1-83-234, Dubna, 1983.
9. Strugalski Z. — Stopping and Energy Deposition of Hadrons in Target Nuclei. JINR, E1-83-850, Dubna, 1983; references in it.
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. Winzeler H. — Proton-Nucleus Collisions in the Multi-GeV Region. Nuclear Phys., 1965, v.69, p.661—694.
12. Otterlund I. et al.— Nuclear Phys., 1978, v.B142, p.443.
13. Strugalski Z., Strugalska-Gola E. — Nuclear Energy Release in Hadron-Nucleus Collisions. JINR, E1-98-99, Dubna, 1998.

Received by Publishing Department
on May 30, 2000.