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THE CALORIMETRIC NUCLEAR AMPLIFIERS OF ENERGY

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Калориметрические ядерные усилители энергии

Анализируются физические аспекты процесса выделения энергии в калориметрических поглотителях, предназначенных работать в составе усилителей энергии.

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The Calorimetric Nuclear Amplifiers of Energy

Physical analysis of the energy deposition process in calorimetric absorbers designed as energy amplifying devices in the energy amplifiers is done.

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1. INTRODUCTION

Now, nuclear reactors constitute a major source of practical energy and they are likely to continue to be so in the foreseable future. However, due to many problems with the nuclear reactors — from the environmental point of view mainly, alternative approaches to nuclear energy extraction methods are of great interest. One of the methods under discussion now in this context is the possibility of nuclear energy extracting with the help of the «calorimetric» [1] absorbers — the blocks of a material working in the calorimeters, e.g., [2—9].

Within the frames of the discussion in question, a series of appropriate works has been performed [10—14].

In this paper, the subject matter is the analysis of the energy deposition process in a calorimetric absorber [2—9] designed as an energy multiplying device in the «Energy Amplifier» [2].

This paper is arranged as follows: after a short introduction in section 1, some considerations about the calorimeters are presented in section 2, the most important characteristics of the yields from the hadron-nucleus and nucleus-nucleus collisions are descreibed in section 3, the hadron-nucleus and nucleus-nucleus nuclear collisions mechanisms are described in section 4, in section 5 the calorimeters as some energy nuclear amplifiers are considered, in section 6 an introduction to a choice of parameters for a calorimetric energy nuclear amplifier is done, section 7 closes the paper with the conclusions and remarks.

2. THE CALORIMETER

The calorimeter consists of a block or blocks of dense materials in which some energy changes may occur and develop totally and be observed, and the characteristics of these processes can be determined; if the processes or changes are accompanied by the ionization effects inside the block of the calorimeter, it is called the «ionization calorimeter» [1]. If in the calorimetric absorber some energy changes occur mainly, the calorimeter is called the energy calorimeter.

The ionization calorimeter, put forward in 1954 [1], was initially intended for use in measurements of individual particle energy, either charged or uncharged, in the range of energy values from 10^{11} eV upwards [1]. Lately, it was used widely in high energy physics; it measures the energy of high energy particle through measurement of its fully contained energy deposition. Investigations of the operation of the calorimeters, however, have shown that they possess wider application, not only for the particle energy measurements, but as the nuclear energy providing devices — as the energy nuclear amplifiers. It is well known that such device can be made to «over-compensate» the energy deposited by an incident high energy hadron if fisionable materials will be used in the absorber of the calorimeter [3,4].

Here, in this paper the application mentioned lately is under interest. And so, in this context, a typical hadronic calorimeter consists of a block of a heavy material or material series, and of the energy extracting device — of the device for energy transportation from the calorimetric nuclear energy amplifier to some energetic arrangements.

3. MAIN PROCESSES IN THE ABSORBER OF THE CALORIMETER WHEN NUCLEAR COLLISIONS ARE OCCURRING IN IT

The behaviour of the incident hadron inside a heavy nucleus in the calorimeter material should be distinguished from the behaviour of the incident hadron in the block of the absorbing material; the passage of the hadron through intranuclear matter layers determines in some large grade the phenomena inside the block of material, when hadrons interact in it. Let us start with the elementary processes occurring in hadron interacting with intranuclear matter.

When a hadron comes into nuclear collision with a massive target nucleus in the calorometer absorber, it passes through it and interacts strongly with the downstream intranuclear matter locally — withinh the cylindrical channel with the radius as large as the strong interaction range R_s is, centered on the incident hadron course. The passage is accompanied by fast nucleon emission with kinetic energies of the emitted nucleons from about 20 up to about 500 MeV; the energy and angular spectra of the nucleons do not depend neither on the identity nor on the energy of the hadron interacting inside the target nucleus. Definite part of the incident hadron energy is lost in the passage through intranuclear matter [7]. A certain part of the incident hadron energy is transferred to the produced secondary particles, mainly pions, in its passage through layers of the intranuclear matter [7]. The pions, kaons, and other particle production happens in some of its collisions with downstream nucleons — on the background of the fast nucleon emission [9,11]. Particles are produced via some intermediate objects decaying into usually observed «producing» particles after having left the parent nucleus. The produced particles, if with energies high enough — higher than about pion energy threshold — behave themselves in the calorimeter material block as the incident hadron uses to do it.

Let us turn to the behaviour of the particles in their passages inside the calorimeter absorber — inside the block of a material dense enough.

An electron or photon with the energy $E_0 >> m_e c^2$ either incident upon the adsorber or formed within it — from the created particle decays — leads to the development of an electromagnetic cascade inside the block of material. When the cascade is located totally within the calorimeter block,

$$E_0 = \left(\frac{dE}{dx}\right)_i \int_0^{\infty} n_e(x)dx; \qquad (1)$$

$\left(\frac{dE}{dx}\right)_i$ is the specific ionization loss of relativistic electrons, $n_e(x)$ is the total number of the cascade electrons present at a depth x.

A strongly interacting particle incident on the working block of material — on the calorimeter absorber — or formed within it leads to more complex processes in passing through a material dense enough, in interacting with the downstream atomic nuclei. It produces particles which are able to behave themselves as the incident hadron uses to do it. A hadronic cascade in the absorber block will develop, and on the background of this hadronic cascade the erlectromagnetic cascade will develop as well. About 1/3 of the produced pions are the neutral ones which use to decay into pairs of gamma quanta after lifetime of about 10^{-16} s; these quanta are initiating the electromagnetic cascades. The hadron-electromagnetic cascade develops inside the calorimeter absorber up to the moment when the secondary hadron kinetic energy decreased to be lower than the pion production energy threshold.

In any of the hadron-nucleus nuclear collisions, in the cascading process, the target nucleus is damaged and as such it becomes to be in some unstable state, and it should decay into nuclear fragments after about 10^{-17} s.

In result of the hadron-electromagnetic cascade development in the calorimetric absorber a lot of nucleons with energies from about 20 up to about 500 appear during about 10^{-22} s after the elementary nuclear collisions started; after about 10^{-17} s the evaporation products of the residual target nuclei appear. During the time of about from 10^{-23} up to about 10^{-17} s the damaged target nuclei are in the unstable states and they use to disintegrate into nucleons and nuclear fragments. The disintegration products are isotropically distributed in the c.m. of the decaying nuclei and with the definite well enough spectra [16].

The yields from hadron-nucleon, hadron-nucleus, and nucleus-nucleus collisions are known qualitatively and quantitatively from many former works, e.g., [10—16] and in references in them.

4. CHARACTERISTICS OF THE MAIN NUCLEAR PROCESSES IN THE CALORIMETRIC ABSORBERS WORKING AS THE ENERGY NUCLEAR AMPLIFIERS

It has been pointed out above that two main stages in the hadron-nucleus collision processes may be distinguished clearly which are directly related to the energetic transformation in the calorimetric absorbers:

1. The fast stage of the collision during the time $\tau = D/c$ s, where D is the target nucleus diameter and c is the light velocity, the duration of the fast stage of the collision is then about 10^{-23} s for the nuclei with A from about $A \approx 120$ up to about 10^{-22} s for the nuclei with $A \approx 260$.

In this stage the target nucleus is pierced at some impact parameter by the incident hadron energetic enough — with the kinetic energy over about 3 GeV if pions are employed as the projectiles, and over about 6 GeV if the projectiles are protons.

The cylindrical channel of the intranuclear matter is involved in the collision with the radius as large approximately as the diameter D_0 of the nucleon is or as the strong interaction range R_s is, which is approximately as large as D_0, $R_s \approx D_0$. All the nucleons met by the projectile inside this channel are ejected from the target nucleus with kinetic energy of about 20 up to about 500 MeV; the energy spectrum of the nucleons is [17]:

$$N(E)dE = E^{\gamma}dE, \tag{2}$$

E is the nucleon kinetic energy, $\gamma = 1.09 \pm 0.02$ [17,18]. The angular distribution is [18]:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\vartheta}\, e^{0.96\cos\vartheta}. \tag{3}$$

The spectra are independent of the energy and identity of the incident hadrons.

And so, after 10^{-21}—10^{-20} s starting from the hadron-nucleus collision the target nucleus uses to be in the damaged and unstable state [6].

The damages of the target nuclei in the collisions are located predominantly on the nuclear peripheral parts — e.g., for the Ag target nuclei about 70% of the events are of such a category; the radial deep of the damages is of about 2/3 of the nucleus radius, in average [19].

The target nucleus damage is due to the projectile kinetic energy loss; 0.180 GeV/(nucleon/S) is needed for the incident pion and 0.360 GeV/(nucleon/S) for the incident proton. Only definite part of the projectile kinetic energy is used for the target nucleus damage [19].

After about 10^{-17} s the target nucleus uses to transit into nuclear stable fragments or other nuclei [6,7,19].

2. The slow stage of the collision — the duration of it is of about 10^{-17} s, after the hadronic projectile or its successors having left the target nucleus and the damaged target uses to disintegrate into fragments [12]. The transition of the damaged target nucleus into the nuclear fragments, including the evaporated nucleons, goes due to nuclear energy released from the disintegrating damaged target nucleus.

The mean number ⟨ n_b *symbol* 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 protons predominantly, $n_g \approx n_p$ — exhibit the same behaviour through the energy range from 6.2 GeV to 400 GeV and practically one function describes it well [12]:

$$\langle n_b = 1.25\left(n_p + \frac{A-Z}{Z}\right) \tag{4}$$

this relation is valid for the incident hadron energy larger than $D\varepsilon_h$, 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), $S \approx 10$ fm^2 [12].

After the emission of the fast nucleons and the evaporation of the target fragments, the residual target nucleus becomes to be in an unstable state and then it must decay into stable nuclear fragments.

5. THE CALORIMETER AS AN ENERGY NUCLEAR AMPLIFIER

The claim that the well-known «calorimetric» technique, widely used in High Energy Physics, may be potentially used for extraction of the nuclear energy with the help of accelerator induced nuclear cascades in the calorimeter's absorber can be found in the works of many authors [2,4,5]. In this paper, additional facts for the operational principle of the method are indicated on, as experimentally based — the newly obtained results from our recent studies of the hadron-nucleus collision reaction mechanism [7,9,11]. An additional experimentally based information about the possibility of the nuclear energy release in the residual target nucleus disintegration is given [15]. The residual target nucleus, damaged in nuclear collision with fast hadron, disintegrates in about 10^{-17} s after the collision starting — into evaporated nucleons and nuclear fragments. In many cases, the residual target disintegration may be overcompensating the energy of the incident hadron [15].

After performing the analysis of the hadron-nucleus and nucleus-nucleus collisions reactions mechanisms [7,9,11], we are in a position to choose the optimal hadron beam and to determine the parameters of the calorimeter which has to work in an energy amplifier driven by an accelerator [2].

6. AN INTRODUCTION TO A CHOICE OF PARAMETERS FOR A CALORIMETRIC ENERGY NUCLEAR AMPLIFIERS

In choosing and determining the parameters, two desiderata should be taken into account: 1. To arrange for the incident hadron and its all successors the conditions for total development of the nuclear collision reaction processes inside calorimetric absorber; 2. All the deposited in the absorber energy of the hadron-electromagnetic cascade induced by the incident hadronic projectile should be possible to extract from the calorimetric device and supply it to some energetic apparatus.

The choice may be realized on the basis of the experimental data collected in our works, e.g., [9—14, 17—23], and in references cited in them.

6.1. The Statement of the Problem

The main physical parameters of the calorimetric energy multiplier are:

1. The incident hadron identity;

2. The energy of the hadron adequate for causing the hadron-nucleus nuclear reactions leading to the fast nucleon emission, particle production, and target nucleus damage appropriate for occurring of the energy overcompensating decays and disintegrations of the residual nucleus;

3. The thickness of the calorimetric absorber;

4. The linear vertical dimensions of the absorber — perpendicularly to the absorber length;

5. The area of the calorimeter.

6.2. Preparation of the Preliminary Estimation of the Energy Overcompensation Expected

It should be done after choosing the resolution of the fulfilment of the works according to points 1—5 from section 6.1.

The choosing of the resolution of the fulfilment of the desiderata, according to section 6.1 , will be described in a separate raport.

7. CONCLUSIONS AND REMARKS

It would be mostly convenient to apply the hadron-induced energy overcompensating hadron-nucleus collision reactions [15], occurring in an calorimetric nuclear amplifier. The accelerator of nuclei up to about 4 GeV/nucleon is needed in order to produce collimated and dense beams of neutrons and protons for bombarding atomic nuclei within the calorimetric amplifier absorber. The beams of neutrons and protons may be produced easily from the accelerated nuclei thrown on nuclear targets [20].

The accelerator in question should be energetically as efficient as it is possible; its beam should carry near to 80% of the energy required to operate it. Then, the energy overcompensating hadron-nucleus nuclear collisions might be applied for nuclear energy extraction from the calorimetric amplifier.

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