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HEAVY-ION-DRIVEN ELECTRONUCLEAR PROCESS

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It is well known that specific energy losses of a particle moving inside a target rise intensively with the increase of its charge due to ionization processes and even the first inelastic collision occurs at an energy which is noticeably lower than the incident one. Multiplicities of hadrons created in this collision are also lower than those in the proton-nucleus collision in case of the same total energy $E = AE_N$ where E_N is the kinetic energy per one nucleon of the projectile (see Table 1 where some calculated characteristics of proton and ion beam interactions with natural uranium target at incident energy $E = 1$ GeV/A are cited).

On the other hand, the cross-sections of nucleus-nucleus collisions are larger than the proton-nucleus ones. Owing to this circumstance a nucleus mean free path in the media and, respectively, ionization losses fall down. As a result, ion beams may have an advantage over the proton beam.

Table 1

Particle:	p	d	α	^{12}C
Energy of the primary inelastic collision E^*,Gev/A	0.76	0.92	0.83	0.63
Inelastic cross-section ratio $\sigma_A(E^*)/\sigma_p(0.76)$	1	1.10	1.23	1.85
Ratio of the total secondary particle multiplicities in inelastic ion- and proton-nucleus collisions $N_A(E/A) / AN_p(E/A)$ at $E/A = 1$ GeV/A	1	0.71	0.51	0.27
The some for the neutron multiplicities	1	0.64	0.42	0.19
Ratio of the ionization and total heat production Q_{ioniz}/Q_{tot},%	13	9	12	21

We investigated this possibility by means of a mathematical experiment using Monte Carlo simulation of particle transportation in various homo- and heterogeneous uranium and thorium targets (with admixtures of ^{239}Pu and ^{233}U). The Monte Carlo method is performed in one cycle considering both intra- and internuclear cascades as well as preequilibrium and equilibrium decays of excited residual nuclei. At high energies, especially for nucleus-nucleus collisions, it is necessary to take also a depleting of colliding nuclei owing to a knock-out of intranuclear nucleons by fast cascade particles into account.

The hadron and nucleus mean free path between two successive nuclear interactions is determined from the integral equation

$$\int_0^l, dl/\lambda(E(\mathbf{r}),\mathbf{r}) = -\ln\xi,$$

where

$$\lambda = 1/\sum_i \sigma_i(E(\mathbf{r}))\rho_i(\mathbf{r})$$

is the mean free path at the point $\mathbf{r}$, $\sigma_i$is the total cross-section for the interaction of the particle under consideration with a target nucleus of type i at the point $\mathbf{r}$. ρ_i is the atomic density of these nuclei (1/cm**3), ξ is a random number, uniformly distributed in the interval (0,1). The integration is carried along the particle trajectory.

Ion-nucleus cross-sections are calculated by means of phenomenological formulas [1]. Hadron-nucleus cross-sections at energies $E > 14$ MeV are interpolated using the library of estimated experimental data [1,2]. The 26-group neutron data library with subgroup division [3] appears to be sufficient at lower energies when one is interested in average quantities (neutron yield and spectrum, k_{eff} etc.). However, to calculate accumulation of waste one needs more detailed information on cross-sections. The energy dependence of level density and other parameters as well as its dependence on the type of interacting nuclei must be considered in this case also.

Employment of statistical weights allows one to simulate electronuclear systems close to the critical point $k_{eff} = 1$ with rather large neutron yield.(One can look for the details of our method in book [4] and papers [5, 6]).

Calculations indicate that at fixed energy of the projectiles E most of the average characteristics of inelastic interaction of light ions with heavy target nucleus ($A > 30$) appear to be weakly dependent on the type of the projectile and are rather close to the characteristics of the proton-nucleus collisions. This effect is rather useful for qualitative estimations and is illustrated in in Figs. 1, 2 and in table 2 where the calculated relative fissility $D_i = (\sigma_f/\sigma_{in})_i/(\sigma_f/\sigma_{in})_p$ for uranium nuclei irradiated by deuterons and α-particles with energy E is shown.

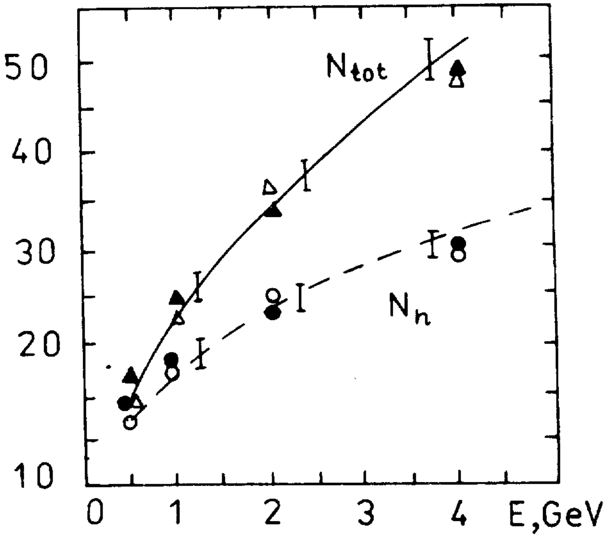

Fig. 1. Average multiplicity of particles created in inelastic interactions of protons (curves), deuterons (o, △) and α-particle (• and black triangles) with an nucleus ^{238} at the energy E.

Such a weak sensitivity is stipulated by a smallness of projectile geometrical dimensions in comparison to the target nucleus, therefore a contribution of fragmentation channels when a part of high-energy projectile nucleons fly forward without any interaction with the target nucleus is insignificant and the energy introduced by the projectile into the nucleus is spent on the production of cascade particles and on the excitation of the residual nucleus. The multiplicity of secondary particles and their properties depend in this case on the energy of the projectile but not on its mass. Essential dependence on the type of the projectile becomes apparent only in partial reaction channels.

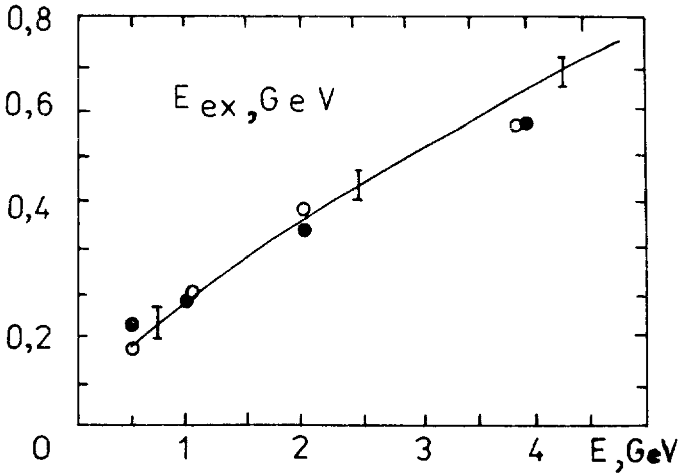

Fig. 2. Average excitation energy of an aftercascade residual nucleus. All notations are the same as in Fig. 1.

Table 2

E,GeV:	**0.5**	**1**	**2**	**4**
D_d	0.98	1.03	1.00	1.02
D_α	1.00	1.06	1.00	1.10

The calculated neutron yield in a large, practically infinite natural uranium target (the neutron leakage is a few percent) is showing in Fig. 3. One can see that deuterons appear to have an advantage. At $E = 1$

GeV/A this gain is $(N_d - 2N_p)/2N_p \simeq 15\%$ where N_d is the neutron yield per two deuteron nucleons. When protons are accelerated up to $E = 2$ GeV, then the gain is $(N_d - N_p)/N_p$ where N_p is the neutron yield at 2 GeV. At high energies both estimations give practically the same value, however, at $E \ll 1$ GeV the latter is significantly lower (see Fig. 4).

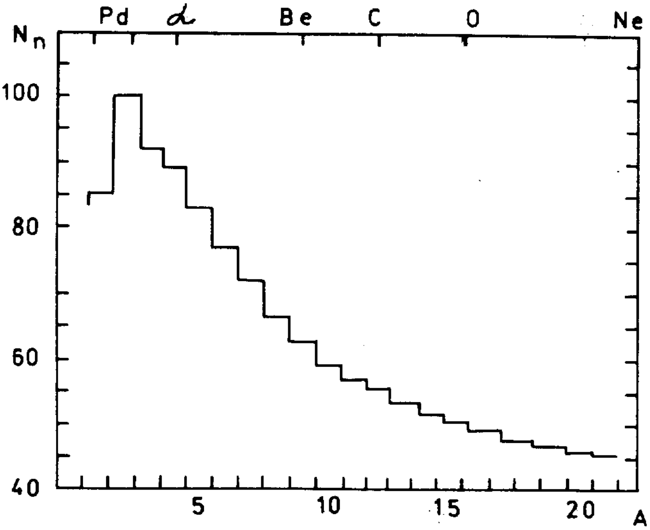

Fig. 3. Neutron yield in collisions of protons and ions with nucleus of the mass number A (per one intranuclear nucleon and for the energy 1 GeV/A.

The peak in Fig. 3 corresponds to minimal ionization losses in Table I but already in the case of the α-particle neutron yield becomes almost equal to N_p and decreases for heavier ions. The similar results are obtained also for thorium and lead targets.

Cascade calculations of particle-nucleus and nucleus-nucleus collisions as well as the Monte Carlo simulation of their transportation in various targets are compared to the experiments and their good agreement is observed. A drastic contradiction of the calculated results with the experimental data obtained by Tolstov's group for a leaden slab at $E = 3.65$ GeV/A [7,8] looks even more surprising. Analyzing the results of their measurements, these authors concluded that the use of the α-particle or the carbon ion beams must lead to an increase in the neutron yield by $28 \pm 6\%$ and $19 \pm 6\%$ respectively in comparison with the proton beam.

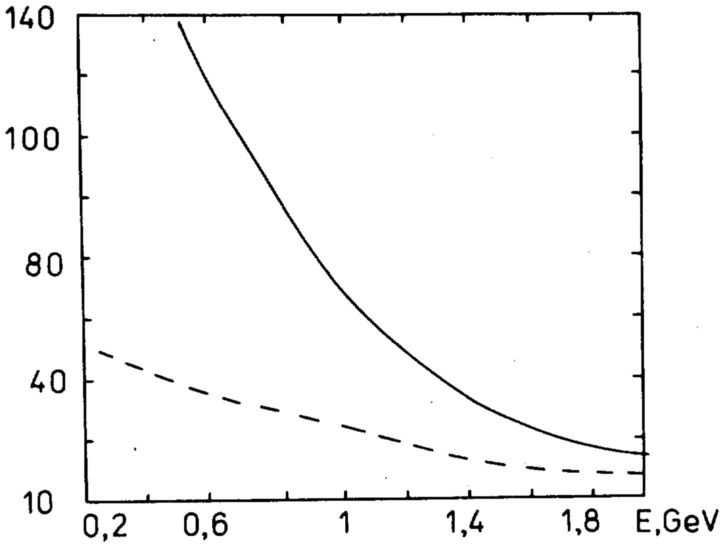

Fig. 4. The relative effectiveness of deuteron beam with total energy E $[N_d(E) - N_p(E)]/N_p(E)\%$ (dotted line) and $[N_d(E) - 2N_p(E/2)]/2N_p(E/2)\%$ (solid line) in comparison to protons beams with the energy E and $E/2$ but with doubled intensity. Large natural uranium target is considered.

One can attain an agreement with the Tolstov's data only by supposition that our current notions about high-energy nucleus-nucleus interactions (E ¿ 2 GeV/A) are essentially wrong what provides significantly lower probability of the channels with almost complete disintegration of a target nucleus into nucleons. According to the current theoretical estimations, such a probability does not exceed a few percent'. At the same time one needs the disintegration probability to be one order of magnitude higher to explain the neutron yield obtained [7, 8]. Exactly this value is obtained from photoemulsion experiments [8]: 6% for $p + Pb$ interactions and 22% for $\alpha + Pb$, To make things clear, one must investigate the disagreement experimentally. A program of such investigations is performed at present in Dubna.

Considering the theoretical data we must conclude that in comparison to the proton beam "energy costs" of one neutron produced by means of the deuteron beam at $E \leq 1.5$ GeV is less. It becomes larger if one uses heavy ions with $A > 4$. Nevertheless, at the equal initial energy E/A and the same beam intensity one can produce significantly larger neutron flux (for example, at $E/A = 1$ GeV the ratio $N_n(^{12}C)/N_n(p) \simeq 9$, see Table 1). In some cases, particularly, in solid body physics and in special applications it may be more important than the "energy costs".

We should lake to notice also that for the equal initial energies (for example, for an deuteron with $E = 2$ GeV and two protons with $E = 1$ GeV) the intensity and, respectively, a space charge of the ion beam are twice less what is very important from the accelerator viewpoint [1].

The data considered above concern the $U - Pu$ systems. Comparing these systems with the thorium ones, we must bear in mind that though average multiplicity of particles created in collisions of high-energy protons and heavy ions with thorium nuclei is practically the some as in collisions with uranium nuclei (about 25 and 20 particles at $E = 1$ and 0.5 GeV), at "reactor energies" $E < 10.5$ MeV thorium fission cross-section and therefore a created neutron number is noticeable less than for uranium. Nevertheless, one can see from Table 3 where the ratios of the neutron yields N, the fission number n, and the produced heats Q for very large thorium and uranium (pure ^{238}U) targets are presented,

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[1] We wish to thank A. A. Glasov for the fruitful discussion

Table 3

N_{Th}/N_U	0.66	Q_{Th}/Q_U, *total*	0.43
n_{Th}/n_U at $E > 10.5$ MeV	0.73	ionis. losses	1.0
n_{Th}/n_U at $E < 10.5$ MeV	0.15	fission at $E > 10.5$ MeV	0.72
		fission at $E < 10.5$ MeV	0.14

the total neutron yield for thorium is still rather significant. At some time the heat production in thorium targets is more than twice lower than in uranium ones.

Data in the Table are calculated for proton beam. Data for ion beams appear to be similar.

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Барашенков В.С. и др.　　　　　　　　　　　　　　　　E2-96-211
Электроядерный процесс,
управляемый ускорителем тяжелых ионов

Представлены результаты математического монте-карловского эксперимента с электроядерными процессами в гомо- и гетерогенных мишенях, облучаемых протонами и тяжелыми ионами. Показано, что выход нейтронов максимален при использовании дейтронного пучка и быстро снижается при переходе к тяжелым ионам. Обсуждаются зависящие от времени нелинейные эффекты, обусловленные накоплением легко делящихся изотопов.

Работа выполнена в Лаборатории вычислительной техники и автоматизации ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 1996

Barashenkov V.S. et al.　　　　　　　　　　　　　　　　E2-96-211
Heavy-Ion-Driven Electronuclear Process

Results of Monte-Carlo mathematical experiments with electronuclear process in uranium and thorium homo- and heterogeneous targets irradiated by protons and heavy ions are presented. It is shown that neutron yield is the highest while using the deuteron beam and sharply decreases in case of heavier projectiles. A time dependent non-linear effects stipulated by an accumulation of fissile nuclides are discussed.

The investigation has been performed at the Laboratory of Computing Techniques and Automation, JINR.

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