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V.S.Barashenkov, A.Polanski*, A.N.Sosnin

INTERACTIONS OF PROTON AND HEAVY ION BEAMS WITH URANIUM AND THORIUM TARGETS

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*Soltam Institute for Nuclear Studies, Otwock-Swierk n. Warsaw, 05-400 Poland

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Specific energy losses of a bombarding particle rise intensively with the increase of its charge Z due to ionization processes ($\sim Z^2/A$, where A is the particle mass number) 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 is 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
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). Both inter- and intranuclear cascades are calculated by Monte Carlo method, taking into account the decrease of energies of cascade particles due to the ionization processes along their trajectories, decays of created pions, aftercascade preequilibrium processes and "evaporation" and fission of exited residual nuclei. It is also important, especially in the case of nucleus - nucleus collisions, to take depleting of both colliding nuclei owing to a knock-out of intranuclear nucleons by cascade particles into account. (One can look for the details of our method in book [1] and papers [2, 3]).

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. It is illustrated 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

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

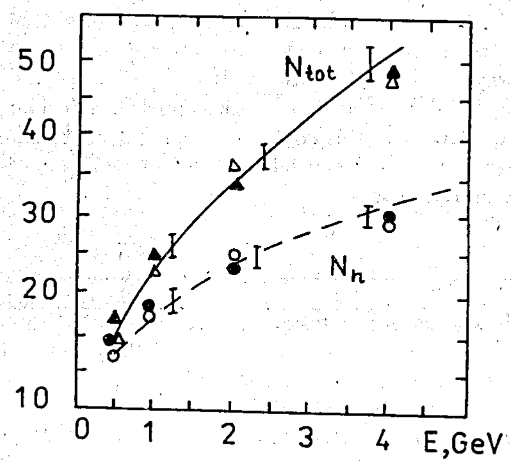

Fig. 1. Average multiplicity of particles created in inelastic interactions of protons (curves), deutrons (∘, △) and α-particle (• and black triangles) with an nucleus ^{238}U at the energy E.

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.

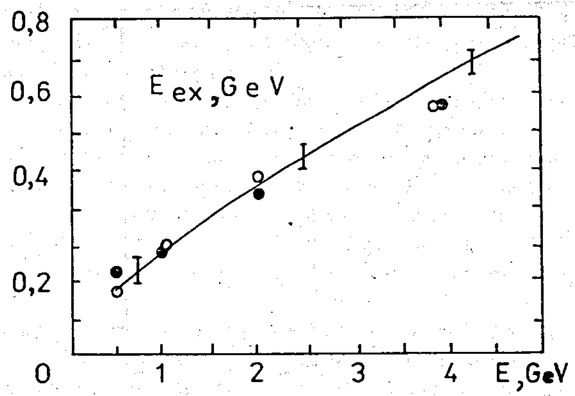

Fig. 2. Average excitation energy of an aftercascade residual nucleus. All notations are the same as in Fig. 1.

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 deutron 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 later is significantly lower (see Fig. 4).

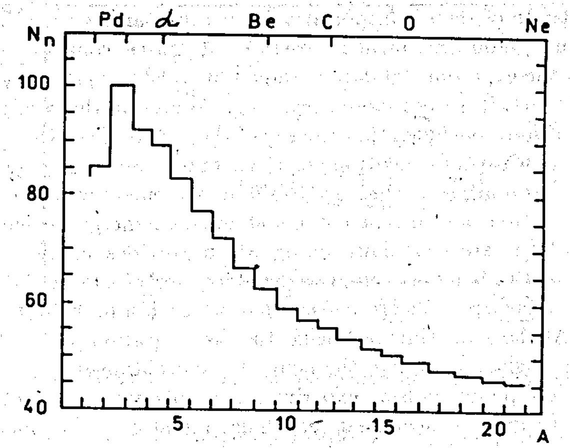

Fig. 3. Neutron yield in collisions of protons and ions with nucleus of the mass number A (per one intranuclear nucleon and for the energy 1 GeV/A.

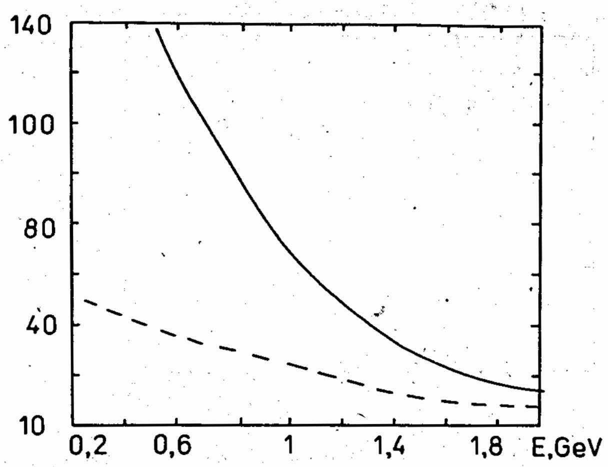

Fig. 4. The relative effectiveness of deuteron beam with thetotal energy E $[N_d(E) - N_p(E)]/N_p(E)\%$ (dotted line) and $[N_d(E) - 2N_p(E/2)]/2N_p(E/2)\%$ (solid line) in comparison to the protons beams with the energy E and $E/2$ but with doubled intensity. A large natural uranium target is considered.

The peak in Fig. 3 corresponds to minimal ionization losses in Table 1 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 [4,5] is even more surprising. Analysing 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±6% and 19±6% respectively in comparison with the proton beam. 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 which 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 [4,5]. Exactly this value is obtained from photoemulsion experiments [5]: 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 "energy costs" of one neutron produced by means of a heavy ion beam is large. Nevertheless, at 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".

Important feature of our model is the possibility to investigate the dynamics of electronuclear systems. Straight simulation of time alterations in the concentration of fissile nuclei is rather time consuming. We take these alterations into account by means of dividing total time interval into stages Δt. At each stage all parameters of the electronuclear system are considered to be constant during the simulation, but the initial conditions at the subsequent stage are adjusted taking into account the accumulated alterations by normalizing the nuclear reaction rates (production and burnout) to the predefined average enrichment level.

In this connection we should also like to focus attention on the peculiarity of the time dependence of the k_{eff}. Fig. 5 shows the variations of the k_{eff} depending on the neutron generation number. One must notice a "burst" of the k_{eff} over the the first 10 – 15 generations. The phenomenon is stipulated by an energy inflexibility of the neutrons created in intranuclear cascades and in decays of exited residual nuclei and also by the high neutron flux in the central part of the target owing to small initial leakage. The phenomenon is caused by the spallation neutrons which possess enough energy to induce intensive fission of ^{238}U as well as by the fact that the process is limited to a narrow central fraction of the target volume which results in the low level of the neutron leakage. It means that fluctuations of the beam intensity influence the average value of the k_{eff} which may appear dangerous. This problem must be further investigated in greater details.

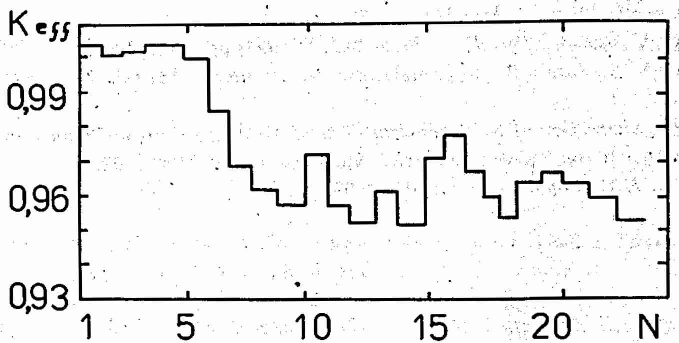

Fig. 5. Dependence of k_{eff} on neutron generation number N. Statistical errors of the calculation are shown

While simulating the internuclear cascades in electronuclear reactors keeping close to the $k_{eff} = 1$, one must also consider that the protons are introduced into the assembly over a definite period of time and therefore one always possesses a definite fraction of neutrons in the flux belonging to the first few generations, thus the superposition of the "humps" in the distribution of k_{eff} owing to such a displacement may cause significant increase of the multiplication factor.

The data considered above concern the $U - Pu$ systems. Comparing these systems with 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 same as in the 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 ratios of neutron yields N, fission number n, and produced heats Q for very large thorium and uranium (pure ^{238}U) targets are presented the total neutron yield for thorium is still rather significant. At some time the heat production in thorium targets is more than two time lower than in uranium ones.

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

If we take into account that power plants fueled with uranium where one can produce plutonium are still to be exploited for a long time employment of thorium in first experimental electronuclear systems appears to be untimely. The development of thorium systems is the next step of electronuclear technology.

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