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V.S.Barashenkov, S.Ju.Shmakov

NUCLEAR FISSION INDUCED BY HIGH-ENERGY PROTONS

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Барашенков В.С., Шмаков С.Ю. **E2 - 12902**

Деление ядер под действием высокоэнергетических протонов

На основе модели внутриядерных каскадов рассмотрено деление свинца и более тяжелых ядер в области энергий 0,1 ÷ 2 ГэВ. Учтена конкуренция деления и испарения возбужденных ядер. Для расчета деления использована модель Фонга, учитывающая затухание оболочечной поправки для нагретых ядер. Обсуждаются множественность вторичных частиц различных типов, энергетические спектры нейтронов, распределения остаточных ядер. Имеется хорошее согласие с экспериментом и расчетными данными, полученными другими авторами.

Работа выполнена в Лаборатории вычислительной техники и автоматизации ОИЯИ.

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Barashenkov V.S., Shmakov S.Ju. **E2 - 12902**

Nuclear Fission Induced by High-Energy Protons

The fission of lead and heavier nuclei in the energy region $T \simeq 0.1 \div 2$ GeV is considered on the basis of intranuclear cascade model. The competition between fission and evaporation of excited nuclei remaining after the cascade phase of the interaction is taken into account. Fong's model is used to calculate the fission process. The multiplicity of produced particles of various types, the energy spectra of neutrons, the distributions of residual nuclei are discussed. The calculated results are compared with the experiment and with the known theoretical data.

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

Communication of the Joint Institute for Nuclear Research. Dubna 1979

The inelastic interactions of high-energy particle with heavy nucleus proceed, as a rule, via the development of the broad ramified intranuclear cascade and the subsequent decay of a highly excited residual nucleus by the competing evaporation and fission processes. In outline this picture is known for a long time, nevertheless, a few articles were devoted up to now to the detailed quantitative analysis of it in a sufficiently broad energy interval.

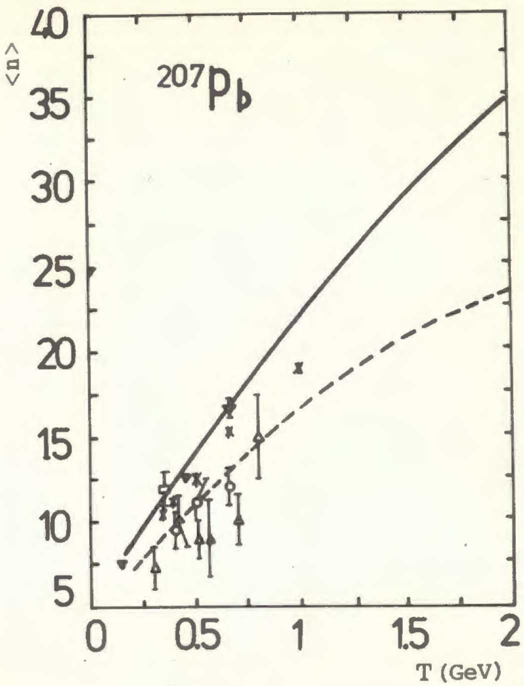
It should be noted, first of all, the latest papers of H.Bertini and R.Hahn /1,2/, where as a basis the intranuclear cascade model is used* developed by Bertini and applicable in the energy region $T \simeq 0.1 \div 3$ GeV. However, in paper /1/ it was assumed that the decay of residual nuclei proceeds via the evaporation completely; the fission process was not taken into account at all. In the subsequent paper /2/ the competition between the evaporation and fission is described using the rough phenomenological expression for the evaporation-to-fission width ratio Γ_n/Γ_f averaged over a broad interval of the excitation energies. In addition the nuclear depletion during the cascade (the so-called trailing effect) was not taken into consideration, too. This has led to significant overestimation of the multiplicity of produced particles at $T \gtrsim 5$ GeV.

The trailing effect and the evaporation-fission competition were taken into account in papers /5,6/, this allowed one to carry out the more detailed consideration of different aspects of the phenomenon and resulted in the better agreement with the experiment in these papers, however, the final stage of the fission of the excited residual nucleus and the fission products properties remained unconsi-

* Here and in what follows T is the kinetic energy of the primary particle in the lab. system.

The bibliography of the early calculations of the high-energy fission by means of more rough cascade models can be found in refs. /3,4/.

Fig. 1. The average number of particles created in inelastic interactions $p+^{207}Pb$. The dashed and solid lines are the calculated values $\langle n_n \rangle$ and $\langle n_t \rangle$ respectively. The marks * indicate values of $\langle n_n \rangle$ calculated by Bertini /1/. The marks O, Δ, □ indicate the experimental values $\langle n_n \rangle$ from refs. /10-12/. The marks ▼ show the experimental multiplicities $\langle n_t \rangle$ from ref. /13/.



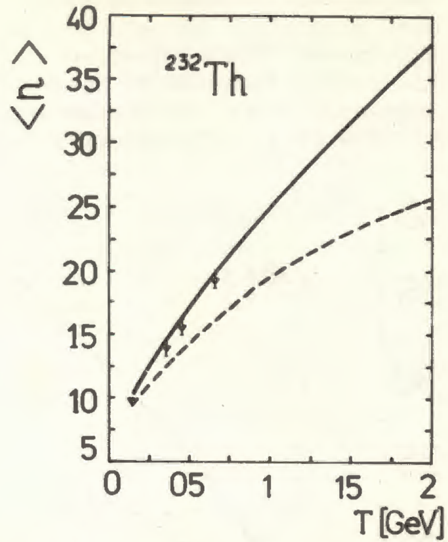
dered. Our work devoted to the systematic consideration of inelastic hadron-nucleus interactions fills up this gap.

It should be emphasized that the development of the theory of heavy nucleus spallation and decay at high energies has got now particular significance in view of projects of the plants using these phenomena for the electro-nuclear fissile fuel breeding /7,8/. As estimation show, the energy region $T \lesssim 2$ GeV is the most convenient for this purpose. Our calculations concern these energies.

Since the trailing effect appears in heavy nuclei at energies $T \lesssim 2$ GeV still weakly (see ref. /9/) we have disregardered this effect and used for calculations simpler version of cascade model described minutely in the book /4/. The fission of excited nuclei was calculated by means of Fong's model (see details in ref. /4/). Taking into account shell and odd-even effects, the calculations of fission barriers and width ratios were carried out by the same method as in refs. /5,6/. The values of the level density parameters in evaporating and fissioning nuclei are $a_n = a_f = A/10$ MeV^{-1} (A is the nucleus mass number).

The calculated values of the neutron yield $\langle n_n \rangle$ and the summary multiplicity of secondary particles $\langle n_t \rangle$ are shown

Fig. 2. The average number of particles created in inelastic interactions $p+^{232}Th$. All the designations are the same as in Fig. 1.



in figs. 1-3 for lead, thorium and uranium nuclei. Table 1 shows the corresponding data for isotopes ^{235}U and ^{239}Pu, which are of particular interest for the electronuclear breeding. The statistical uncertainty of these data is about 3-5%, the accuracy of the theoretical curves in figs. 1-3 is some more *.

From the listed data it is seen that the yield of particles depends upon the target mass number, roughly speaking, linearly. But the summary multiplicity of charged particles remains nearly constant in the region of mass numbers $A \gtrsim 200$: $\langle n_\pm \rangle \approx 3$ at $T = 0.5$ GeV and $\langle n_\pm \rangle \approx 12$ at $T = 2$ GeV.

In figs. 1-3 experimental data known for us are shown. The calculated neutron yield is in the best agreement with the data measured by Vasil'kov et al. /10/, which are considered to all appearance to be the most accurate at present.

*300-400 inelastic proton-nucleus interactions were calculated at both the energies $T = 0.3$ and 2 GeV, about a thousand of inelastic events were calculated at each of several intermediate values of T. The theoretical data shown in table 1 and in figs. 1-3 were obtained by means of the joint least-square smoothing of the calculated points for all considering nuclei. When using such method one can improve the statistical accuracy of calculated values significantly. The accuracy of other listed below values of the multiplicity is the same.

The results of Crandall et al.[12] are obtained in the experiment with thick targets by means of extrapolation to zero thickness. This is just an explanation of the fact, that the points measured by Crandall et al.are overestimated in comparison with the theoretical curve and the data of Vasil'kov et al. The measurements of Bercovitch et al. are

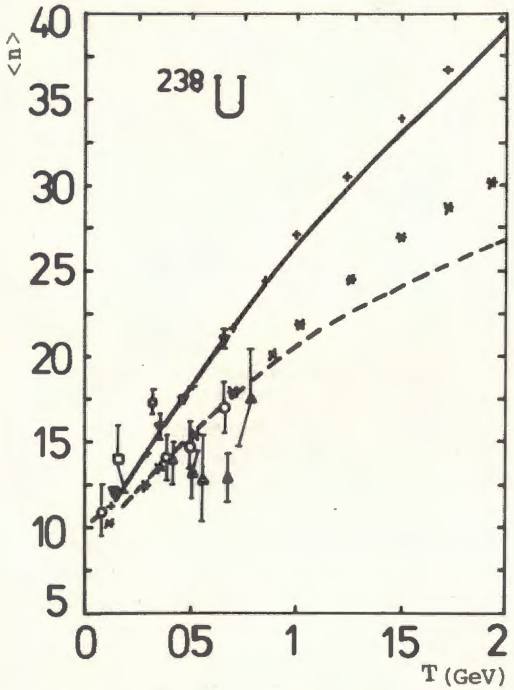


Fig. 3. The average number of particles produced in inelastic interactions $p + {}^{238}U$. The marks + + indicate the values $\langle n_t \rangle$ calculated by Hahn and Bertini in ref. [2]. All other designations are the same as in fig. 1.

Table 1

The neutron multiplicity and the total particle multiplicity in inelastic collision $p + {}^{235}U$ and $p + {}^{239}Pu$

Target	T = 1 GeV		T = 2 GeV	
	$\langle n_n \rangle$	$\langle n_t \rangle$	$\langle n_n \rangle$	$\langle n_t \rangle$
^{235}U	20.1	26.2	26.	38.2
^{239}Pu	20.5	26.5	27.	39.2

fulfilled with cosmic rays and so their accuracy is comparatively low.

The calculated multiplicity of charged particles is in good agreement with measurements of Ivanova and P'janov[13]*. For comparison in figs. 1,3 the multiplicities calculated by Hahn and Bertini are also shown. In case of the interactions $p + {}^{238}U$ these data agree quite well with our data and with the experiment at $T < 0.9$ GeV while at higher energies Hahn and Bertini's results are overestimated. Hahn and Bertini's data for interactions with lead nucleus significantly exceed the experimental and our data. The reason for the discrepancy is still unclear for us.

It is seen from table 2, that the main share of neutrons in the case of inelastic reactions $p + Pb$ is produced in the course of the evaporation process not accompanied by the fission of residual nuclei. In the considered region $T \leq 2$ GeV the relative contribution of the fission channel is only about 10%, approximately a one-third of these neutrons is evaporated from the excited residual nuclei prior to their fission. In the interactions $p + U$ at $T \leq 1$ GeV the fission channel becomes predominant; at $T \simeq 2$ GeV the

Table 2

The relative contribution of charged particles and different channels of neutron production to the total multiplicity of secondary particles $\langle n_t \rangle$ inelastic proton-nucleus collisions at energy T = 1 GeV.

Channel	$\langle n \rangle / \langle n_t \rangle$%					
	^{207}Pb	^{209}Bi	^{232}Th	^{235}U	^{238}U	^{239}Pu
Intranuclear cascade	16	15	14	14	13	13
Decay with fission	11	12	35	46	47	54
The total yield of neutrons	74	72	77	77	78	78
The total yield of charged particles	26	28	23	23	22	22

*The multiplicity $\langle n_t \rangle$ indicated by the marks ▼ is the sum of the measured value $\langle n_\pm \rangle$ and calculated by us neutron multiplicity $\langle n_n \rangle$.

contributions of the evaporation and fission channels are compared. About a quarter of neutrons in the fission channel of the reaction $p+U$ is produced due to the evaporation process prior to the fission.

A relative contribution of cascade particles $\langle n_{casc} \rangle / \langle n_t \rangle$ increases, naturally, with increasing the energy T. In the interactions $p+U$ it consists about 15% at T= 0.3 GeV and approximately 25% at T = 2 GeV. Nucleons are the cascade particles mainly.

Figure 4 shows the energy dependence of the average number of α-particles creating in the collisions $p+U$. This dependence is of analogous form in case of interactions with other heavy nuclei. The multiplicity of α-particles

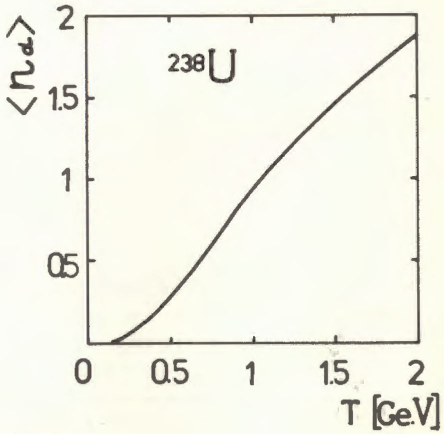


Fig. 4. The multiplicity of α-particles in inelastic interactions $p+{}^{238}U$.

Table 3

The share of α-particles among all secondary particles created in inelastic proton-nucleus collisions

Target	$\langle n_\alpha \rangle / \langle n_t \rangle$%	
	T= 0.35 GeV	T =1 GeV
^{207}Pb	1.4	4.4
^{232}Th	1.5	4.4
^{235}U	–	4.3
^{238}U	0.9	3.6
^{239}Pu	–	3.5

depends weakly on the mass of target nucleus. The energy dependence of $\langle n_\alpha \rangle$ appears to be more strong than that one for the secondary particle multiplicity $\langle n_t \rangle$ (see table 3).

The estimation of α-particle yield is of particular interest for electronuclear breading because though their contribution is of the order of some per cent, the micro-

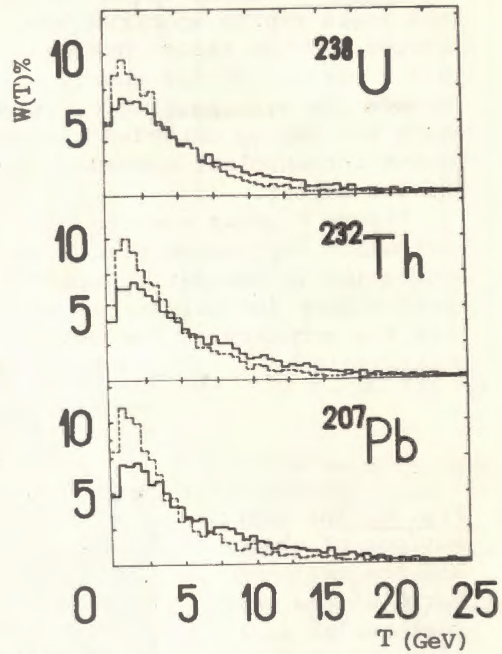


Fig. 5. The energy spectrum of produced neutrons. The solid and dashed lines are calculations for the primary proton energy T = 1 and 0.35 GeV, respectively.

Table 4

The relative multiplicity of heavy particles of different types $\langle n \rangle / \langle n_h \rangle \% \cdot \langle n_h \rangle$ is the summary multiplicity of secondary particles

Particle	$p+{}^{207}Pb$ T= 0.35 GeV $\langle n_h \rangle = 0.27$	$p+{}^{238}U$ T =1 GeV $\langle n_h \rangle = 2.1$
d	29	29
t	15	21
^3He	1	3
α	55	47

amounts of helium may change essentially macroproperties of target causing, in particular, additional radiative swelling of the irradiated material.

The contribution of α-particles is predominant among the heavy secondary particles (see table 4) and slowly decreases with the increasing of the primary energy T (approximately 40% in an interval 0.1÷2 GeV).

Figure 5 demonstrates how the summary integrated over all angle energy spectrum depends on the primary proton energy and the target nucleus mass number. The neutron yield has a maximum at the energy of the order of some MeV's broadening with passing to heavier nuclei and higher energies and has an extended high-energy tail generating subsequent intranuclear cascades when particles spread inside target matter.

Figure 6 shows clearly the variation of the fragment distribution in fission reactions and the residual nuclei distribution in spallation reactions with the target nucleus mass number and primary proton energy T. Figure 7 illustrates the accuracy of the cascade calculations of the fragment yield*.

T=0.3 GeV T=1 GeV

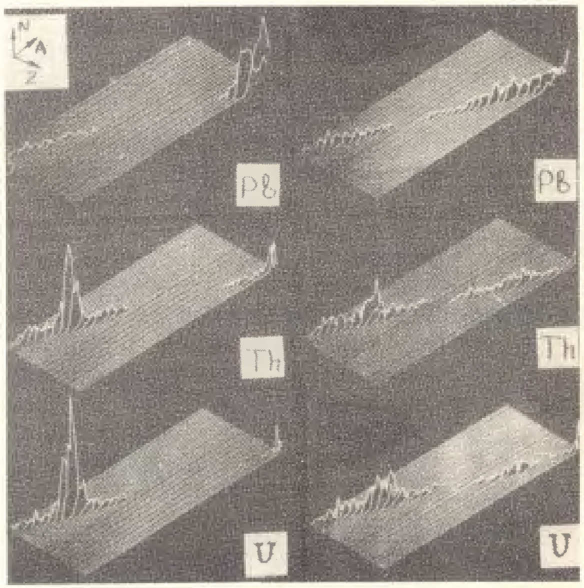


Fig. 6. The distributions of charge Z and the mass number A of the residual nuclei in fission and spallation reactions of lead, thorium and uranium nuclei at primary proton energies T = 0.3 and 1 GeV.

* The comparison of the experimental and theoretical data over yield of different isotopes in accompanying spallation reactions is given in ref. /6/.

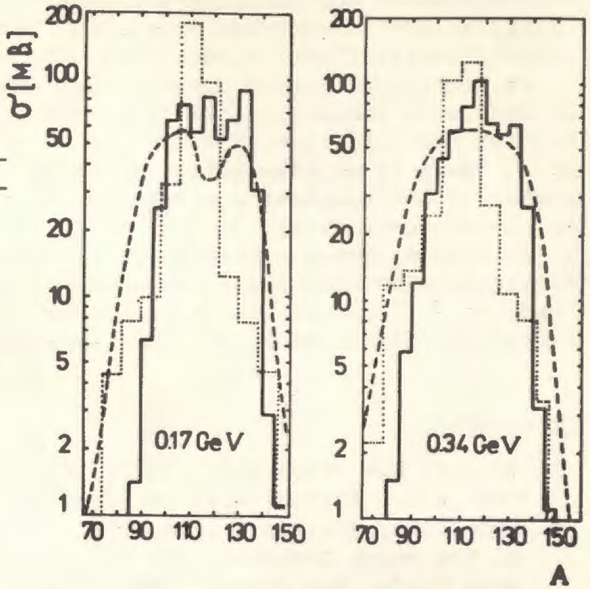


Fig. 7. The yield of fission fragments of nucleus ^{238}U in proton-induced reactions versus the mass number of fission fragment. The solid and dotted histograms are the results of the calculation with and without taking into account shell corrections. The dashed lines are drawn through the experimental points from refs. /14-17/.

The calculated histograms in fig. 7 describe roughly the general features of the experimental distributions $\sigma(A)$, but their form occurred to be more narrow near the centers. One can increase the distributions width taking into account the shell corrections ΔM_s to the masses of fission fragments and fissioning nuclei. The contribution of ΔM_s seems to be very small because the excitation energy of residual nuclei is rather high however there is a significant share of low excited nuclei for which the corrections ΔM_s are essential.

Sensitivity of our calculations with respect to the shell corrections is seen from figure 7 where the data calculated in the rough approximation $\Delta M_s(t) = \Delta M_s(0)\cdot(1-t^2/t_0^2)$ for the temperatures $t < t_0 = 2.5$ MeV and $\Delta M_s(t)=0$ for $t \geq t_0$ are listed*. Taking into account the shell corrections essentially improves the agreement with the experiment for the main part of fission fragments. But in our rough approximation the isotope yield at the distribution wings is still lower than experimental one.

The listed data and results of the ref. /6/ show that the intranuclear cascade model including the competing proces-

* The corrections ΔM_s have been calculated according to Cameron's formulas (see refs. /4,19/).

ses of fission and particle evaporation of excited residual nuclei allows to reproduce the main characteristics of inelastic interactions of particles with heavy nuclei.

At higher energies a special consideration is necessary because a theoretical cascade inside a heavy nucleus becomes too intensive with increasing of the particle energy T (even if we take into account the decreasing of the number of intranuclear nucleons due to their knocking out by cascade particles).

In case of heavy nuclei of photoemulsion ($A \simeq 100$) a marked discrepancy between the experiment and theory appears already at $T \simeq 10$ GeV. In the region $A \simeq 200 \div 240$ one can expect the disagreement at lower energies.

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