Eur. Phys. J. A **8**, 447–450 (2000)

THE EUROPEAN PHYSICAL JOURNAL A

Short note

Possible explanation of the difference in nuclear fission induced by the intermediate energy protons and neutrons

V.E. Bunakov[1,a], L.V. Krasnov[2], and A.V. Fomichev[3]

[1] Petersburg Nuclear Physics Institute, 188350 Gatchina, Russia
[2] Physical Institute of Petersburg State University, 198904, St.Petersburg, Russia
[3] Khlopin Radium Institute, 194021, St.Petersburg, Russia

Received: 13 June 2000
Communicated by V.V. Anisovich

Abstract. A possible explanation is given of the experimentally observed differences between the the fission cross-sections in the reactions induced by the intermediate energy (hundreds MeV) neutrons and protons.

PACS. 25.85.-w Fission reactions.

The experimental studies of nuclear fission stimulated in the recent years by the development of the transmutation program demonstrated (see, *e.g.*, [1]) that the cross-section of fission induced by the intermediate (hundreds MeV) protons is usually higher than that caused by the same energy neutrons. While this difference is rather small (30–40 %) for highly fissioning nuclei (*e.g.*, U or Th), it might reach a factor of about 3 for lighter nuclei (like Pb or Bi) — see fig. 1. The physics of the nucleon-induced fission seems to be fairly well understood and reasonably well described by the cascade-evaporation model. At the initial fast stage of the process the incident nucleon performs a few pairwise collisions with the target nucleons, sharing its energy and creating secondary fast particles. Since the nuclear radius is comparable with the mean free path of these particles, they usually carry the major part of the incident energy away from the target. The remaining part of the incident energy is left in the residual nuclei in the form of the holes in the Fermi-sea and is rapidly thermalized. Thus by the end of the initial fast stage we have a number of excited nuclides, which cool down at the next evaporation stage by the competing processes of fission or particle evaporation. According to the experimental data evaluation of [2] the reaction cross-sections of the intermediate energy protons and neutrons on, say, ^{208}Pb are practically equal, which is a reflection of the charge independence of nuclear forces. Thus one might expect that the fast stage of the process goes in the same way for neutrons and protons. Therefore it seems rather puzzling that the fission cross-sections for them differ by a factor of 3.

The only seemingly obvious difference between the incident neutrons and protons is the possibility for a proton to produce the additional excitation of the giant resonances in the target by its Coulomb field. The detailed theoretical analysis [3] of the inelastic scattering of protons on ^{208}Pb shows that the major contribution to the excitation of Giant Dipole Resonances comes indeed from the Coulomb (and not the nuclear) forces. Therefore a fraction $w = \sigma_{\mathrm{GDR}}/\sigma_{\mathrm{r}}$ of residual nuclei in the proton-target interaction would get additional excitation energy $E_{\mathrm{GDR}} \approx 13$ MeV, thus increasing their fission probability at the evaporation stage. Here σ_{GDR} is the cross-section of the Giant Resonance excitation, which was estimated by us with the use of the standard DWUCK code to be 0.54 mb. The reaction cross-section σ_{r} was estimated in the cascade-evaporation model CEM [4] to be 1521 mb. In order to calculate the increase of the fission probability W_{f} we used the standard expression of [2]:

$$W_{\mathrm{f}} = \frac{(2\sqrt{a_{\mathrm{f}}(E^* - B_{\mathrm{f}})} - 1)\exp(2\sqrt{a_{\mathrm{f}}(E^* - B_{\mathrm{f}})})}{4\pi a_{\mathrm{f}} \exp(2\sqrt{a_0 E^*})}. \quad (1)$$

Here E^* is the excitation energy of fissioning nucleus, a_0 and a_{f} are the parameters of level density of this nucleus at equilibrium deformation and at the saddle point, correspondingly.

For the estimates of fission barrier B_{f} one can use different approximations of the liquid-drop model together with various "irregular" quantum corrections. For our qualitative estimates of the fissility increase due to the additional GDR excitation we assumed the liquid-drop approximation formula:

$$B_{\mathrm{f}} = \gamma A^{2/3} f(x). \quad (2)$$

[a] e-mail: bunakov@thd.pnpi.spb.ru

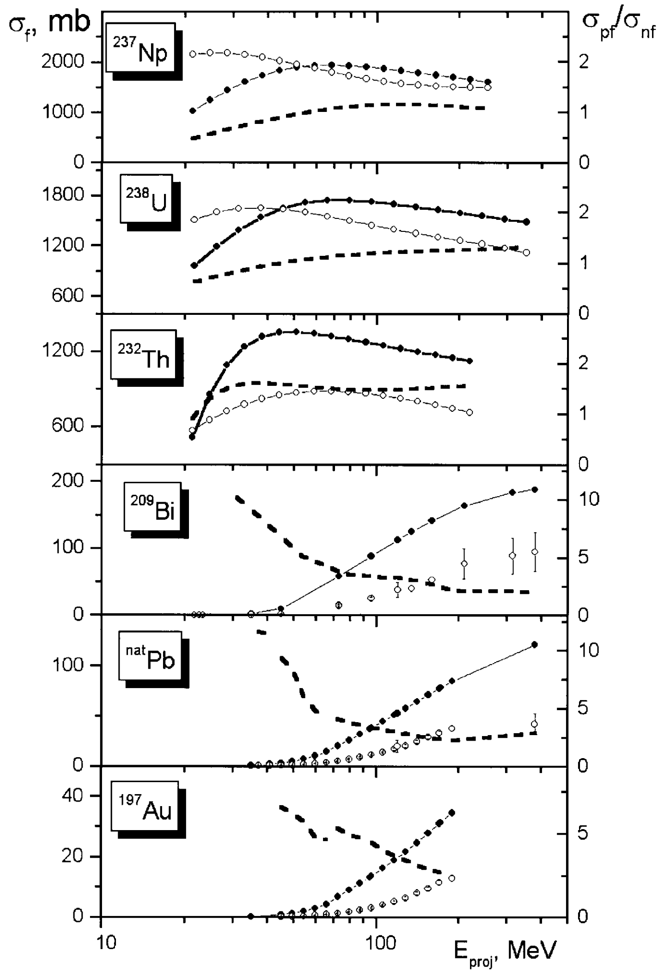

Fig. 1. Comparison of fission cross-sections of heavy nuclei induced by protons and neutrons with the same energy. The left scale gives the absolute fission cross-sections. Open circles are the (n,f) reaction. Solid circles are the (p,f) reaction. Dashed lines and the right scale represent the ratios of (p,f)/(n,f) cross-sections. All the data are the evaluation of the different experimental results performed by A.Prokofiev and published in [1].

Here $\gamma \simeq$ 15–20 MeV; the fissility parameter $x = (Z^2/A)/(Z^2/A)_{\rm crit} = (Z^2/49A)$; $f(x) = 0.728(1-x)^3 - 0.661(1-x)^4 + 3.330(1-x)^5$.

The distribution of excitation energies of the residual nuclei after the fast stage of the process for 200 MeV protons and neutrons interacting with ^{208}Pb calculated in CEM is shown in fig. 2 by open circles and crosses, correspondingly. The additional excitation of 13 MeV increases in this case the fission cross-section from 22.2 mb up to 46.0 mb, but the small value of $w = 0.54/1521 \approx 4 \cdot 10^{-4}$ makes this increase quite negligible.

However, the calculations with CEM code without any modifications produced for ^{208}Pb the ratio of $\sigma_{\rm p}^{\rm f}\sigma_{\rm n}^{\rm f} \approx 2.3$, which is quite close to the experimental data. This unexpected result demanded to find what kind of physics allows the cascade-evaporation model to reproduce such a large difference in the fission cross-sections induced by protons and neutrons. As we see from fig. 2, the excitation energies of the residual nuclei in the proton and neutron cases are the same. Therefore our next step was to compare the distributions of the residual nuclei in those two cases along A and Z. Those distributions are shown in Tables 1 and 2 for incident neutrons and protons, respectively. Comparing the tables, we see that the two distributions strongly resemble each other. Their major difference is the presence of residual nuclei with $Z = 83$ (Bi isotopes) in the case of proton-induced reactions and their absence in neutron-induced process. The origin of these isotopes is quite obvious — they are formed when the incident fast proton looses the major part of is energy and gets stuck in the target after the emission of one or more neutrons. The fissility parameters x for these isotopes are larger than for all the other residual nuclei, which means that their fission barriers are the lowest. We have checked their contribution into the total fission cross-section, changing all the $Z = 83$ residual nuclei in the CEM calculations by the $Z = 82$ ones. In spite of the fact that Bi isotopes make up only 14% of all the residual nuclei, such a change reduces the fission cross-section by a factor of 1.7, thus covering the major part of the initial difference in fission cross-sections. The rest of the difference is explained by the corresponding decrease by 14% of the yields of the $Z < 82$ isotopes with higher fission barriers in the case of incident protons (41% instead of 55% in the neutron case).

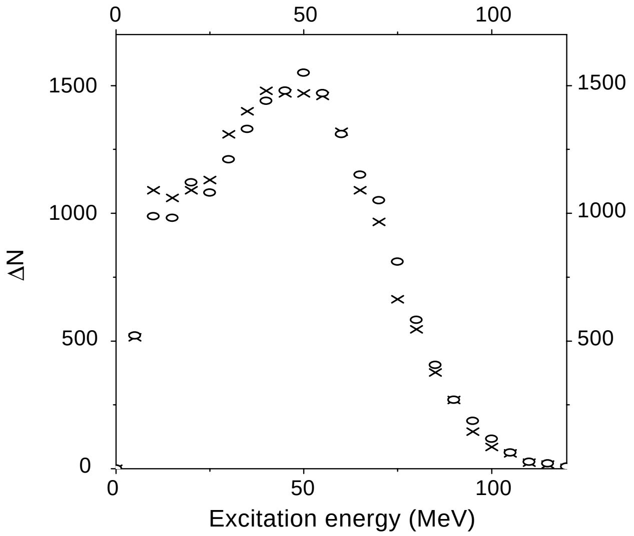

Fig. 2. Excitation energy distribution for the residual nuclei after the fast stage of reactions $^{208}{\rm Pb}+{\rm p}$ (circles) and $^{208}{\rm Pb}+{\rm n}$ (crosses). ΔN is the number of the residual nuclei in the 5 MeV bin.

Consider now the case of 200 MeV nucleons interacting with the ^{238}U. As we see in fig. 1, the experimental ratio $\sigma_{\rm p}^{\rm f}\sigma_{\rm n}^{\rm f} \approx 1.3$ in this case. Calculations with CEM code give for this ratio 1.05. Changing in this calculations the $Z = 93$ isotopes by $Z = 92$ ones, like it was done in lead case, reduces this ratio to about 1.01. Tables 3 and 4 show the distribution of residual nuclei after the fast stage of interaction of the 200 MeV neutrons and protons with ^{238}U. As we see, the Np isotopes are even more abundant

Table 1.

A, Z distribution of residual nuclei for n $+^{208}$ Pb.

199	**200**	**201**	**202**	**203**	**204**	**205**	**206**	**207**	**208**	**209**	**A/Z**	**fraction**
19	28	86	90	157	87	55	3	0	0	0	**79**	0.03
12	95	150	520	532	905	403	338	31	0	0	**80**	0.16
2	17	122	325	957	1141	1648	1312	1063	191	0	**81**	0.36
0	5	16	181	348	1105	1224	2381	2398	989	0	**82**	0.46
0	0	0	0	0	0	0	0	0	3	5	**83**	0.00

Table 2.

A, Z distribution of residual nuclei for p $+^{208}$ Pb.

199	**200**	**201**	**202**	**203**	**204**	**205**	**206**	**207**	**208**	**209**	**A/Z**	**fraction**
27	23	58	59	74	31	17	0	0	0	0	**79**	0.01
39	118	176	427	343	562	234	178	0	0	0	**80**	0.11
9	42	200	384	934	980	1310	902	741	0	0	**81**	0.29
1	19	60	351	592	1516	1345	2051	1894	797	2	**82**	0.45
0	2	4	21	111	200	431	450	735	677	0	**83**	0.14

Table 3.

A, Z distribution of residual nuclei for n $+^{238}$ U.

229	**230**	**231**	**232**	**233**	**234**	**235**	**236**	**237**	**238**	**239**	**A/Z**	**fraction**
29	39	98	88	127	65	45	4	0	0	0	**89**	0.03
31	137	236	597	487	715	308	278	46	0	0	**90**	0.15
12	43	251	443	1077	983	1465	997	952	248	0	**91**	0.34
3	19	42	332	515	1404	1257	2339	2293	962	1	**92**	0.48
0	0	0	0	0	0	0	0	0	4	0	**93**	0.00

Table 4.

A, Z distribution of residual nuclei for p $+^{238}$ U.

229	**230**	**231**	**232**	**233**	**234**	**235**	**236**	**237**	**238**	**239**	**A/Z**	**fraction**
21	20	52	40	52	20	12	0	0	0	0	**89**	0.01
47	150	163	430	310	410	137	120	0	0	0	**90**	0.09
37	81	302	428	963	755	1060	657	719	0	0	**91**	0.26
7	60	160	636	796	1605	1235	1918	1612	815	1	**92**	0.46
0	1	22	82	283	318	615	530	785	741	2	**93**	0.18

for incident protons than the Bi ones in the lead case. In order to understand, why do they not cause the significant changes as in the lead case, consider the ratio of fission probabilities R for the nuclei $A, Z+1$ and A, Z. Using eq. (1) and denoting the difference of the barrier heights as $\Delta = B_\mathrm{f}(Z+1) - B_\mathrm{f}(Z)$, we obtain

$$R \approx \frac{\sqrt{a(E^* - B_\mathrm{f}(Z+1))}}{\sqrt{a(E^* - B_\mathrm{f}(Z))}} \times \exp\left[2\sqrt{a}(\sqrt{E^* - B_\mathrm{f}(Z+1)} - \sqrt{E^* - B_\mathrm{f}(Z+1) - \Delta})\right] = \sqrt{\frac{E^* - B_\mathrm{f}(Z+1)}{E^* - B_\mathrm{f}(Z)}} \exp\left[\frac{\sqrt{a}\Delta}{\sqrt{E^* - B_\mathrm{f}(Z+1)}}\right]. \quad (3)$$

If we consider now the x dependence of the liquid drop barrier function $f(x)$ (see, *e.g.*, fig. 6.56 of ref. [5]), we shall see that both the barrier heights B_f and *the differences* Δ are much larger in the *Pb* region ($x \approx 0.66$) than in the U one ($x \approx 0.73$). In the lead region $B_\mathrm{f} \approx$ 18–20 MeV and $\Delta \approx$ 3–4 MeV. In the U region $B_\mathrm{f} \approx$ 8–9 MeV, while $\Delta \approx$ 1–2 MeV, which is comparable with the value of the quantum corrections to the liquid-drop barrier. Therefore the ratios R in U region are much smaller than in the lead one (according to the simplified eq. (3) for $E^* = 40$ MeV they are 6 times smaller). This explains the experimental fact that the proton-induced fission cross-section for the U region is much closer to the neutron induced one.

The work was partially supported by ISTC (project 609).

References

1. V.P. Eismont et al., in *Up-to-date status and problems of the experimental nucleon-induced fission cross-section data base at intermediate energies. in Proceedings of the 3rd International Conference On Accelerator Driven Transmutation Technologies and Applications, Praha (Pruhonice), Czech Republic, June 7-11, 1999* (CD ROM publication, paper P-C23).
2. V.S. Barashenkov and V.D. Toneev, *Interaction of High Energy Particle and Nuclei with Atomic Nuclei.* (Atomizdat, Moscow, 1972).
3. C.Djalali et.al.. Nucl.Phys. A **380** 42 (1982).
4. S.G.Mashnik, *User Manual for Code CEM95* (IAEA 1247/01 1995).
5. A.Bohr and B.Mottelson, *Nuclear Structure*, V.II, (Benjamin, New York 1974).