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Fast proton-induced fission of ^{238}U from threshold to 40 MeV

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Abstract. The fast proton-induced fission of ^{238}U has been analyzed from the threshold up to 40 MeV. Fission observables and isotope production were analyzed using TALYS and our own programs. Fission process was described by Brosa model. In the fast proton interaction, residual nuclei by mean of different (p,p'), (p,xn), (p,xp), (p,xα) (x=1,2,…,n) and other processes are formed. In the case of ^{238}U, residual nuclei can also fission, contributing to the investigated observables and isotope production. Comparing theoretical results and experimental data from literature, parameters of the optical potential, fission barrier and type of nucleus deformation were extracted. Cross sections and isotope yields obtained in neutron-induced fission process were compared with proton case and with EXFOR data.

1 Introduction

It was demonstrated that in the fast neutron-induced fission, proton spectra are obtained. By producing fast protons with energies up to 20 MeV, fast neutron reactors will generate a large amount of isotopes whose neutron cross sections will be very high, affecting the reactor operation and resulting in the activation of walls and vessels around the facility [1]. Radioisotopes are produced by proton-induced fission of ^{238}U with energies higher than 20 MeV that can be used in medicine, electronics, industry, and other fields [2]. Fast proton - induced fission with energies up to 40 MeV on ^{238}U was analysed. The investigation was focused on the fission observables like cross sections, fragment mass distribution, yields of select nuclides of interest, prompt neutron emission and theoretical evaluations were compared with experimental data from literature.

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2 Codes and elements of theory

Evaluations of fission variables were realized with TALYS [3], which is a free software dedicated to nuclear reactions and structure of atomic nuclei calculations, working under Linux. In TALYS are implemented all nuclear reaction mechanisms, together with a large database containing spin, parity, energy of nuclear levels, parameters of states density and of optical potential with volume (V), surface (d) and spin-orbit (SO) components, each with real and imaginary part. Compound processes are described by Hauser-Feshbach formalism, direct mechanism by Distorted-Wave-Born-Approximation and pre-equilibrium ones by two-component exciton model [3].
In TALYS all nuclear reaction mechanisms are enabled taking into account discrete and continuum states of residual nuclei [3]. This is important at higher incident energies when other channels like (p,xn), (p,xp), (p,xα) and others (x = 1,2,…,n) are open. These channels can also produce fissionable nuclei which can contribute to the investigated observables.

3 Results and Discussions

The theoretical and experimental total fission cross sections of ^{238}U induced by fast protons up to 40 MeV are represented in Fig. 1.

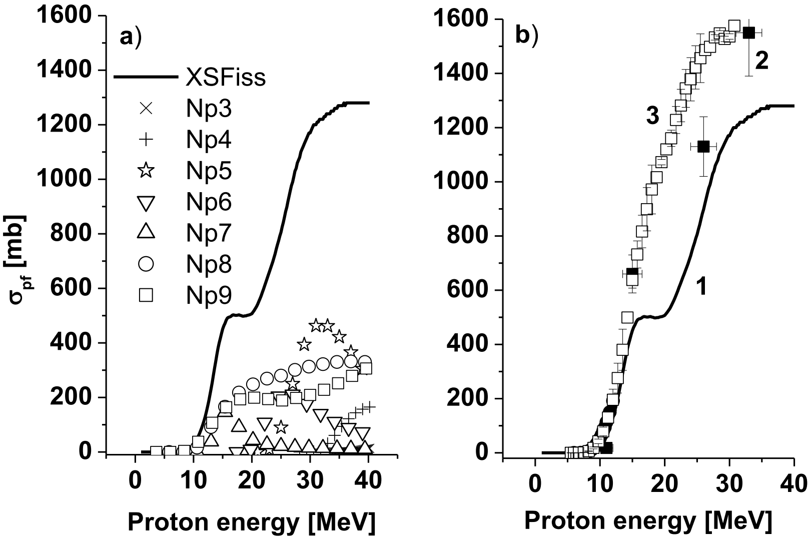

Fig. 1. Fast proton-induced total fission cross section of ^{238}U a) Theory. $^{238}U(p,f)$. Line – Total; "x" – ^{233}Np; "+" - ^{234}Np; Star - ^{235}Np; Down triangle -^{236}Np; Up triangle - ^{237}Np; Circle -^{238}Np; Square - ^{239}Np. b) Theory and Experiment. 1 – Theory; 2, 3 – Experiment.

In Fig. 1.a total fission cross section of ^{238}U induced by fast protons with energy up to 40 MeV is represented. In this process excited states of Np are formed due to the (p,xn) and (p,pxn) processes, respectively, and these excited residual nuclei will fission. The fission cross section of the $^{238}U(p,f)$ is of order of 15 mb at an energy of 40 MeV. In comparison, the fission cross section for $^{238, 239}Np$ is approximately 320 mb. The $^{238,239}Np$ nuclei are giving the main contribution to the total fission cross section. Fig. 1.b presents a comparison of two sets of experimental data [4,5] with the theoretical evaluation. Up to 15 MeV it is a very good agreement between theory and experiment. At higher energies differences can be explained by the presence of open channels with participation of ions of different masses. In the results from Fig. 1 are considered Np and U isotopes. Other fissionable nuclei, resulted from ^{238}U+p process were not included in the calculations. Their contribution to the cross sections and fission observables will be analyzed in the future.

In Figs. 2ab, mass distributions of fission fragment, for energies E_p = 5 and 35 MeV, are represented. Cross sections mass dependence has the same shape. Mass distribution enlarges and becomes more symmetric with the increasing energy.

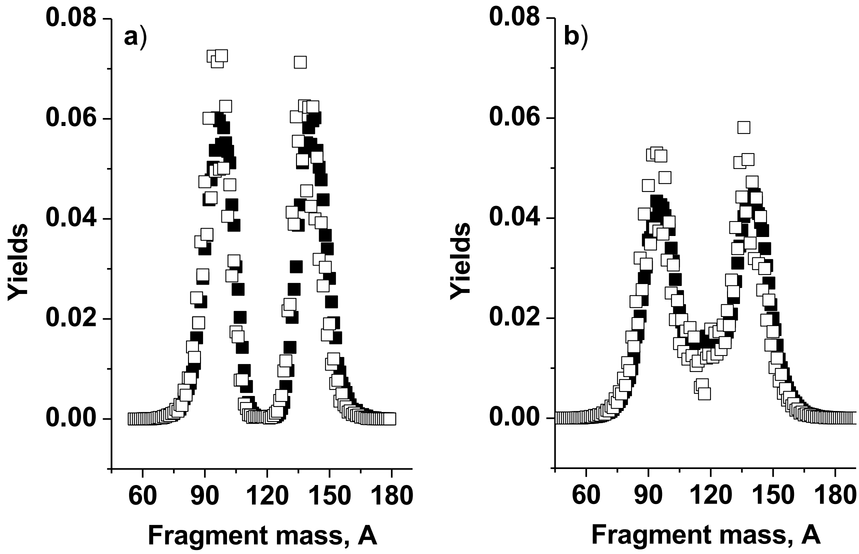

Fig. 2. Yields of ^{238}U(p,f) fission fragment mass distribution. Protons energy: a) E_p = 5 MeV; b) E_p = 35 MeV. Neutrons emission. Squares: full – Pre; Empty - Post.

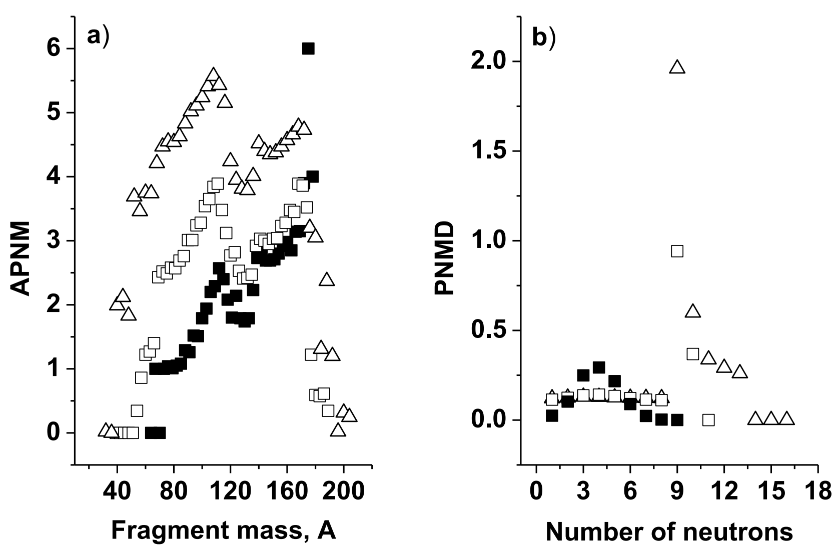

Fig. 3. Prompt neutron emission by fission fragments. a) APNM; b) PNMD. Full squares – 5 MeV; Empty squares – 15 MeV; Empty triangles – 35 MeV.

Prompt neutron emission can be described by two fission observables. First is the average prompt neutron multiplicity (APNM) depending on the fission fragment mass and the second is prompt neutron multiplicity distribution (PNMD). Theoretical evaluations of APNM for 5, 15 and 35 MeV are represented in Fig. 3.a and of PNMD in Fig. 3.b. In the case of proton - induced fission of ^{238}U experimental data are significantly poorer in comparison with neutron - induced fission. As is expected for both observables, the number of emitted neutrons by fission fragments and their distribution is increasing with incident energy. A global parameter related to APNM and PNMD is representing the average number of emitted prompt neutrons as a function of incident energy. This is an important parameter in nuclear engineering. Calculated values of nu-bar prompt, for 5, 15 and 35 MeV are 3.92, 4.93 and 6.77 incident neutron energy, respectively.

An interesting effect can be observed in Fig. 3. At 5 MeV, the number of neutrons is higher compared to 15 and 35 MeV for mass around A = 200. This result may be related to the structure of the excited nuclei but the theoretical evaluations need to be verified in the experiment.

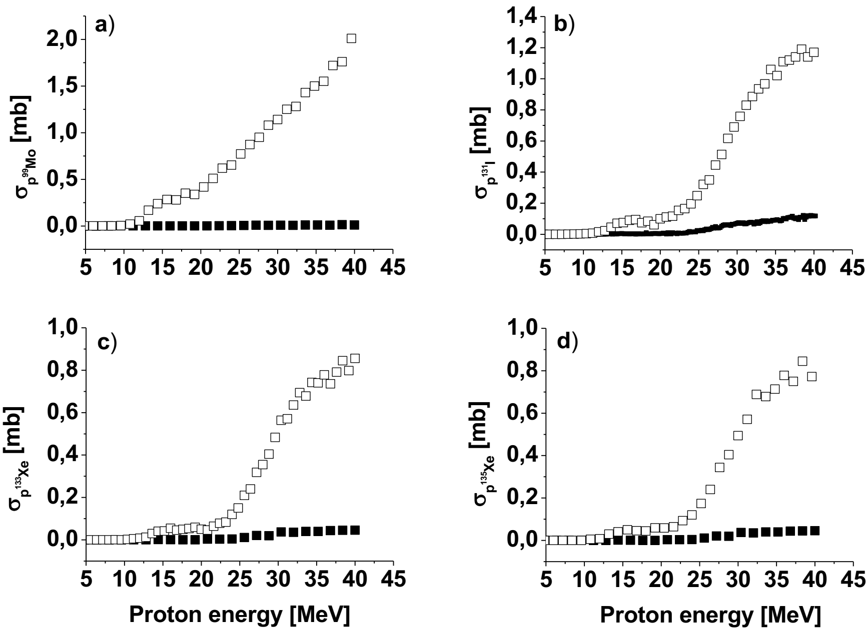

Fig. 4. Production cross sections of: a) ^{99}Mo; b) ^{131}I; c) ^{133}Xe; d) ^{135}Xe in $^{238}U(p,f)$. Neutron emission. Full squares – Pre; b) Empty squares - Post

In Fig. 4, production cross section of ^{99}Mo, ^{131}I and $^{133,135}Xe$ are represented. The isotope ^{99}Mo has significant interest in oncology, ^{131}I radiobiological protection, industry and ^{133}Xe in medicine. The ^{135}Xe nucleus is considered a major product in neutron - induced fission and high neutron absorber, which affects nuclear reactor function.

Isotopes ^{99}Mo, ^{131}I and $^{133,135}Xe$ are produced in very low amount in proton - induced fission. In TALYS it was necessary to enhance the precision of calculations in order to obtain the results from Fig. 4. With default TALYS run results from Fig. 4 cannot be obtained. The ^{99}Mo, ^{131}I, ^{133}Xe production cross section calculated by the authors is an order of magnitude higher for neutrons induced fission than for protons. Production cross section of ^{135}Xe nucleus are shown in Fig.4d. Cross section theoretical evaluation at E_p = 9.4 MeV is σ_{pf} =

0.037 mb and in experiment where obtained σ_{pf} = (0.03 ± 0.02) mb and (0.104± 0.04) mb, respectively [6] There are large discrepancies between theory and experiment among many authors.
A good description of the production cross section for the isotopes $^{90,\,91}$Y was obtained. Results are shown in Fig. 5 with experimental data from [7,8]. Yttrium nucleus has one isotope. Other Y isotopes are fission products and they are of interest in many applications.

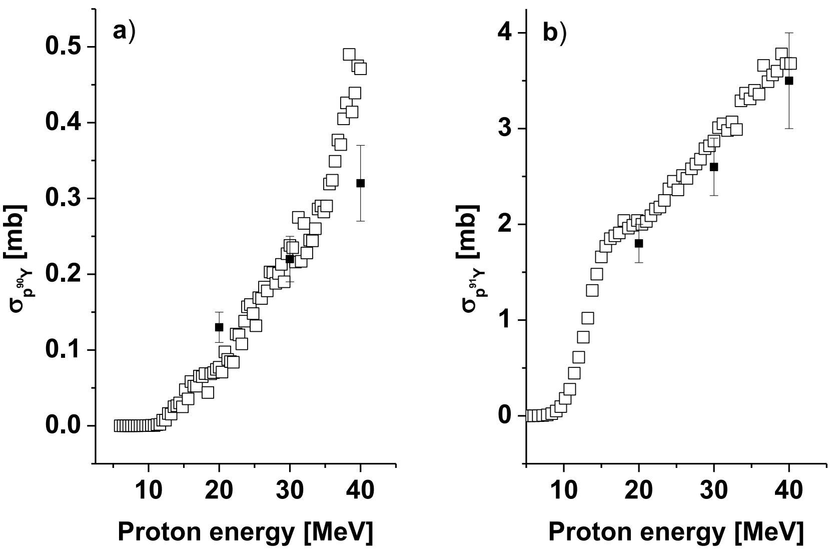

Fig. 5. Cross section production of a) ^{90}Y; b) ^{91}Y in ^{238}U(p,f). Squares: Empty – Theory; Full – Experiment.

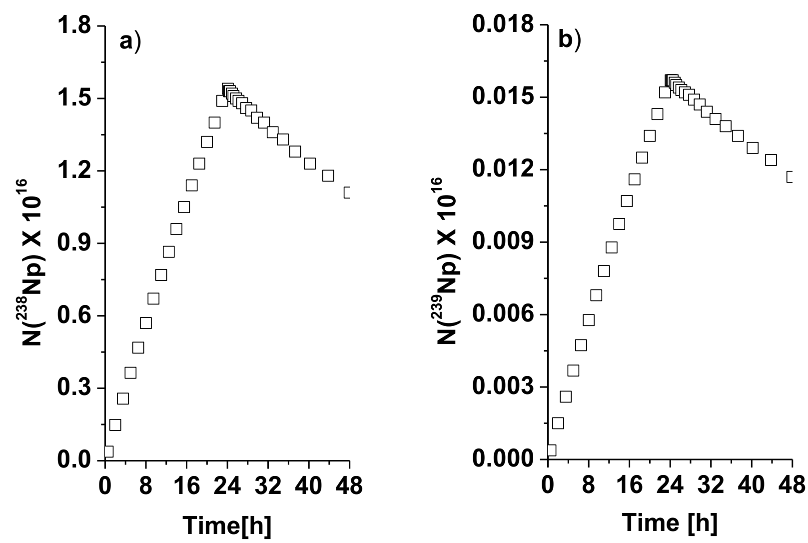

Fig. 6. Np isotopes production in ^{238}U(p,f). Absolute yields (number of nuclei, N). a) ^{238}Np; b) ^{239}Np.

Computer simulations were carried out for the production of isotopes. A sample of ^{238}U with 1 cm^2 transversal area was irradiated by a proton beam with 0,15 mA intensity and 40 MeV energy. Thickness of the target was chosen in such a way that protons cannot emerge from the target and it was equal to 1.85 mm. Proton energy loss was calculated with SRIM [9]. Irradiation and cooling time were equal both to 24h. Initial number of ^{238}U nuclei was $8.94\cdot10^{21}$. Fig. 6 represents the number of ^{238,239}Np nuclei produced as function of time (irradiation + cooling). Number of ^{238}Np nuclei is two orders of magnitude higher than the number of ^{239}Np.
Results presented in Figs. 1-6 were obtained considering 30 levels of residual nuclei for elastic and inelastic scattering, 10 levels for reaction channels and 5 rotation levels. The description of the Wood-Saxon potential is given in [3]. The parameters of the Wood-Saxon potential in the incident channel are shown in Table 1. Fission process was described by random neck rupture model [10]. In the evaluations were considered two fission barriers with parameters taken from experimental data [3]. The height of first barrier has 6.3 MeV, width 1 MeV and triaxial left-right asymmetry and the second barrier has 5.5 MeV height, 0.6 MeV width and left-right asymmetry type of axiality [3].

Table 1. Parameters of Wood-Saxon potential in p+^{238}U channel.

Volume						Spin-Orbit		
Real			Imaginary			Real		
V [MeV]	R_V [fm]	a_v [fm]	W [MeV]	R_W [fm]	a_W [fm]	V_{SO} [MeV]	R_{VSO} [fm]	a_{VSO} [fm]
55.12	1.245	0.66	0.1	1.248	0.594	5.66	1.121	0.590

4 Conclusions

In the ^{238}U(p,f) process for protons up to 40 MeV, fission observables and isotope productions were evaluated together with related computer simulations. The theoretical and experimental data for fission cross sections and the resulting isotopes are in good agreement but there are also cases with significant differences. New parameters of optical potential and fission barriers were also extracted. Fast proton-induced fission was less investigated in comparison to neutron-induced fission and therefore new measurements of fission observables are necessary to improve data processing and computer simulations, considering the importance of fission process for fundamental and application research.

References

[1] R.W. Eaker, A.T. Kandil, G.R. Chopin, Journal of Inorganic and Nuclear Chemistry, **18**, 5, 969(1976)

[2] J. Pandey, B. Pandey, A. Pal, S.V. Suryanarayana, S. Santra, B.K. Nayak, R.T. Mirgule, A. Saxena, D. Chattopadhyay, A. Kundu, V.V. Desay, A. Parihari, G. Mohanto, D. Sarkar, P.C. Rout, B. Srinivasan, K. Mahata, B.L. Roy, S. De, H.M. Agraval, Phys. Rev. **C 99** 014611 (2019)

[3] A.J. Koning, S. Hilaire, M.C. Duijvestijn, "*TALYS-1.0*" Proceedings of the International Conference on Nuclear Data for Science and Technology, April 22-27, Nice, France, editors Bersillon, (2007)

[4] S. Baba, H. Umezawa, H. Baba, Nuclear Physics **A175**,1, 177 (1971)

[5] J.R. Boyce, T.D. Hayward, R. Bass, H.W. Newson, E.G. Bilpuch, F.O. Purser, H.W. Schmitt, Phys. Rev. **C**, **10**, 231 (1974)

[6] H. Baba, A. Yokoyama, N. Takahashi, N. Nitani, R. Kasuga, T. Yamaguchi, D. Yano, K. Takamiya, N. Shinohara, K. Tsukada, Y. Hatsukawa & Y. Nagame, Z. Physik A - Hadrons and Nuclei, **356**, 61 (1996)

[7] A. H. Khan, G. B. Saha, L. Yaffe, Canadian Journal of Chemistry, **48**, 12, 1924 (1970)

[8] A. H. Khan, G. B. Saha, L. Yaffe, Canadian Journal of Chemistry, **47**, 20, 3818 (1969)

[9] SRIM Ion Stopping and Range in Targets – http://www.srim.org

[10] U. Brossa, S. Grossmann, A. Muller, Physics Reports, **197**, 167 (1990)