# Nucleon-induced Fission Cross-sections at Transitive Energy Region 20 - 200 MeV

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The new approach to the calculation of nucleon induced fission cross sections at energies 20-200 MeV is presented. The cross sections of multiconfiguration fission is calculated as a sum of fission cross-sections for nuclei formed in process of fast (direct) and precompound stage of fission reaction. The intranuclear cascade model is used for description of direct stage and precompound-statistical model for calculation of fission and de-excitation cross sections. Calculated with new optical model parameters sets fission cross sections are compared with experimental data for neutron-induced fission of $^{237}$Np, $^{239}$Pu, $^{235,238}$U and proton-induced fission of $^{235,238}$U. Brief information about new code system is also presented.

## 1. Introduction

Investigation of the properties of nuclear reactions on heavy nuclei induced by nucleons with energies more than 20 MeV is a one of actual problems of modern nuclear physics. The commission of new powerful neutron sources with energies up to 200-250 MeV (such as n_TOF facility in CERN ) and need in nuclear data for the development of accelerator-driven hybrid systems lead to the growth of both experimental and theoretical efforts at this energy region.

The energy region 20-200 MeV is a transition region between well-investigated low energy nucleon-induced reactions to reactions where the reaction mechanism is defined by sequential collisions with intranuclear nucleons and as a rule described by the intranuclear cascade model. The enlargement of direct process contribution to the total reaction cross-section leads also to the broadening of spectra of fissionning nuclei in different quantum states and to the appearance of additional fission chances. These facts let us possibility to say on the development of the multiconfiguration fission (MCF) for higher beam energies.

The existing models for the description of nuclear reaction characteristics at the transitive energies can be divided at two main groups. The first one includes pre-equlibrium+statistical approaches to reaction mechanism and the second one is based on the different versions of intranuclear cascade models. The application of statistical codes for higher energies meets with significant difficulties caused mainly by the underestimation of the role of entrance reaction channel and as a consequence by the overestimation of compound nucleus formation cross-section without any account of nuclear configurations populated at the direct stage of the reaction. The second group of models working fairly well for highest energies is in turn can't be directly used for the description of nuclear reactions at transition energies where the effects of nuclear structure have to be taken into account in details.

In the present work the new approach to description of the nucleon-induced reactions at transitive energies is proposed where the detailed statistical code is added by accurate pre-equilibrium and direct reaction stage calculations. The significant reduction of the number of fitting parameters allows to arise the predicting ability of the approach and to obtain rather reliable nuclear data sets for neutron- and proton-induced reactions on heavy nuclei (fission cross-sections at present as the first step).

## 2. The model approach and MCFx code system

The fission cross-section for MCF reaction can be presented in the following form [1-3]:

$$\sigma_f(A_i,Z_i,E_i)=\sigma_R(A_i,Z_i,E_i)\cdot\sum_j \int dU_j Y(A_j,Z_j,U_j;p_j,h_j)\cdot \sum_{A_f,Z_f} \int dU_f Y_f(A_j,Z_j;A_f,Z_f;U_j,U_f) \sum_n \sigma_f^n(A_f^n,Z_f^n,U_f^n) \quad (1)$$

The physical sense of this expression is as follows:

- The probability to penetrate of the incoming nucleon to target volume is defined by *the reaction cross-section* $\sigma_R$;
- Due to a number of inelastic collisions inside target volume some fast particles escape the volume forming the distribution $Y$ of residual nuclei (configurations) with *mass and charge numbers* $A_j, Z_j$, *excitation energies* $U_j$ *and particle-hole state* $p_j, h_j$;
- Each of these nuclei are in the pre-equilibrium state and after emission of a number of pre-equilibrium particles the new distribution $Y_f$ of equilibrated nuclear configurations $(A_f, Z_f, U_f)$ is formed;
- Nuclei in the equilibrium state may undergo fission or particle evaporation forming *fission chances* with *cross-sections of fission chances* $\sigma^n_f$.

The code system **MCFx** has been developed for the description of MCF reaction and fission cross-section calculations. The following codes and models are used in **MCFx**:

- The reaction (absorption) cross-section is calculated in the framework of coupled channel method (code ECIS[4]) with modified optical potentials;
- The cascade stage is calculated on the base of adopted Dubna version of intranuclear cascade model [5];
- The pre-equilibrium stage is calculated within HMS version of hybrid exciton model with Monte-Carlo simulation [6];
- The fission/evaporation stage is calculated with modified version of STAPRE code [7,8];

Some results of our calculations are presented in Fig.1-5. The comparison of the calculated reaction cross-sections with experimental data for proton-induced reaction on $^{238}$U is shown in the Fig.1 where calculations have been done with real part of optical potential developed by ours recently [3]. The example of intranuclear cascade model calculations are presented in the Fig.2 where the yields of residual nuclei formed due to direct cascade interaction of incoming proton with $^{232}$Th are presented. It can be seen form the Figure that for the lowest energies presented the yield of compound nucleus $^{233}$Pa is dominate and strongly decreases as energy increases. Such a behaviour indicates on the importance of the accurate account of direct processes for beam energies E ≥ 60-70 MeV in the actinide region. Starting from ~ 100 MeV the formation probability of compound nucleus is close to other one and it is necessary to take into account the fission of mixture of daughter nuclei formed in different quantum particle-hole states with different excitation energies. The pre-compound particle emission also leads to the broadening of spectra (A,Z,E$^*$) of fissionning nuclei (multiconfiguration fission).

The comparison of fission cross-sections calculated in the MCF approach with experimental ones is shown in the Fig. 3-5 as for neutron-induced and proton-induced fission of actinides. It is seen that our approach is able to reproduce the experimental data with rather high degree of reliability without any parameter fitting (only standard sets of level density parameters, fission barriers, binding energies and so on [1] have been used in the calculations).

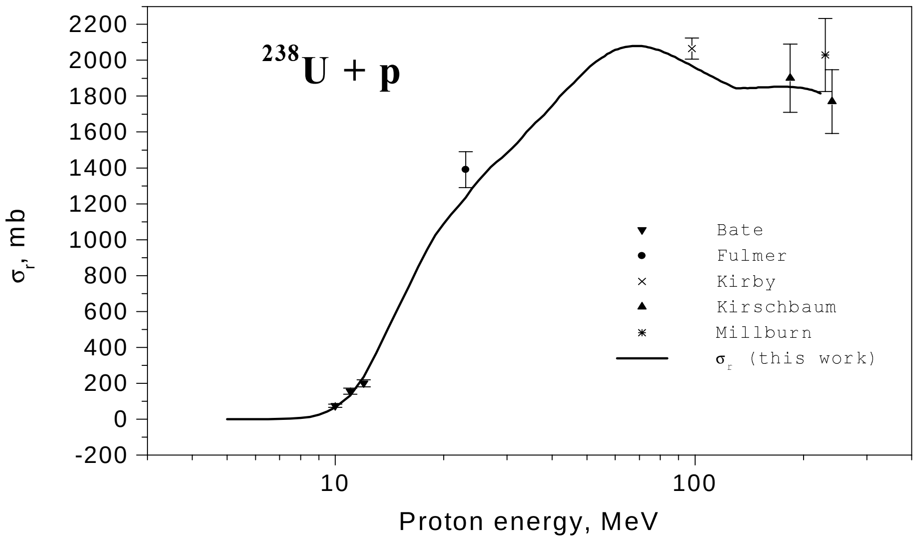


Fig. 1. Experimental and calculated reaction cross-sections for p+$^{238}$U reaction.

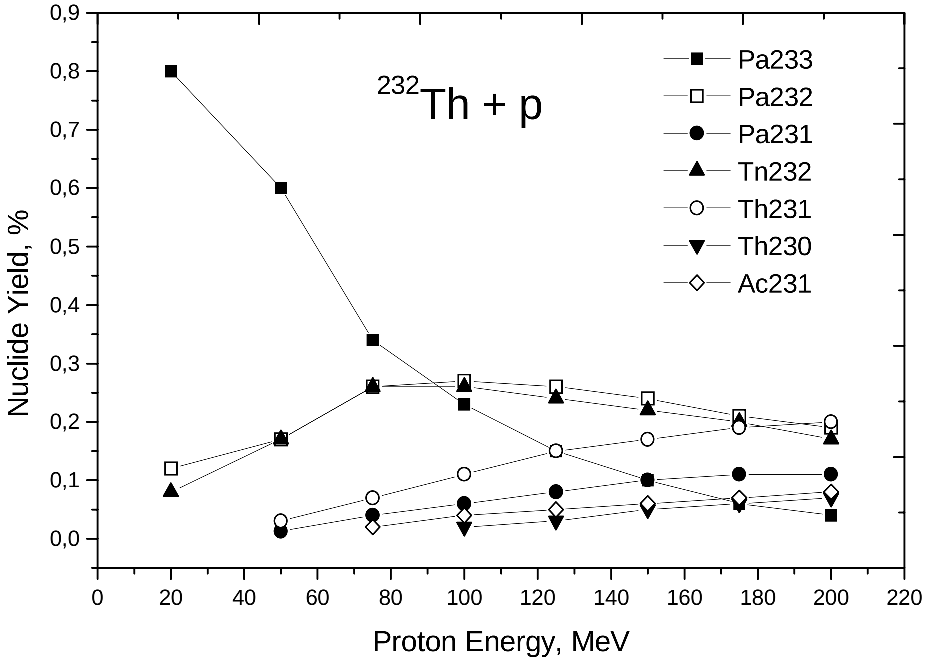


Fig.2. The yield of residual nuclei after cascade stage for proton-induced reaction on $^{232}$Th.

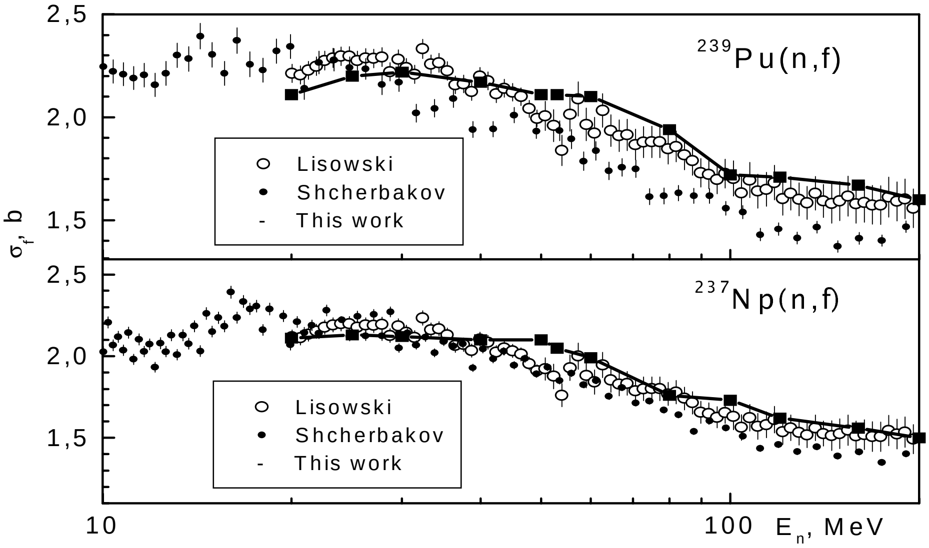


Fig. 3. Fission cross-sections for neutron-induced fission of $^{237}$Np and $^{239}$Pu.

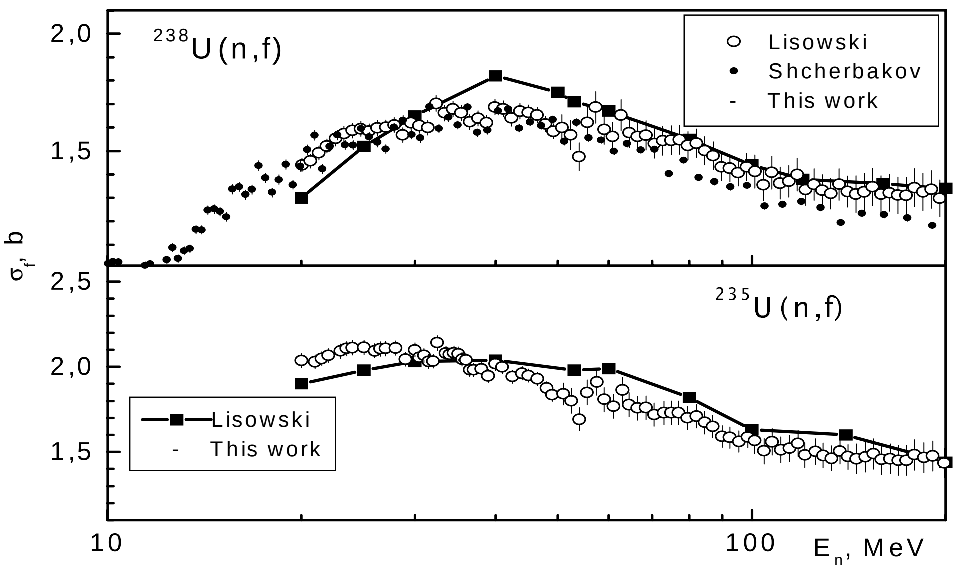


Fig. 4. Fission cross-sections for neutron-induced fission of $^{238,235}$U.

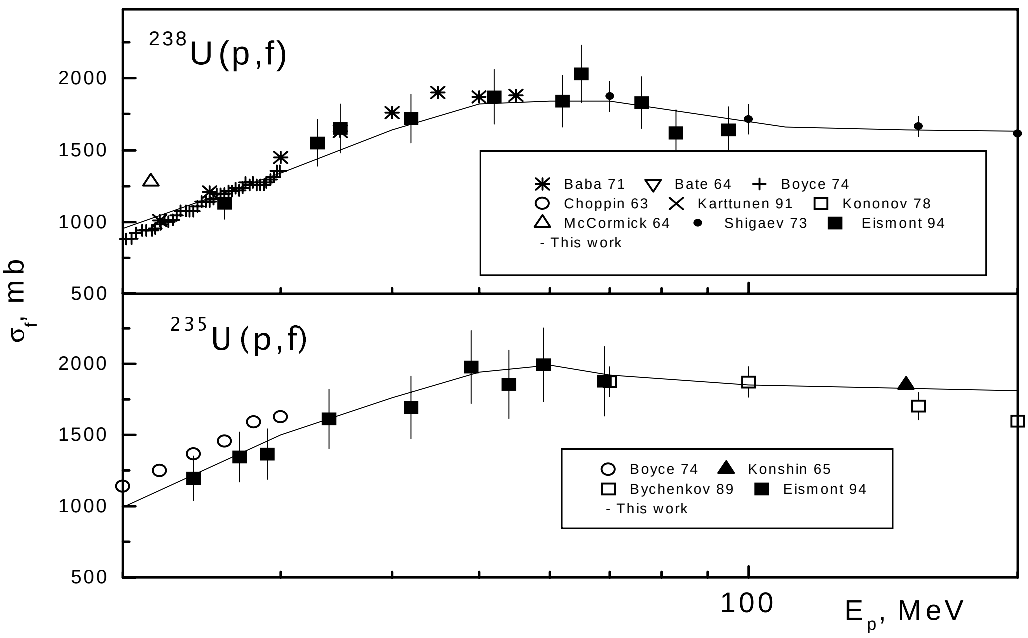


Fig. 5. Fission cross-sections for proton-induced fission of $^{238,235}$U.

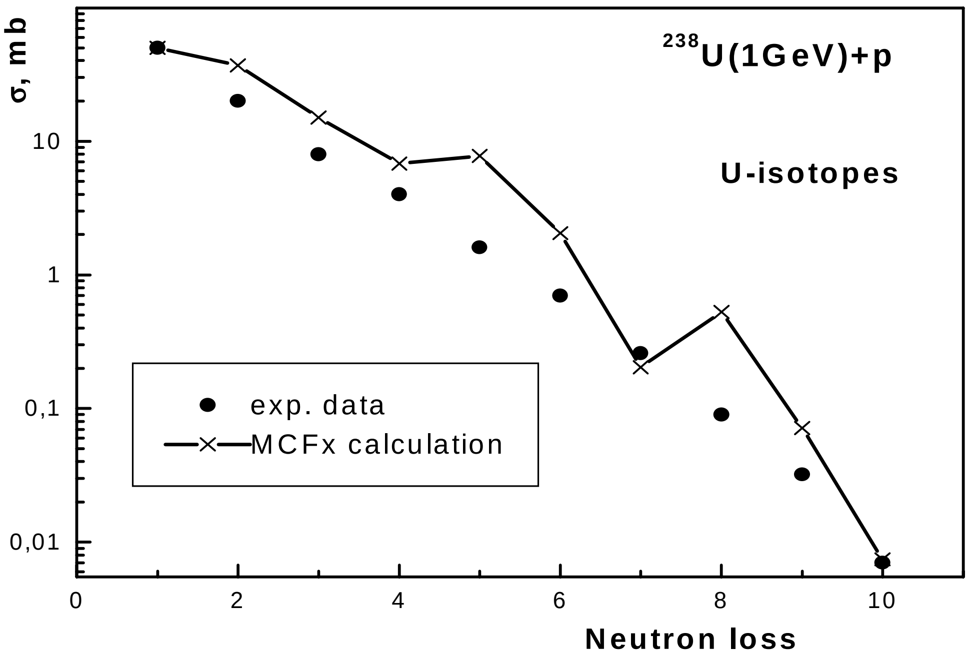


Fig. 6. Neutron loss in $^{238}$U+p reaction.

## 3. Conclusions

- The new approach for nucleon-induced fission cross-section calculations at transition energies has been developed on the base of detailed description of *all* reaction stages (entrance channel, direct, pre-equilibrium and statistical fission/ evaporation stages);
- The importance of account of large number of nuclear configurations is shown; multiconfiguration fission takes place at higher energies;
- The results of MCF cross-sections calculations are in a rather well accordance with experimental data *with standard set of parameters.*

## 4. Perspectives

Other important point of nuclear data evaluation for nucleon-induced reactions on heavy nuclei is the evaluation of reaction total and elastic cross-sections and yields of reaction products (particles and residual nuclei including fission fragment). The preliminary calculations of residual nuclei yields for $^{238}U$ (1 GeV) + p shown (Fig. 6) that the results obtained in the framework of approach developed agree satisfactorily with experimental data too. The detailed description of fission chances with inclusion of the statistical model for fission fragment production at each chance let us possibility to compute both fission fragment production and spectra of fission neutrons and to obtain the rather complete set of nuclear data for this kind of reaction.

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