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ISTC Project No. 2524

MCFx CODE SYSTEM AND NUCLEAR DATA LIBRARIES FOR 20 MeV – 1 GeV NUCLEON-INDUCED REACTIONS ON HEAVY NUCLEI

Final Project Technical Report
on the work performed from 01.12.2003 to 30.04.2007

S.G. Yavshits[1], O.T. Grudzevich[2], G.S. Boykov[1], V.T. Ippolitov[1], Yu.M. Martirosyan[2]

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May 2011

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ABSTRACT

The main goal of given work is to the development of new nuclear data generation tools for innovative hybrid nuclear technologies, first at all for technology of radioactive waste transmutation and energy production.

On the base of the approach developed to the description of nucleon-induced reactions in the energy region 20-1000 MeV the code for calculation of main reaction characteristics was worked out. The code allows tracing in detail all reaction stages and includes:

- Optical model for description of total cross-sections, reaction cross-sections and cross-sections of elastic scattering as well as angular distributions of elastically scattered particles;
- Intranuclear cascade model for description of fast particles spectra and parameters of configurations of excited nonequilibrium nuclei;
- Preequilibrium model of multiparticle emission for description of the spectra of preequilibrium particles and parameters of configurations of excited equilibrium nuclei;
- Statistical model of evaporation/fission;
- Models for calculation of fission fragment mass distribution and fission barriers.

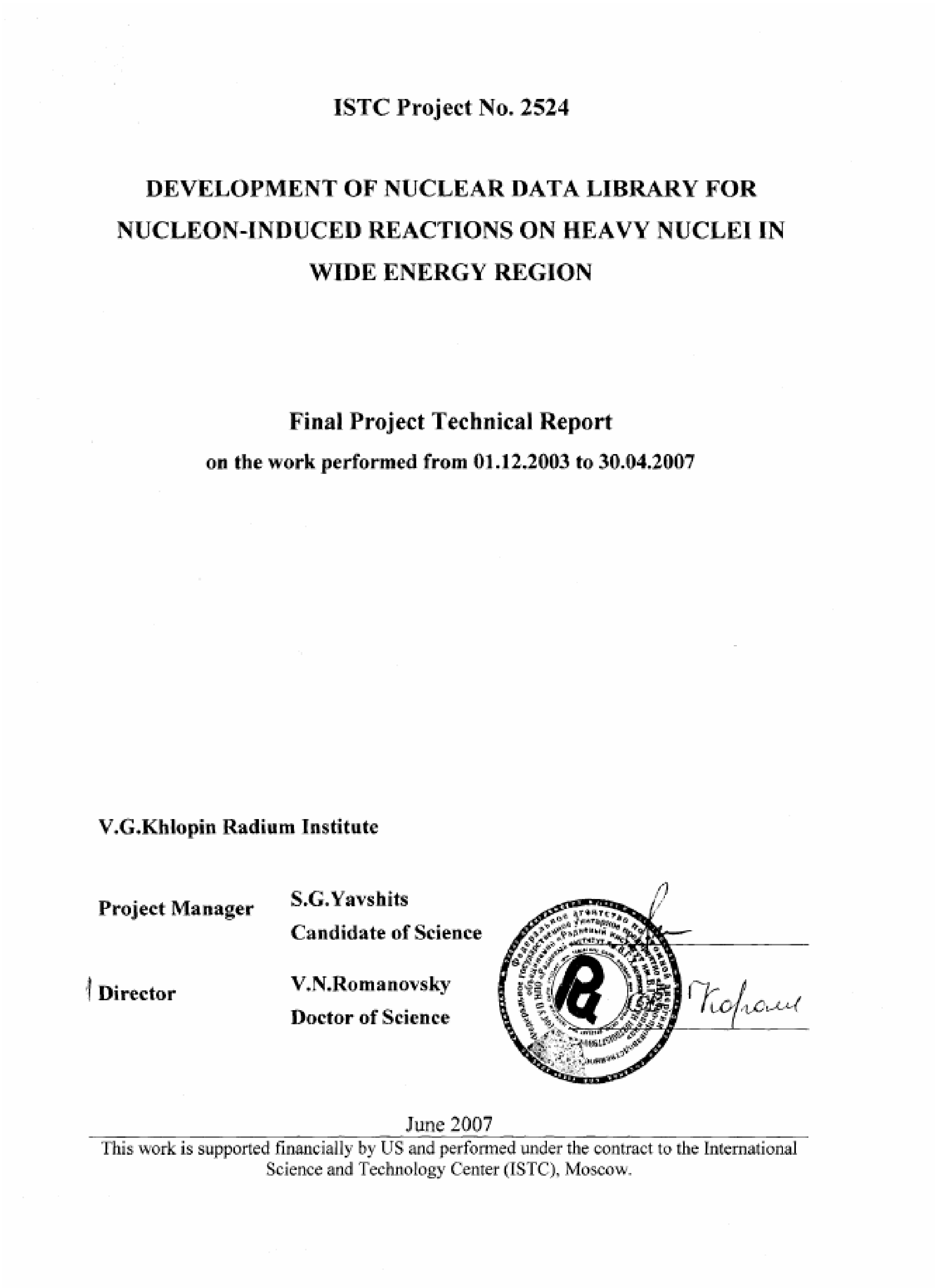
The library of transport files includes 18 files for 9 nuclei: 208-Pb, 209-Bi, 232-Th, 235-U, 238-U, 237-Np, 239-Pu, 241-Am, 243-Cm, irradiated by neutrons and protons with energy 20-1000 MeV.

Files developed consist of

- total cross section, reaction cross section and cross section of elastic scattering;
- fission cross section;
- double differential cross sections of secondary protons and neutrons;
- multiplicities of secondary particles;

The list of reactions may be extended for new evaluations and following projects.

May 2011



ISTC Project No. 2524

DEVELOPMENT OF NUCLEAR DATA LIBRARY FOR NUCLEON-INDUCED REACTIONS ON HEAVY NUCLEI IN WIDE ENERGY REGION

Final Project Technical Report

on the work performed from 01.12.2003 to 30.04.2007

V.G.Khlopin Radium Institute

Project Manager	**S.G.Yavshits** **Candidate of Science**
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June 2007

This work is supported financially by US and performed under the contract to the International Science and Technology Center (ISTC), Moscow.

Title of the Project: Development of nuclear data library for nucleon-induced

June 2007

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reactions on heavy nuclei in wide energy region

Commencement Date: 01.12.2003

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Keywords: Nucleon-induced nuclear reaction, 20-1000 MeV energy range, optical model, intranuclear cascade, multiparticle preequilibrium exciton model, Hauser-Feshbach statistical model, fission, complete ENDF-6 transport files for Pb, Bi, U, Pu, Np, Am, Cm

Brief description of the work plan

Project Objectives

The main goal of the project is to the development of nuclear data calculation technique for innovative hybrid nuclear technologies, first at all for technology of radioactive waste transmutation and energy production.

Within the framework of the project two main problems were decided:

- development of a reliable code enabling for calculation of main characteristics of nuclear reactions induced by nucleons in wide energy range;
- development of nuclear data library containing complete transport files for hybrid accelerator-driven systems.

Main Results

The results of the project have both fundamental and applied character. Within the framework of the project the following main results were obtained:

- The analysis of experimental and theoretical data for all items in question of new data library;
- The development of new parameterization of global optical potential which is necessary for entrance channel simulation and development of appropriate subroutines for a code realizing method of coupled channels for reaction cross-section calculations;
- The updating of existing models and codes and the development of new ones for a fast reaction stage (intranuclear cascade model), preequilibrium stage (model with a multiple emission of particles) and final stage (statistical model of fission/particle emission competition) for reactions with intermediate energy nucleons;
- The development of model for fission barriers and fission products yield calculations; inclusion of the appropriate subroutines in a statistical code;
- The test calculations with the code system developed and analysis of the results and comparison with existing experimental data;
- The systematical calculations for reactions with protons and neutrons (20-1000 MeV) for a wide range of targets;
- For each reaction (fixed target + projectile (proton or neutron) for fixed energy) the nuclear data file in the ENDF-6 format has been developed, including:
  - total cross section, reaction cross section and cross section of elastic scattering;
  - fission cross section (for heavy nuclei);
  - double differential cross sections of secondary protons and neutrons
  - multiplicities of secondary particles;
  - mass distribution of fission fragments.

The development of model insight on reactions induced by nucleons in the intermediate energy region allows to obtain new information about fundamental processes in excited nuclei. The code developed give possibility both participants of the project and other experts to analyze new experimental data obtained after completion of the project. The libraries of nuclear data generated in the international ENDF-6 format can be directly used for design of new nuclear facilities, for calculations of radiation transport and activation in structural elements. The developed libraries will be accessible to all institutions and experts dealing with development of hybrid technologies.

Technical Approach

The nucleon-induced reaction at intermediate energies passes through four stages. At the first stage incoming nucleon penetrates into volume of target nucleus initiating collisions with the intranuclear nucleons and causing secondary intranuclear cascades. After emission of several fast particles the nuclear system moves to preequilibrium state characterized by exciton number distributions (numbers of particles and holes) and corresponding excitation energies. The transition from preequilibrium to equilibrium state is characterized by emission of several preequilibrium particles and complication of exciton states up to a moment when it is possible to consider a nuclear system as the excited equilibrium nuclear configuration undergoing further a deexcitation by evaporation of particles and/or nuclear fission leading in turn to forming of a spectrum of excited fission fragments.

For the calculations of reaction cross sections (probability of incoming nucleon penetration inside target volume) in the entrance channel for energies higher 200 MeV it is necessary to take into account relativistic effects and use a relativistic global optical potential. The inclusion of the appropriate module in the ECIS code realizing a method of coupled channels and new parameterization of global optical potential with parameters selected both from theoretical assumptions (one-boson exchange model) and from the comparison with experimental data on reaction cross section allows to calculate energy and angular dependences of elastically scattered particles as well as total and reaction cross sections in all range of energies in question.

For projectile energies from approximately 200 MeV nucleon–nucleon collisions will produce mesons in the target volume which should be taken into account. Besides high-energy particles generate long intranuclear cascades leading to broad distributions of nuclei just after fast reaction stage in different quantum states. For account of these effects it was necessary to modify the intranuclear cascade model used earlier for energies up to 200 MeV. Important but not completely solved point here is the problem of a transition point from stage of direct processes to preequilibrium stage where exciton model with a possibility of multiple emission of particles has to be used. The study of the transition point (energy of the cascade cutting) and population of large number of complicated initial exciton states will also require updating the code for preequilibrium stage calculations.

The statistical model of particle evaporation and nuclear fission should be also reconsidered. In fission channel the dependence of fission barriers on excitation energy should be taken into account. For this purpose one-dimensional collective Schrodinger equation for a fission coordinate will be solved directly instead of usually used parabolic approximation for calculation of barrier penetration. The potential surface of deformation energy is calculated according to a Strutinsky prescription as the sum of smooth (liquid drop) part and shell correction with the weight depending on excitation energy of fissioning nucleus. For each fissioning nucleus reaction is considered practically up to the end, i.e. up to formation of fission fragments**.** For calculation of fission fragment yields the model of collective oscillations will be used while particle evaporation was proposed included in statistical Hauser-Feshbach model.

In such a code all stages of nucleon induced reaction are considered with the greatest possible degree of details and reliability; that results in large computational burden. To carry out the full cycle of planned calculations it was necessary to optimize the codes.

For formation of datafiles in the ENDF-6 format the additional program modules reprocessing the accumulated results to this kind of the format were developed. For convenience of work with such large program complex the developed early program blocks of input-output flows management and code operation control were modified and new subroutines were worked out.

The block scheme of the calculation flow is presented in the Fig.1.1

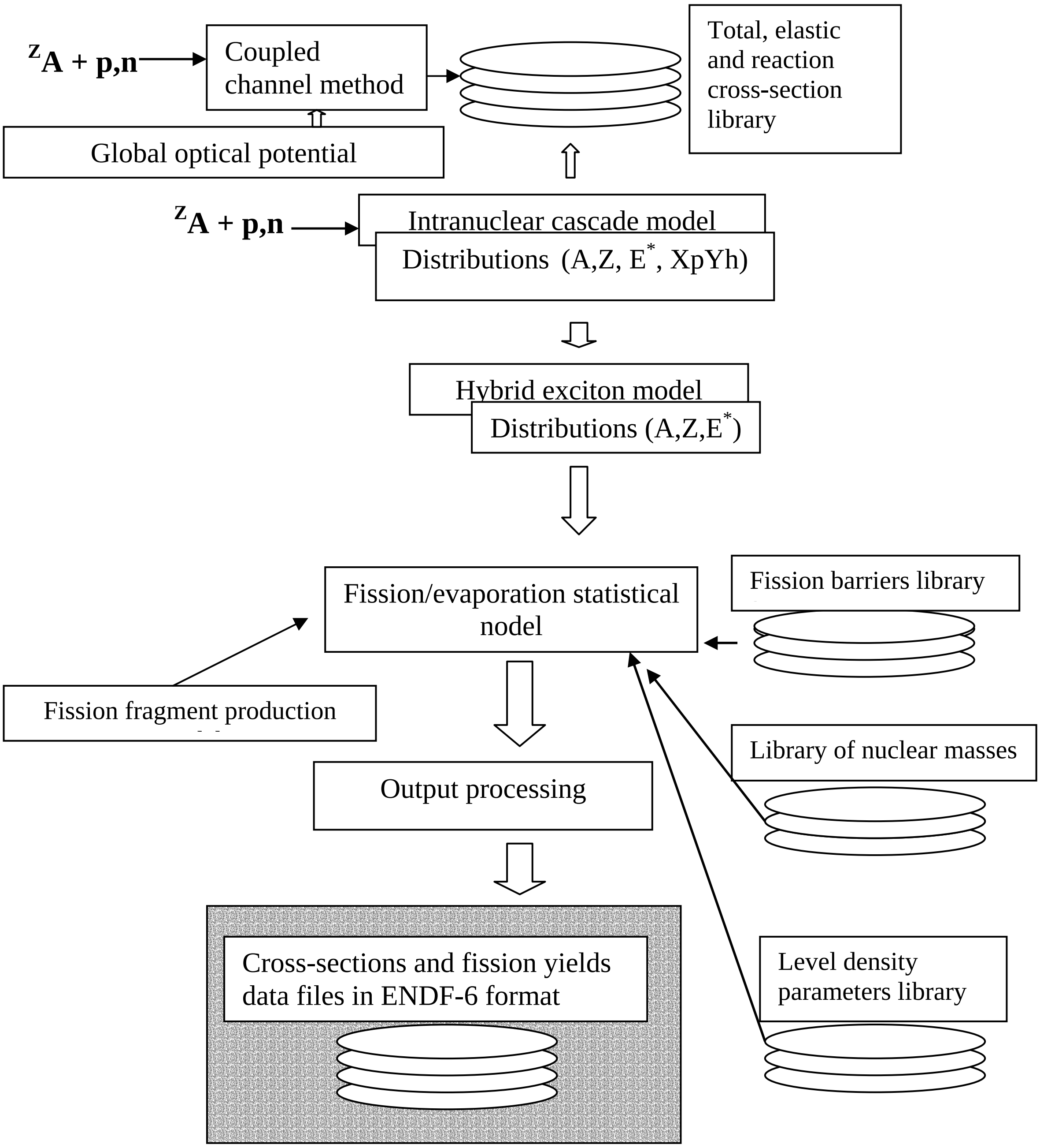
The following tasks were indicated in the work plan of the project:

Task 1. Analysis of existing experimental data on reaction cross-sections and secondary particle characteristics;

Task 2. Analysis of existing model codes and the results of other authors on cross-sections and secondary particle characteristics in the reactions with the nucleons of transitional and intermediate energies;

Task 3. Simulation of the entrance channel within the framework of a coupled channel method in a relativistic approximation and development of a global optical potential for heavy nuclei in wide energy region;
Task 4. Updating of intranuclear cascade and preequilibrium emission codes for the reactions with nucleons of intermediate energies;
Task 5. Updating of a statistical model of evaporation/fission for account of a particle emission and fission from highly excited nuclear states;
Task 6. Development of models for fission products yields and emission of nucleons from fission products, development of appropriate program routines and inclusion them into a code system;
Task 7. Development of the code for accumulation and reprocessing of output results for ENDF-6 format presentation;
Task 8. Development of library of total, reaction and elastic scattering cross sections;
Task 9. Development of fission barrier library;
Task 10. Test calculations, comparison with known experimental data and analysis of results;
Task 11. Systematic calculations under the list of the high-priority requests, accumulation of results;
Task 12. Packaging of data files in the ENDF-6 format.

Fig.1.1 Block scheme of the MCFx code and calculation flow



1. Models and codes

2.1.Simulation of the entrance channel within the framework of a coupled channel method in a relativistic approximation and development of a global optical potential for heavy nuclei in wide energy region, comparison with available experimental and theoretical data on total and reaction cross-sections, development of cross-sections library

2.1.1 Introduction

New nuclear applications based mainly on reactions with intermediate energy nucleons meet needs in evaluated nuclear data on neutron- and proton-induced reactions above 20 MeV and up to a few GeV. A scarcity of the experimental data in this energy range requires carrying out of theoretical model calculations, the most of which contains as a necessary physical component nucleon probability of penetration into a target nucleus, *i.e.* the optical model reaction (absorption) cross section, σ_r. Optical potentials are key quantities in any optical model calculations and therefore their reliable definition is very important.

The goal of the present part of the project is to give a nucleon-nucleus optical potential suitable for reaction cross section calculations for heavy (fissionable) target nuclei and projectile energy 20 – 1000 MeV in such a way as to results of these calculations could be employed further for calculations of nuclear fission cross sections and relative characteristics.

To avoid the ambiguities of purely phenomenological analyses and unphysical discontinuities of optical model parameters we use as far as possible a microscopic approach. The point of our approach is that the simple structure of the Skyrme effective interaction allows to apply the Vautherin-Brink procedure [1] to express the density of nuclear Hamiltonian and mean field as algebraic functions of the nuclear and kinetic energy densities. Furthermore, relationships between parameters of effective interaction and nucleon-nucleon (N-N) interaction and real (isoscalar V^{IS} (E) and isovector V^{IV} (E)) components of a central optical potential obtained by Pozdnyakov *et al.* [2] give us possibility to connect the optical parameters to parameters of N-N interaction such as meson coupling constants and meson masses used in meson field theories.

We use the one-boson exchange potential (OBEP) which provides the realistic description of the N-N interaction and N-N scattering data. The potential includes actual mesons π, η, ρ, δ, and ω and the dummy scalar-isoscalar meson σ which simulates correlated two-pion exchange to provide necessary attraction at middle N-N distance. Effect of nuclear medium (Pauli blocking) requires renormalization of light meson (π, σ) coupling constants (g_π^2 and g_σ^2) for calculation of effective N-N interaction. We considered these two constants as free parameters and define them by fitting to empirical values of the nuclear binding energy per particle (E_b/A) and equilibrium nuclear density (ρ_0) to fix the real part of central optical potential.

Other components of optical potential could be found from comparison of the calculated quantities with the experimental data for integrated observables (proton reaction σ_r and neutron total σ_t cross sections) and results of phenomenological analysis performed by Young [3], Madland [4], and Konshin [5]. All cross section calculations were carried out with ECIS code [6].

The isospin dependence of a central potential V_C (E) is represented by the Lane formula [7]

$$V_C(E) \ = \ V^{IS}(E) \ + \ A^{-1}\,(\boldsymbol{tT})\,V^{IV}(E)\,, \tag{2.1}$$

where E is the projectile energy, t and T are the isospin vectors of the incoming particle and target nucleus with atomic mass number A = N + Z.

The real part of a central nucleon optical potential can be expressed as follows:

$$ReV_C\,(E) \ = \ V_0(E) \ \pm \ \alpha\,V_1(E)\,, \tag{2.2}$$

where $\alpha \equiv 1/4(N-Z)/A$, the upper (lower) sign corresponds to a neutron (proton) entrance channel and isovector potential depth $V_1(E)$ has a sign opposite to an isoscalar one $V_0(E)$. We use the standard isospin convention: $t_3 = +1/2$ (for neutron), $t_3 = -1/2$ (for proton).

The questions of N-N interaction and effective forces used for the $V_0(E)$ and $V_1(E)$ definition are considered in sect. 2.1.2. In sect. 2.1.3 we describe shortly our previous results related to the energy range up to 200 MeV (the KRI 2000 optical potential). The optical potential for the nucleon energy 20 – 1000 MeV (KRI 2004 parameterization) as well as the comparison with experimental data are given in sect. 2.1.4. In sect. 2.1.5 we consider the generalization of the optical model for the case of relativistic energies and in the sect. 2.1.6 the brief description of the ECIS code which was base code for all our optical model calculation is presented.

2.1.2 The microscopic approach

The usual representation of the nucleon-nucleon one-boson exchange potential is

$$V_{NN}(\mathbf{r}) = V_c(\mathbf{r}) + V_\sigma(\mathbf{r})\,(\sigma_1\sigma_2) + V_t(\mathbf{r})\,S_{12} + V_\Delta(\mathbf{r})\,\nabla^2, \qquad (2.3)$$

where $\mathbf{r}$ is the nucleon relative coordinates, $\sigma_{1,2}$ denote the nucleon spin operators, and the tensor operator S_{12} is equal to $[3/r^2\,(\boldsymbol{\sigma}_1\mathbf{r})(\boldsymbol{\sigma}_2\mathbf{r}) - (\boldsymbol{\sigma}_1\boldsymbol{\sigma}_2)]$. Note that only terms with non zero contribution to central nuclear field and binding energy of nuclear matter are taken into account in (2.3). The functions $V_c(\mathbf{r})$, $V_\sigma(\mathbf{r})$, $V_t(\mathbf{r})$ and $V_\Delta(\mathbf{r})$ are superpositions of the mesons exchange contributions for the different type of mesons and in the case of scalar (S), vector (V) and pseudoscalar (P) mesons are given by the following prescriptions from meson field theory (see *e.g.* Refs. [8,9])):

Scalar mesons (s, sτ):

$$V_c(r) = V^S(r) + a^2/4\,\langle\nabla^2 V^S(r)\rangle, \quad V_\sigma(\mathbf{r}) = V_t(\mathbf{r}) = 0\,, \quad V_\Delta(\mathbf{r}) = a^2\,V^S(r)\,. \qquad (2.4)$$

Vector mesons (v, vτ):

$$V_c(r) = -V^V(r) - a^2/2\,(1+f/g)\,\langle\nabla^2 V^V(r)\rangle, \quad V_\sigma(\mathbf{r}) = -a^2/6\,(1+f/g)^2\,\langle\nabla^2 V^V(r)\rangle, \qquad (2.5)$$

$$V_t(\mathbf{r}) = a^2/12\,(1+f/g)^2\; r\frac{d}{dr}\left(\frac{1}{r}\frac{dV^V(r)}{dr}\right), \qquad V_\Delta(r) = a^2\,V^V(r).$$

Pseudoscalar mesons (p, pτ):

$$V_c(r) = V_\Delta(\mathbf{r}) = 0, \quad V_\sigma(\mathbf{r}) = -a^2/12\,\langle\nabla^2 V^P(r)\rangle, \qquad (2.6)$$

Here $a \equiv 1/M$, M is the nucleon mass, the brackets $\langle\ \rangle$ denote boundaries of the operator ∇^2; f/g is the ratio of tensor to vector meson-nucleon coupling constants (for vector mesons). In the case of isovector mesons exchange the factor $(\tau_1\tau_2)$ describing the isospin state of the nucleon pair should be inserted into the formulae (2.4) – (2.6), $\tau_{1,2}$ are the nucleon isospin operators. Functions $V^\alpha(r)$ (where α = s, v, p, sτ, vτ, pτ) are regularized Yukawa functions for the isoscalar and isovector mesons exchange [8,9].

The regularization is produced by introduction of form factor at each meson-nucleon vertex. Dipole regularization is used for the sake of simplicity to eliminate singularities from numerical calculations with eqs. (2.4) – (2.6). It results in the expression:

$$V^\alpha(r) = -g_\alpha^2\left(1-\frac{m_\alpha^2}{\Lambda_\alpha^2}\right)^{-2}\left[e^{-m_\alpha r} - e^{-\Lambda_\alpha r}\left(1+\frac{(\Lambda_\alpha^2 - m_\alpha^2)\,r}{2\Lambda_\alpha}\right)\right]\frac{1}{r}\,, \qquad (2.7)$$

where m_α , g_α^2 and Λ_α are masses, coupling constants and regularization parameters (“regulator masses”) for exchange of the type α meson, correspondingly.
The parameters of OBE potential adjusted to the nuclear matter parameters as mentioned above are presented in the Table 2.1.1.

Table 2.1.1. OBEP model

α	π	η	ρ	ω	δ	σ
J_α^π	0^-	0^-	1^-	1^-	0^+	0^+
T_α	1	0	1	0	1	0
m_α, MeV	138.7	548.5	763.0	782.8	960.0	570.0
g_α^2	(14.19)	3.09	0.43	9.92	0.33	(6.97)
f/g			6.38			
Λ_α	1414	1414	1414	1414	1414	1414

The effective forces consideration follows Skyrme's short-range expansion for the two-body force, v_{12}, thus the matrix elements in momentum space are

$$< k \,/ v_{12} /\, k' > \; = \; t_0 \,(1 + x_0 P_\sigma) + 1/2 \; t_1 (k^2 + k'^2) + t_2 (kk') \,, \tag{2.8}$$

where **k** and **k'** are relative wave vectors of two nucleons, P_σ is a spin-exchange operator; as before we omit the unnecessary terms (see the note just below Eq. (2.3)) and also neglect the contribution proportional to t_3 representing many-body effects.

To see how one deals with such an interaction in practical calculations it is convenient to write it in configuration space,

$$\begin{aligned} v_{12} = \; & t_0 \,(1 + x_0 P_\sigma)\, \delta(\mathbf{r}_1 - \mathbf{r}_2) \; - \; 1/8 \,(t_1 + x_1 P_\sigma)\, [(\nabla'_1 - \nabla'_2)^2 \,\delta(\mathbf{r}_1 - \mathbf{r}_2) \; + \\ & \delta(\mathbf{r}_1 - \mathbf{r}_2)\,(\nabla_1 - \nabla_2)^2] \; + \; 1/4 \,(t_2 + x_2 P_\sigma)\,(\nabla'_1 - \nabla'_2)\, \delta(\mathbf{r}_1 - \mathbf{r}_2)\,(\nabla_1 - \nabla_2)\,, \end{aligned} \tag{2.9}$$

where ∇ (∇') denotes the operator acting on the right (left). It is enough for the determination of the coefficients t_i and x_i represent matrix elements of the potential (2.3) as the following sums

$$\begin{aligned} < \mathbf{k} \,/ V_{NN} /\, \mathbf{k}' > \; = \; & < \mathbf{k} \,/ \Sigma_\alpha V_c^\alpha /\, \mathbf{k}' > + < \mathbf{k} \,/ (\sigma_1\sigma_2)\, \Sigma_\alpha V_\sigma^\alpha /\, \mathbf{k}' > - \\ & < \mathbf{k} \,/ (\sigma_1\sigma_2)\, \Sigma_\alpha V_t^\alpha /\, \mathbf{k}' > + < \mathbf{k} \; \Delta \; \Sigma_\alpha V_\Delta^\alpha /\, \mathbf{k}' > \,, \end{aligned} \tag{2.10}$$

and expanding each of the addendum in series over $\mathbf{k}^2$ with taking into account the symmetry of wave functions the following expressions can be obtained for relations of t_i and x_i with all possible OBEP components:

$$\begin{aligned} & t_0 = t_0^c + t_0^t \,; \quad x_0 = x_0^c + x_0^t \,; \\ & t_1 = t_1^c + t_1^\nabla + t_1^\sigma + t_1^t + t_1^\Delta \,; \quad x_1 = x_1^c + x_1^\nabla + x_1^\sigma + x_1^t + x_1^\Delta \,; \\ & t_2 = t_2^c + t_2^\nabla + t_2^\sigma + t_2^t \,; \quad x_2 = x_2^c + x_2^\nabla + x_2^\sigma + x_2^t \,. \end{aligned} \tag{2.11}$$

The tedious formulae for t_i^k and x_i^k as the functions of the OBEP parameters m_α , g_α^2 and Λ_α are given in Appendix.

It is easy now to calculate all the necessary quantities using formulae from the papers [1,2]. As noted earlier we adjust the values of g_π^2 and g_σ^2 for the effective interaction in nuclear medium to the empirical nuclear matter values of the binding energy per particle and equilibrium density. The correct quantities $E_b/A \cong 16$ MeV and $\rho_0 \cong 0.16$ fm^{-3} are arrived at $g_\pi^2 = 1.8 - 1.9$ and $g_\sigma^2 = 5.3 - 5.4$ and these constants (together with other data from Tab. 2.1) we used further for the calculations of real components of central optical potential $V^{IS}(E)$ and $V^{IV}(E)$.

2.1.3 The KRI 2000 optical potential

The following expressions for the components $V_0(E)$ and $V_1(E)$ of the formula (2.2) have been obtained in this way:

$$V_0(E) = (48.5 - 0.22\,E)\ MeV\ ; \qquad V_1(E) = (-50.0 + 0.18\,E)\ MeV\ . \tag{2.12}$$

Comparison of the potentials obtained according (2.2) and (2.12) with the Young [3], Madland [4], and Konshin [5] potentials as well as results of test calculations showed that parameters of $V_0(E)$ have to be modified. The best description of the experimental data for integrated observables (proton reaction and neutron total cross sections) was obtained for the form of $ReV_C(E)$ as follows:

$$\begin{aligned} ReV_C(E) &= 49.8 - 0.29E + 0.0005E^2 \ \pm \alpha\,(-50.0 + 0.18E)\,, \qquad 10 \le E \le 100\ \text{МэВ};\\ &= 105.5\,[1 - 0.1625\ \ln E]\ \pm \alpha\,(-50.0 + 0.18E)\,, \qquad 100 \le E \le 200\ \text{МэВ}. \end{aligned} \tag{2.13}$$

The complete microscopic estimation of the imaginary part of the potential, W(E), in a wide energy and target mass ranges is at present still impossible. However one can expect that the isovector component $W^{IV}(E)$ which defines difference of the absorption potential for neutron and proton entrance channels are related to the isoscalar component $W^{IS}(E)$ similarly the relation of ReV_C^{IV} and ReV^{IS}.It means that difference in absorption for neutron and proton potentials is proportional to the difference in the 'refraction' because both are caused by the difference of the exchange NN potentials for the incident neutron and proton interaction with the neutron excess of target nucleus. This assumption is in a qualitative accordance with the rough evaluations of the optical potential components carried out on the base of the momentum approximation [11] and is exact in general for any "sufficiently short range" potential.

Taking into consideration that the best results of the neutron cross section calculations for the energy range of interest and the actinide target nuclei are obtained using Konshin parameters [5] for the imaginary and spin-orbit parts of the potential we have chosen the imaginary potential with isovector component in such a way to get parameters for neutrons close to [5].

With standard notations we will have optical potential (is referred to KRI 2000) as follows:

$$\begin{aligned} U(r,E) = &- V_r(E)\,f_v(r) - i\left[W_v(E)\,f_{wv}(r) - 4a_d W_d(E)\frac{d\,f_{wd}(r)}{dr}\right] - \\ &\left(\frac{\hbar}{m_\pi c}\right)^2 V_{so}(E)\,\frac{1}{r}\frac{d\,f_{so}(r)}{dr}\,\vec{l}\cdot\vec{s} + \Delta V_c\ , \end{aligned} \tag{2.14}$$

where $f_i(r)$ is the Woods-Saxon radial form factors, $f_i(r) = \{1 + exp[(r - R_i)/a_i]\}^{-1}$, $R_i = r_i A^{1/3}$; ΔV_c is the Coulomb energy, $\Delta V_c = 0.4\ Z/A^{1/3}$;

$$\begin{aligned} V_r(E) &= 48.6 - 0.29E + 0.00054E^2 \mp 0.25(50.0 - 0.18E)\eta, \qquad E < 100\,MeV,\\ &= 100.0(1 - 0.1625\ln E) \mp 0.25(50.0 - 0.18E)\eta, \qquad 100 \le E < 200\,MeV,\\ r_r &= 1.26\ ,\ a_r = 0.626\ ;\\ W_v(E) &= 1 + \frac{10.0}{1 + \exp[(51.0 - E)/10]} \mp 4\eta, \qquad E < 80\,MeV,\\ &= 10.66 + 6.5\ln(E/80) \mp 4\eta, \qquad 80 \le E < 200\,MeV,\\ r_{wv} &= 1.20\ ,\ a_{wv} = 0.626\ ; \end{aligned} \tag{2.15}$$

$$\begin{aligned} W_d(E) &= 7.1 - 0.05(E - 10.0)^2 \mp (1.55 - 0.08\ln E)\eta, \qquad E < 10\,MeV,\\ &= (8.88 \mp 6.06\eta)\left\{1 - \frac{1}{1 + \exp[(40.0 - E)/15]}\right\}, \qquad E \ge 10\,MeV, \end{aligned}$$

$r_{wd} = 1.26$, $a_{wd} = 0.535$; $V_{so}(E) = 7.5$, $r_{so} = 1.2$, $a_{so} = 0.5$.

Here radius, r_i, and diffuseness, a_i, are given in units of fm ; the upper (low) sign corresponds to a neutron (proton) entrance channel; $\eta \equiv 1 - 2Z/A$.

The KRI 2000 potential (2.14), (2.15) has been employed in the optical cross section calculations within the framework of the ISTC Project #964. The reaction cross section calculations have been carried out for 60 transactinides (from ^{227}Ac to ^{253}Fm) and nuclei of Pb-Bi region in the energy range of the neutrons 1 - 220 MeV, and protons 5 – 220 MeV (the energy point numbers are 156, and 142, respectively). The results have been presented as the data library and their applications in the fission cross section calculations have been discussed in the reports [12].

2.1.4 The KRI 2004 parametrization

Extension of the beam energy range up to few GeV needs some modification of the parameterization (2.15). Namely, potentials have been simplified slightly;, energy dependence similar to ReV$_C$ (E) has been included in the spin-orbit part; the unphysical linear functions (which are convenient in a narrow energy range) have been replaced by the exponential (or logarithmical) dependences in the spirit of the Koning-Delaroche global potential [13]; some additional fit has been carried out to the available experimental data for the projectile energy up to 1 GeV. Note that these modifications practically have no influence on the reaction cross sections calculated for the energy region below 200 MeV (Sect 2.1.3).

The extended parameterization (KRI 2004) has the following form:

$$\begin{aligned} V_r(E) &= (48.65 \mp 15.22\eta)(1 - 0.0052E), && 10 < E \le 80\ MeV, \\ &= (62.78 \mp 16.16\eta)\exp(-E/100), && 80 < E \le 1000\ MeV, \\ r_r &= 1.26,\ a_r = 0.626; && \\ W_v(E) &= 1 + \frac{10.0}{1 + \exp\left[(51.0 - E)/10\right]} \mp 4\eta, && 10 < E \le 80\ MeV, \\ &= 10.658 + 6.5\ln(E/80) \mp 4\eta, && 80 < E \le 1000\ MeV, \\ r_{wv} &= 1.20,\ a_{wv} = 0.666; && \qquad (2.16) \\ W_d(E) &= (8.88 \mp 6.06\eta)\left\{1 - \frac{1}{1 + \exp\left[(40.0 - E)/15\right]}\right\}, && E \ge 10\,MeV, \\ r_{wd} &= 1.26,\ a_{wd} = 0.535; && \\ V_{so}(E) &= 10.72\exp(-E/160),\quad r_{so} = 1.20,\quad a_{so} = 0.500. && \end{aligned}$$

The different components of the optical model potential (2.14) and (2.16) and their energy dependence are shown in Fig. 2.1.1. The comparison of the experimental and calculated neutron total (Figs. 2.1.2, 2.1.4 and 2.1.5) and proton reaction (Figs. 2.1.3 and 2.1.6) cross-sections has been used for the parameter definitions. The best fit was obtained with parameters (2.16) for target nuclei ^{238}U and ^{242}Pu while for the case of Pb target it was necessary to increase the diffuseness parameters up to $a_r = 0.65$ and $a_{wv} = 0.699$, that is quite explicable for such a highly loose system as a double-magic nucleus plus incident nucleon.

The angular distribution of elastically scattered particles for Pb, Bi, and U targets are shown in the Fig. 2.1.7-2.1.10. Experimental data are taken from library [57] which is off-line prototype of the EXFOR library. The results of angular distribution analysis confirm that developed in the frame of ISTC project#2524 optical model parameter set KRI2004 is rather reliable for the description of i) total cross sections, ii) reaction cross sections and iii) nucleon angular distributions of elastic scattering.

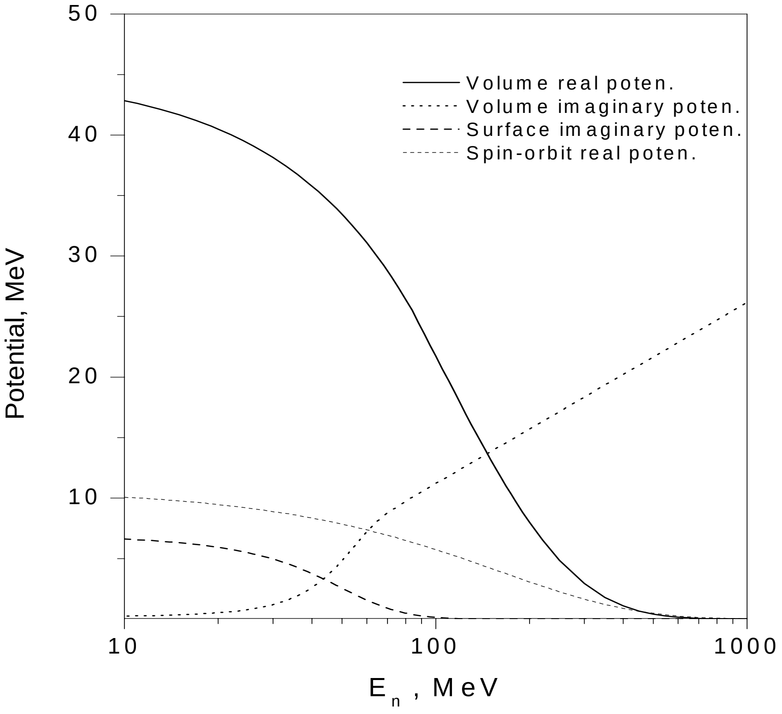


Fig. 2.1.1. Different components of the KRI 2004 optical model potential.

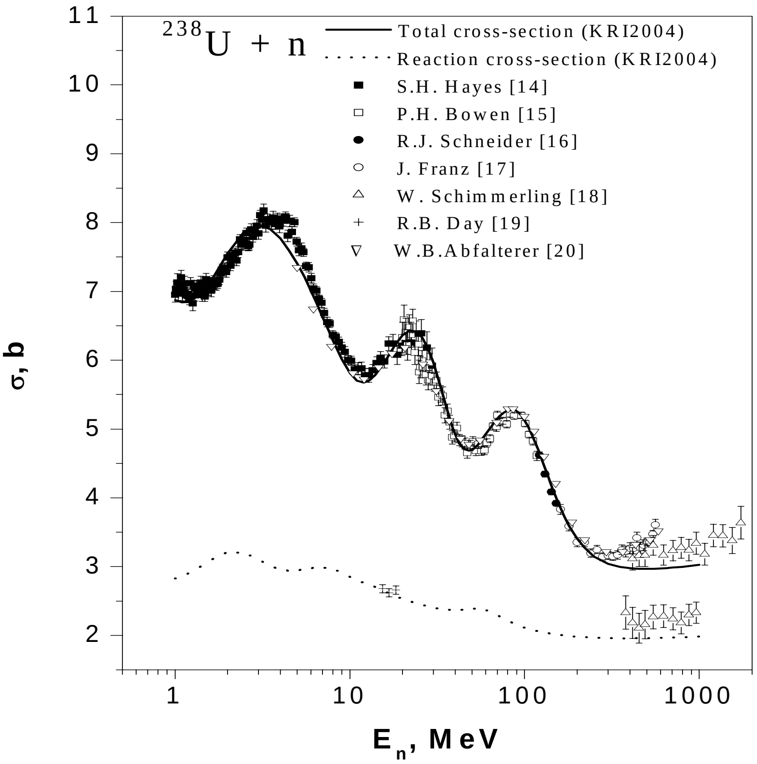


Fig. 2.1.2. Comparison of the experimental and calculated total neutron cross sections.

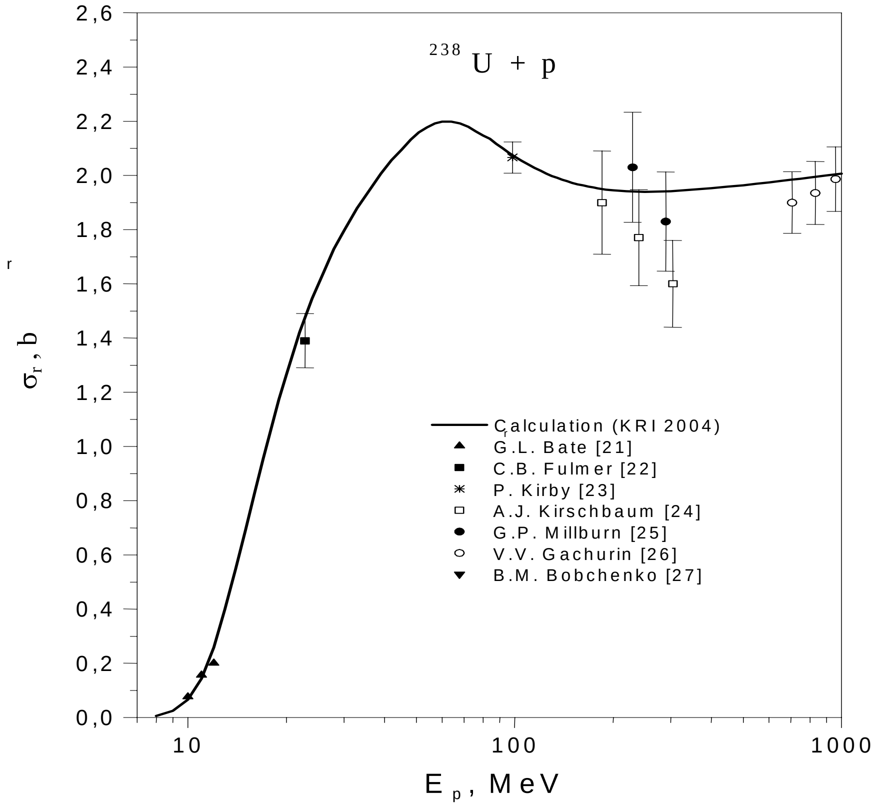


Fig. 2.1.3. Comparison of the experimental and calculated proton reaction cross sections.

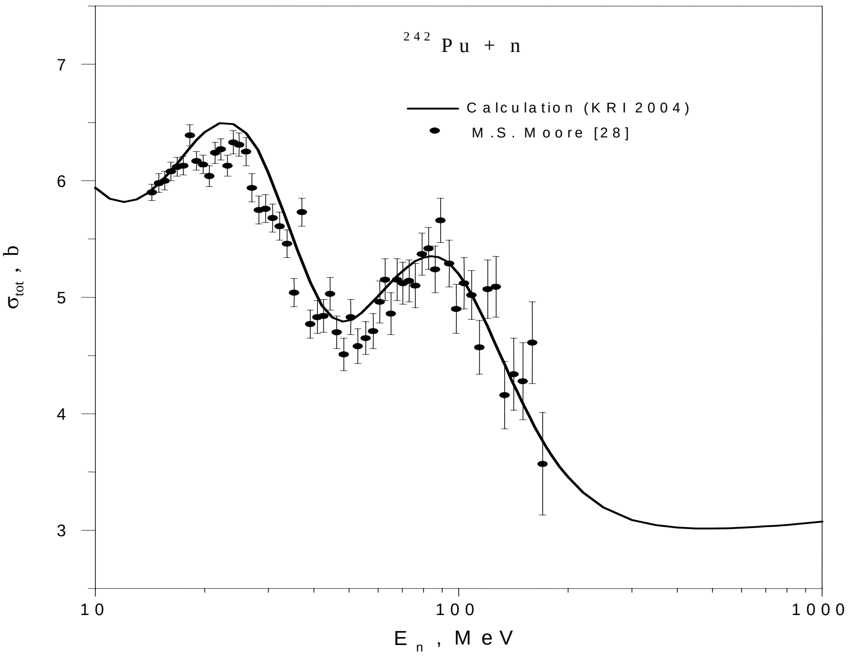


Fig. 2.1.4. Comparison of the experimental and calculated neutron total cross sections.

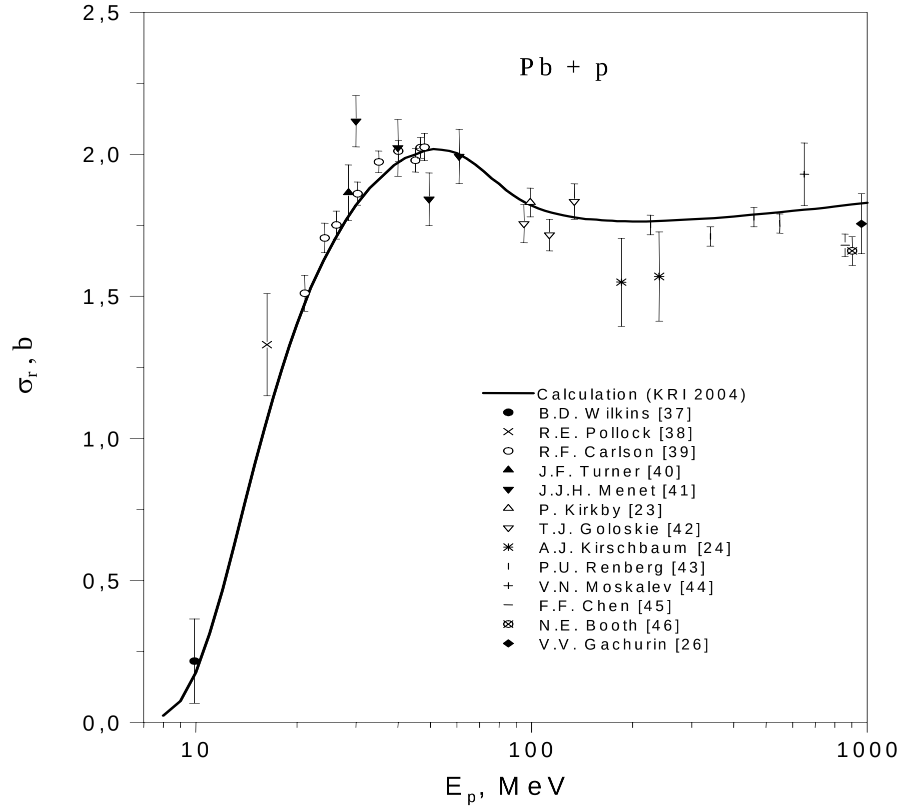


Fig. 2.1.5. Comparison of the experimental and calculated total and reaction neutron cross sections.

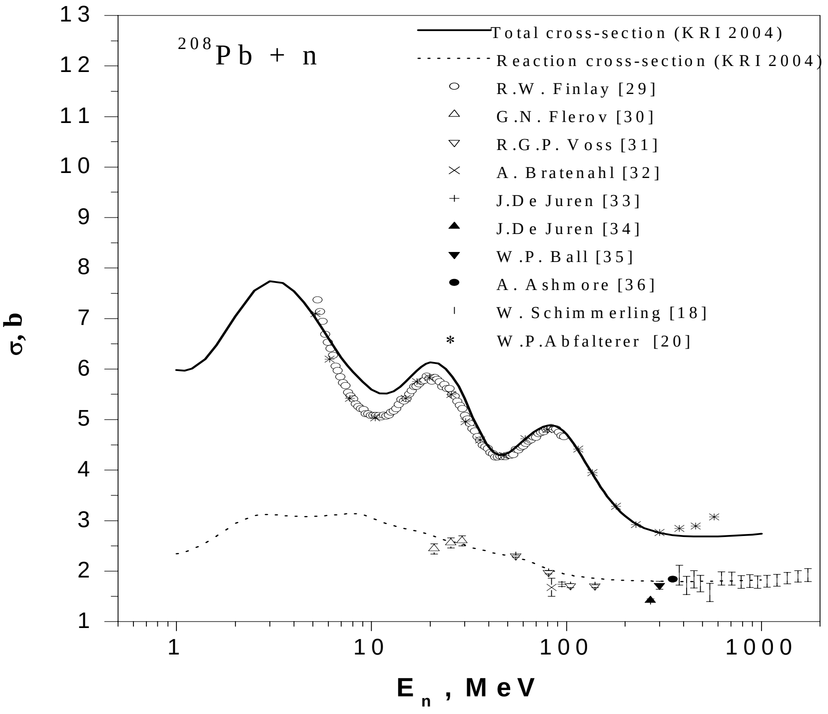


Fig. 2.1.6. Comparison of the experimental and calculated proton reaction cross sections.

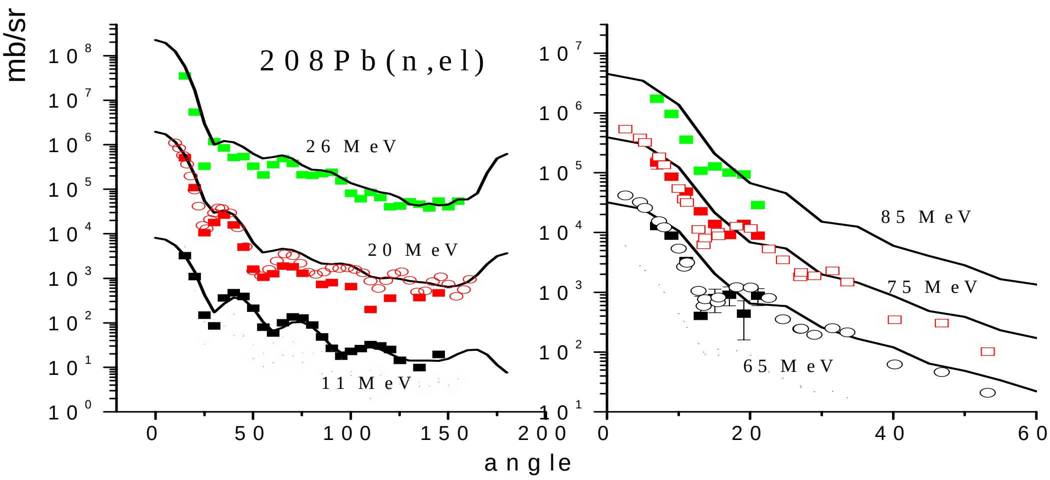


Fig. 2.1.7. Angular distributions of the neutron elastic scattering on 208Pb for projectile energies from 11 MeV up to 85 MeV. The symbols are the experimental data, the lines are the results of optical model calculations. Each upper curve are multiplied on factor 100.

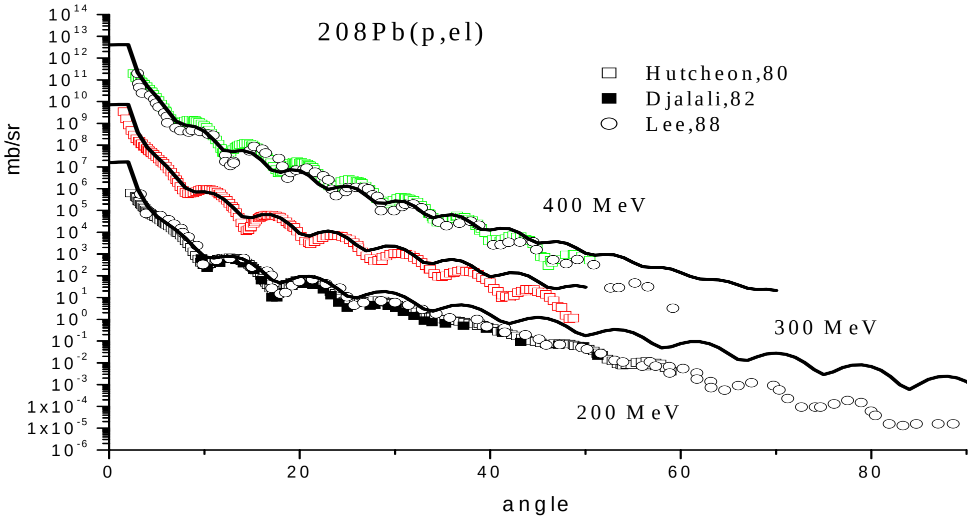


Fig. 2.1.8. Angular distributions of the proton elastic scattering on 208Pb for projectile energies 200, 300 and 400 MeV. The symbols are the experimental data, the lines are the results of optical model calculations. Each upper curve are multiplied on factor 100.

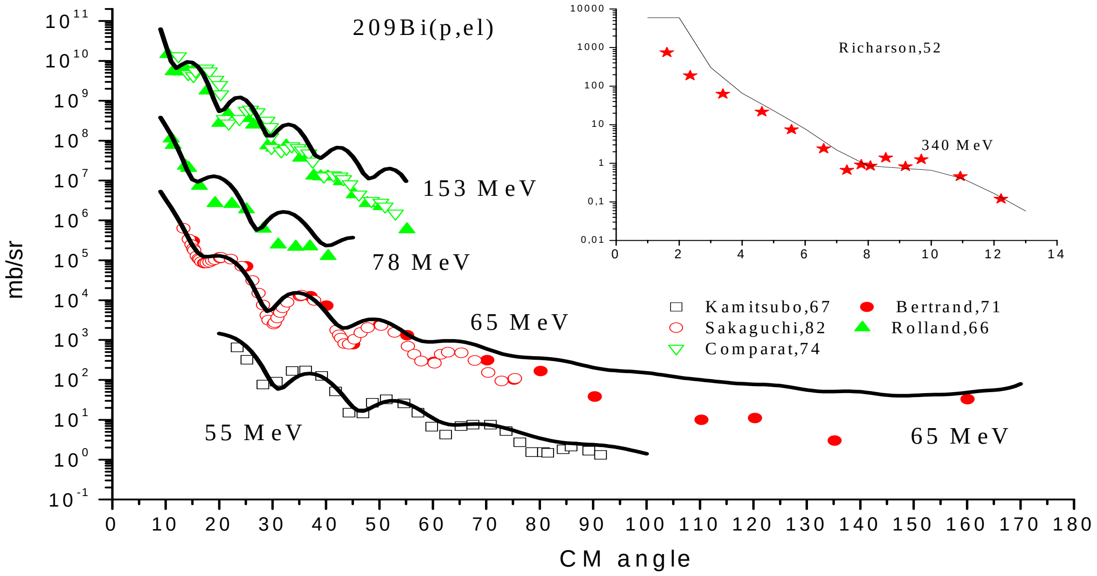


Fig. 2.1.9. Angular distributions of the proton elastic scattering on 209Bi for projectile energies from 55 to 340 MeV. The symbols are the experimental data, the lines are the results of optical model calculations. Each upper curve are multiplied on factor 100.

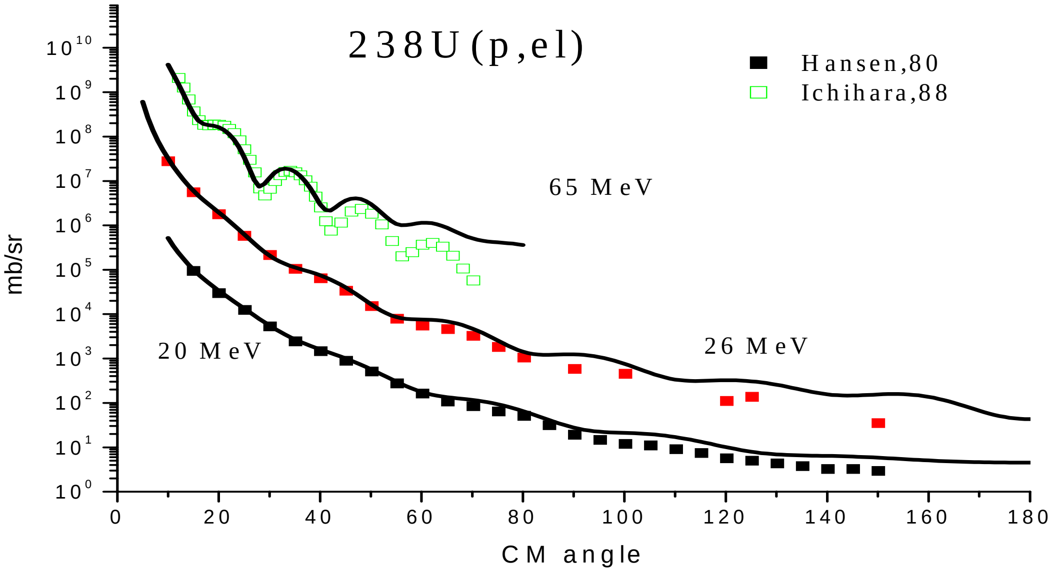


Fig. 2.1.10. Angular distributions of the proton elastic scattering on 238U for projectile energies for 20, 26 and 65 MeV. The symbols are the experimental data, the lines are the results of optical model calculations. Each upper curve are multiplied on factor 100.

2.1.5 The optical model at relativistic energies

The standard optical model of the nuclear reactions can be used up to about 200 MeV without appreciable difficulties due to relativistic effects. The analysis of nucleon-nucleus interactions at relativistic energies in terms of an optical model raises the problem of the generalization of nonrelativistic formalism based on the Schrödinger equation. The account of relativistic kinematics does not cause any difficulties (it is made, in particular, in the ECIS code). Here we shall discuss relativistic corrections which are necessary for inclusion in usual nonrelativistic formalism of the optical model.

Following the Elton paper [47] we shall assume that the motion of the target in the c. m. frame of reference can still be treated nonrelativistically and that the optical potential V can be taken as a scalar function in this frame of reference. The question then arises whether it (*i.e.* V) could be treated as the fourth component of a Lorentz vector or as a Lorentz scalar. We shall refer to these two cases as (v) and (s), correspondingly.

Starting from the Dirac relativistic wave equation in free space, the equation of a particle (with spin $S = 1/2$) in a potential V is then obtained by either of the following replacements [48]:

$$E \rightarrow E - V \qquad \text{(v)}, \tag{2.17}$$

$$M \rightarrow M + V \qquad \text{(s)}, \tag{2.18}$$

Here the signs have been chosen in such a manner that in any case the equation transforms to the nonrelativistic Schrödinger equation in the low-energy limit (the Dirac equation in the Schrödinger form).

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We constrain ourselves to a central field and consider case (v) firstly. The two components of the radial wavefunction, $r^{-1}F(r)$ and $r^{-1}G(r)$ then satisfy the equations [48]

$$(E + M - V)\, F - \frac{dG}{dr} - \frac{\kappa}{r}\, G = 0, \tag{2.19}$$

$$(E - M - V)\, G + \frac{dF}{dr} - \frac{\kappa}{r}\, F = 0, \tag{2.20}$$

where $|\kappa| = j + 1/2$, j is the total angular momentum, and we have kept $\hbar = c = 1$. We now eliminate $F(r)$ and suppose [49] that

$$G = \alpha^{1/2}\, g, \qquad \alpha = E + M - V. \tag{2.21}$$

After some transformations we will have the equation

$$\frac{d^2 g}{dr^2} + \left[k^2 - \frac{\kappa(\kappa+1)}{r^2} - U_\kappa(r) \right] g = 0, \tag{2.22}$$

where

$$k^2 = E^2 - M^2 \tag{2.23}$$

and

$$U_\kappa(r) = 2EV - V^2 + \frac{\kappa}{r}\frac{\alpha'}{\alpha} + \frac{3}{4}\frac{\alpha'^2}{\alpha^2} - \frac{1}{2}\frac{\alpha''}{\alpha} \qquad \text{(v)} . \qquad (2.24)$$

Here as r increases $\alpha \to E + M$ which is constant. Hence g and G have the same asymptotic form and so describe the same scattering process. It is clearly that eq. (2.22) is equivalent to a Schrödinger equation representing nonrelativistic scattering by the potential (2.24).

For case (s), we have to use (2.18) instead of (2.17). Hence the only change is the sign of V in (2.19) which has to be changed. We then derive the same equation (2.22) but must replace (2.24) by

$$U_\kappa(r) = 2MV - V^2 + \frac{\kappa}{r}\frac{\alpha'}{\alpha} + \frac{3}{4}\frac{\alpha'^2}{\alpha^2} - \frac{1}{2}\frac{\alpha''}{\alpha} \qquad \text{(s)} . \qquad (2.25)$$

Taking into account that

$$V << E , \quad V' << kV, \quad V'' << kV' << k^2 V . \qquad (2.26)$$

we will have

$$\frac{\alpha'}{\alpha} \cong -\frac{V}{E+M} << V, \qquad \frac{\alpha''}{\alpha} \cong -\frac{V'}{E+M} << EV . \qquad (2.27)$$

Further taking into account that κ is the eigenvalue of the operator $L\cdot\sigma + 1$ [48] the equations (2.26) and (2.27) could be reduced to

$$U_\kappa(r) = 2EV + \frac{1}{E+M}\frac{1}{r}\frac{dV}{dr}\left(\vec{L}\vec{\sigma}\right) \qquad \text{(v)} , \qquad (2.28)$$

$$U_\kappa(r) = 2MV + \frac{1}{E+M}\frac{1}{r}\frac{dV}{dr}\left(\vec{L}\vec{\sigma}\right) \qquad \text{(s)} . \qquad (2.29)$$

Note that for optical potentials V' is different from zero in the surface region only and it is possible to replace $L\cdot\sigma + 1$ by $L\cdot\sigma$ since the rest is only a small correction to the leading potential term.

It is clear from (2.28) and (2.29) that the two cases (v) and (s) differ essentially only in the strength of the potential V that should be fitted to the experimental data, and we are free to use any form.

However in practical calculations it could be important which kind of model for energy dependence should be used first in the fitting procedure. Thus, Madland and Sierk [50] fitted the experimental data using the following replacement

$$V \;\to\; \gamma V , \qquad (2.30)$$

where

$$\gamma = 1 + E/(E + 2M). \tag{2.31}$$

To obtain the multiplier γ in the form (2.31) they have used the Dirac equation in the mean field approximation where the nucleon (meson) fields are replaced by their expectation values and have taken a spherically symmetric complex Lorentz scalar potential V_S corresponding to the (fictious) σ meson field and a spherically symmetric complex Lorentz vector potential V_V (time-like component of Lorentz four-vector) corresponding to the ω meson field. With this scalar-vector interaction the Dirac equation has the form [4]

$$[\, \alpha\cdot p + \beta\cdot(M + V_S)]\, \psi = [E - V_V\,]\, \psi\, . \tag{2.32}$$

We have used the one-boson exchange potential which provides the realistic description of the N-N interaction and N-N scattering data. For futher model development it is necessary to find out to what kind of relativistic energy factor in optical potential this microscopic approach may lead and now we continue researches in this direction.

2.1.6 Code ECIS

For spherical nuclei in MCFx code the possibility to compute transmission coefficients with well-known code SCAT2 [51] exists. However, heavy fissioning nuclei are strongly deformed in their ground state and show the bands of collective lowest excited states. Coupling with these states modifies the wave function of interacting system. The generalized optical model has been developed for these systems as it was formulated in the coupled channel method [52,53]. On the base of this method the code ECIS [54] has been developed by Raynal et al., which at present is considered as a very successful implementation of the coupled channel method for cross-sections calculations in the wide energy region of projectiles [55].

The ECIS94 has been chosen in our work for entrance channel calculations. The code allows computing of total reaction cross-section, which contains both compound and direct reactions. In the framework of coupled channel method there is possibility to obtain cross-sections of collective states, too. Subtracting them from the total reaction cross-sections one can obtain the reaction (absorption) cross-section of projectile. We modified the code to have possibility of data file on reaction cross-section as a calculations result.

The coupled channel method requires so-called scheme of coupling of low collective levels. The rotation model has been used in our work and only levels from the ground state rotation band taken into consideration. To reduce computation time the coupling scheme was limited by 3 levels (ground and 2 lowest rotation levels). As control calculations show the further increase of coupling levels number modify results less than 1 %. The RIPL library [56] has been used for the level parameters.

In the ECIS code there is option to take into account the deformation of target nucleus. The quadrupole+hexadecapole deformations used to be considered. But as our test calculations shown the effect of hexadecapole deformations is negligible in our case (variation of cross-sections less 1%) and variations of quadropole deformation β_2 from 0.2 to 0.3 modify calculations results less that 5%. So, in our calculations we fixed $\beta_2 = 0.26$.

The software for input data preprocessing for ECIS code has been specially developed to simplify the calculation management. Up to 16 parameters of different optical model potentials may be updated for any chosen energy grid.

Appendix to sect. 2.1

The central forces:

$$t_0^c = (C_1^{c,s} - C_1^{c,s\tau}) - (C_1^{c,v} - C_1^{c,v\tau}) ; \qquad x_0^c = 2\,(C_1^{c,v\tau} - C_1^{c,s\tau}) / t_0^c ;$$

$$t_1^c = 1/3\,[(C_2^{c,v} - C_2^{c,v\tau}) - (C_2^{c,s} - C_2^{c,s\tau})] ; \qquad x_1^c = 2/3\,(C_2^{c,s\tau} - C_2^{c,v\tau}) ;$$

$$t_2^c = -\,t_1^c ; \quad x_2^c = x_1^c ; \tag{A1}$$

$$C_1^{c,\alpha} = -\,4\pi\, g_\alpha^2\, \lambda_\alpha^2\, [\, m_\alpha^{-2} - \Lambda_\alpha^{-2}(1 + \lambda_\alpha^{-1})] ;$$

$$C_2^{c,\alpha} = -\,24\,\pi\, g_\alpha^2\, \lambda_\alpha^2\, [\, m_\alpha^{-4} - \Lambda_\alpha^{-4}(1 + 2\lambda_\alpha^{-1})] ; \qquad \lambda_\alpha \equiv \Lambda_\alpha^2/(\Lambda_\alpha^2 - m_\alpha^2) .$$

The central force corrections:

$$t_1^\nabla = a^2/12\,[\, C_2^{\nabla,s} - C_2^{\nabla,s\tau} + 2C_2^{\nabla,v} - 2(1 + f/g)\, C_2^{\nabla,v\tau}\,] ;$$

$$x_1^\nabla = -\,a^2/6\,[\, C_2^{\nabla,s\tau} + 2(1 + f/g)\, C_2^{\nabla,v\tau}\,] ; \quad t_2^\nabla = -\,t_1^\nabla ; \quad x_2^\nabla = x_1^\nabla ; \tag{A2}$$

$$C_2^{\nabla,\alpha} = -\,24\pi\, g_\alpha^2\, m_\alpha^{-2} .$$

The spin exchange forces:

$$t_1^\sigma = -\,a^2/36\,[2C_2^{\sigma,v} + C_2^{\sigma,p} + 6(1 + f/g)^2\, C_2^{\sigma,v\tau} + 3C_2^{\sigma,p\tau}] ;$$

$$x_1^\sigma = a^2/18\,(2C_2^{\sigma,v} + C_2^{\sigma,p}) ;$$

$$t_2^\sigma = -\,a^2/36\,[10(1 + f/g)^2\, C_2^{\sigma,v\tau} + 5C_2^{\sigma,p\tau} - 2C_2^{\sigma,v} - C_2^{\sigma,p}\,] ; \tag{A3}$$

$$x_2^\sigma = -\,a^2/18\,[2C_2^{\sigma,v} + C_2^{\sigma,p} - 4(1 + f/g)^2\, C_2^{\sigma,v\tau} - 2C_2^{\sigma,p\tau}] ;$$

$$C_2^{\sigma,\alpha} = -\,24\pi\, g_\alpha^2\, m_\alpha^{-2} .$$

The tensor forces:

$$t_0^t = -\,a^2/12\,[C_1^{t,p} + 3C_1^{t,p\tau} - 3(1 + f/g)^2\, C_1^{t,v\tau} - C_1^{t,v}] ;$$

$$x_0^t = 2\,(C_1^{t,v} - C_1^{t,p})\,/[\, C_1^{t,p} + 3C_1^{t,p\tau} - 3(1 + f/g)^2\, C_1^{t,v\tau} - C_1^{t,v}] ;$$

$$C_1^{t,\alpha} = -\,12\pi\, g_\alpha^2\, \lambda_\alpha^2\, [\ln(\Lambda_\alpha\, m_\alpha^{-1}) - 1/2\lambda_\alpha^{-1})] ;$$

$$t_1^t = a^2/36\,[C_2^{t,p} + 3C_2^{t,p\tau} - 3(1 + f/g)^2\, C_2^{t,v\tau} - C_2^{t,v}] ; \tag{A4}$$

$$x_1^c = a^2/18\,(C_2^{t,v} - C_2^{t,p}) ;$$

$$t_2^t = -\,a^2/36\,[C_2^{t,p} + 5(1 + f/g)^2\, C_2^{t,v\tau} - 5C_2^{t,p\tau} - C_2^{t,v}] ;$$

$$x_2^t = -\,a^2/18\,[C_2^{t,v} + 2C_2^{t,p\tau} - 2(1 + f/g)^2\, C_2^{t,v\tau} - C_2^{t,p}];$$

$$C_2^{\sigma,\alpha} = -\,60\pi\, g_\alpha^2\, m_\alpha^{-2} .$$

The p^2 dependent forces:

$$t_1^c = -a^2 [(C_1^{\Delta, v} - C_1^{\Delta, v\tau}) + (C_1^{\Delta, s} - C_1^{\Delta, s\tau})] ;$$

$$x_1^c = 2a^2 (C_1^{\Delta, s\tau} - C_1^{\Delta, v\tau}) ; \qquad \text{(A5)}$$

$$C_1^{\Delta, \alpha} = C_1^{c, \alpha} .$$

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2.2 Intranuclear cascade and preequilibrium emission models and codes for the reactions with nucleons of intermediate energies

2.2.1 Introduction

The recognized approach [1] to calculation of nuclear reaction characteristics for nucleons of transitional (20 - 200 MeV) and intermediate (200 - 1000 MeV) energies is the method where the mechanism of nuclear reaction includes three stages. At the first stage reaction is defined by nucleon-nucleon interactions (intranuclear cascade "INC") where the projectile nucleon may scatters on nucleons of a nucleus some times before its absorption or escape. The excited residual nucleus formed after cascade stage may be in various particle-hole configurations and at different excitation energies. The further development of process in time is described by the exciton model of preequilibrium decay. Last stage of reaction is a decay of an equilibrium nucleus (statistical model) including evaporation of particles, fission etc.

The role of different stages strongly depends on the energy of projectile particle and mass of the target. At low energies the basic contribution to reaction cross section comes from an equilibrium processes in the compound nucleus since incoming nucleon can not initiate any cascade or preequilibrium emission. As the projectile energy increases the contribution of preequilibrium processes increases too and already at energies 15-20 MeV their contribution in cross section becomes to tens per cents. At these energies the contribution of cascade processes is still negligible. All three stages of the reaction are realized at the energies higher then 50 - 70 MeV.

One of difficulties of the approach mentioned above is the correct account of the nucleon emission during an establishment of statistical equilibrium in composite system. Earlier [2] we used for this purpose two models: exciton model (EM) [3] and the hybrid model with a Monte-Carlo method (HMS) [4].

A practical disadvantage of the classical exciton model is the restriction of calculation by emission of one preequilibrium particle only. At the same time, as analysis of calculation results of a cascade stage shows, excitation energies of residual nucleus are sufficient for a sequential emission of several preequilibrium particles. Therefore the EM overestimates excitation energies of equilibrium residual nucleus. Key theoretical problem of EM are well-known doubts [5] in validity of application of exciton state density of the high order for a problem of nucleon - nucleon interaction.

The good decision here may be use of the HMS model which provides multiparticle preequilibrium emission and includes two- and three–exciton state densities only. Meshing of configurations in the HMS occurs due to increase of quantity of three– and two-exciton states. Authors [6] wrote that “HMS model might be a good model to introduce into the intranuclear cascade codes (INC) code and would take each post-cascade nucleon … avoiding ambiguity as to exciton number”.

However for introduction of the HMS model in our calculations it was necessary to refuse its basic idea - the initial particle-hole configuration always is two particles and one hole (2p1h). Besides it was frequently impossible to describe actual configurations formed after cascade stage with the help of combinations 2p1h – states only. Really, the cascade nucleon may create, for example, a 9p0h state which cannot be presented through 2p1h. It seems the hybrid model despite of all its appeal is alternative of INC model and can’t be considered as its addition.

For the further improvement of model of composite system transition to statistical equilibrium we have entered an opportunity of calculation multiparticle sequential emission into the exciton model.

In this section the brief description of the modified intranuclear cascade model and computational method of the calculation of the nucleon spectra and yields of residual nuclei during transition of composite system to equilibrium is described. The method is based on statistical model (Monte-Carlo method) of nucleon emission during the process of solution of master equation system of the exciton model [3].

2.2.2 Intranuclear cascade model

The fast direct stage of nucleon-nucleus interaction in the MCFx code is described with the modified Dubna version of intranuclear cascade model [1]. All calculations of intranuclear cascades are performed in the three dimension geometry. The function of nuclear density distribution are described by Fermi distribution with parameters taken from the experimental data on electron-nucleus scattering. The target nucleus is divided by concentric spheres on 7 zones where the nuclear density is assumed as a constant. The diffuseness of nuclear density and potential edge is taken into account. For intranuclear collisions of nucleons the Pauli principle forbids the collision with energy of secondary particles less the Fermi energy.

The main condition of intranuclear cascade model applicability is the smallness of the length of de Broglie waves for all interacted particles; the wave length must be less than average distance between intranuclear nucleons ~ 1 fm. In this case the picture of interaction is approximately the semiclassical one and it is possible to say about the particle trajectories and two-particle collisions inside nucleus. This condition restricts the energy region of incident particles as $E \geq \sim 50$ MeV. Such a limitation is a significant point of the model; however, in order to improve it the going out from the frameworks of intranuclear cascade is necessary with the description of reaction mechanism in the terms of more strict quantum-statistical approach. Practically the lowest limit of intranuclear cascade applicability can be established by the analysis of calculation results in each given case.

The results of our calculations for main characteristics of residual nuclei formed after cascade stage are presented in Figs. 2.2.1-2.2.4 for ^{238}U irradiation in the transitive energy region 20-200 MeV. The yields of residual nuclei are presented in Figs. 2.2.1-2.2.2 as for neutrons and protons in the entrance channel. The results presented show that at low energies almost all incident particles are absorbed by target nucleus with formation of compound nucleus. For higher energies the yield of compound nucleus falls down significantly. The maximal yield in this case corresponds to the escape of one neutron or proton from target nucleus.

The configuration yields in the direct reactions ^{238}U(n,2n)^{237}U and ^{238}U(n,n’)^{238}U with formation of ^{237}U and ^{238}U in two particle-hole configurations are shown in Figs. 2.2.3-2.2.4 as a function of excitation energy for given residual nucleus. As it can be seen the configurations with low exciton number (p+h) have significantly higher yield as compared with configurations characterized by large exciton numbers. Nevertheless, these configurations have a similar part in the fission cross-sections due to high excitation energies of high-exciton configurations

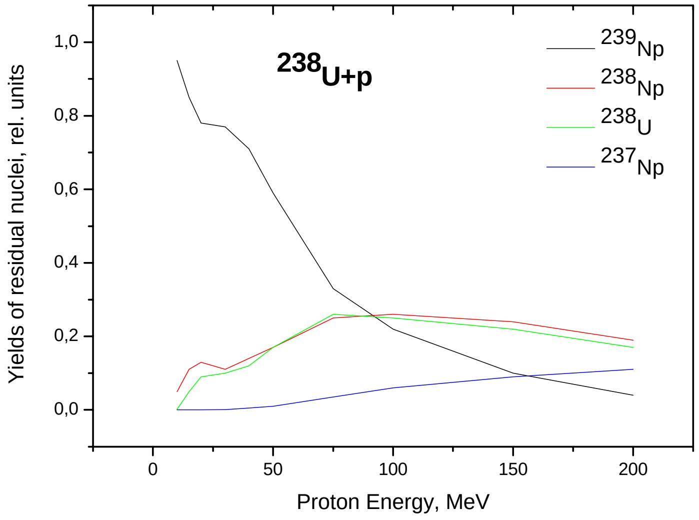

Fig.2.2.1 The yield of residual nuclei after cascade stage for proton-induced reaction.

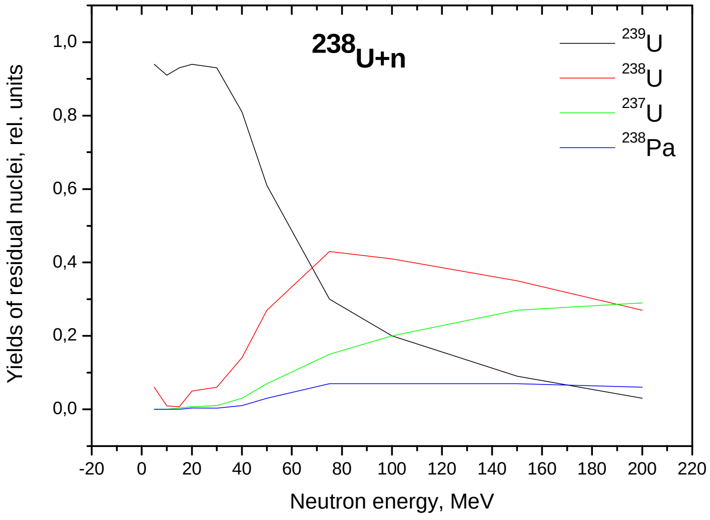

Fig. 2.2.2. The same as for Fig.2.2.1 but for neutron-induced reaction.

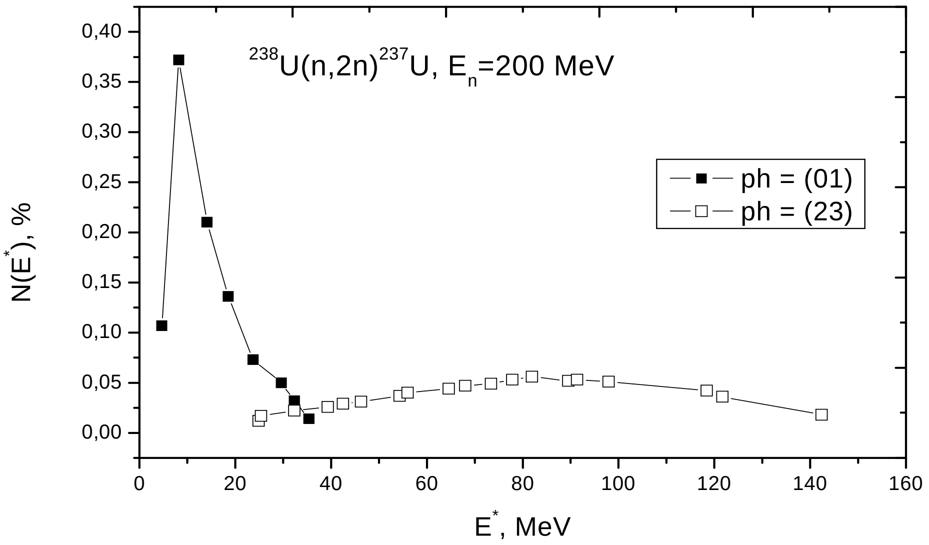

Fig. 2.2.3 The configuration yields in the direct reaction (n,2n) as a function of excitation energy.

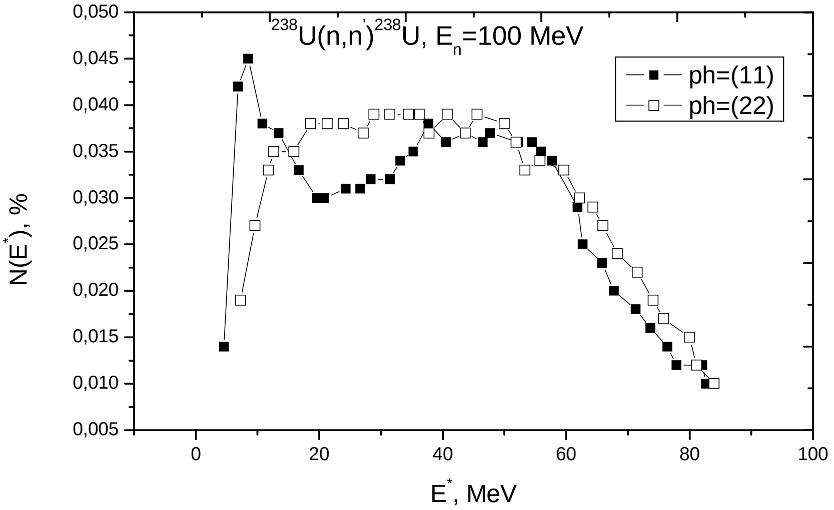

Fig. 2.2.4 The same as for Fig.2.2.3 but for direct reaction (n,n')

The new module for intranuclear cascade calculations has been written down with the results acquisition in the output file. The necessary accuracy is achieved when 1 000 000 histories are taken into account. The configurations with yields more 1 % only were taken into consideration.

These kind of results serve as an input data for the calculations of preequilibrium and equilibrium decay of excited nuclei; for each configuration it is necessary to carried out the calculations of particle emission and fission cross-sections which further are summed with corresponding weights.

2.2.2 Main formulas of MCP (Monte-Carlo Preequilibrium)

The emitted nucleon spectrum in model [6] is mainly determined by two quantities - density of particle-hole states ω(p,h,E) with number of particles p, number of holes h and excitation energy E of composite system as well as matrix elements of two-partial interaction. Thus the nucleon may be emitted at different stages of motion to equilibrium state, i.e. from states with different number of particles p and hole h. Time development of process is governed by system of the master equations:

$$\frac{dP(n,t)}{dt} = P(n-2,t)\cdot\lambda_+(n-2,E) + P(n+2,t)\cdot\lambda_-(n+2,E)$$
$$-P(n,t)\cdot\left[\lambda_+(n,E) + \lambda_-(n,E) + \sum_\nu L_\nu(n,E)\right], \tag{2.33}$$

where λ_+, λ_- are transition probabilities of a nucleus to more complicated or more simple state, correspondingly, L is the probability of a particle emission, P is the population probability of configuration n=p+h at the moment of time t, E is the excitation energy of composite system. These quantities may be calculated as follows:

$$L_\nu = \int_0^{E-B_\nu} W_\nu(n,E,\varepsilon)d\varepsilon\,, \qquad W_\nu(n,E,\varepsilon) = \frac{2s+1}{\pi^2\hbar^3}\mu_\nu\varepsilon\sigma_\nu(\varepsilon)\frac{\omega(p-1,h,E-B_\nu-\varepsilon)}{\omega(p,h,E)} \tag{2.34}$$

$$\lambda(n,E) = \frac{2\pi}{\hbar}\left|\overline{M}\right|^2\omega(n-\Delta n,E). \tag{2.35}$$

The density of the particle - hole states of an excited nucleus is calculated as a rule under the formula [7]:

$$\omega(p,h,E) = g\frac{[gE - A(p,h)]^{n-1}}{p!h!(p+h-1)!}, A(p,h) = \frac{1}{4}\left(p^2 + h^2 + p + h\right), \tag{2.36}$$

where g is the single particle state density.

The matrix element of interaction was parameterized in [8] in the following way:

$$\left|\overline{M}\right|^2 = K\cdot A^{-3}E^{-1} \tag{2.37}$$

The equations (2.33) are solved numerically. A change of probabilities P(n,t) as a function of the equilibriation time is shown in the Fig 2.2.5.

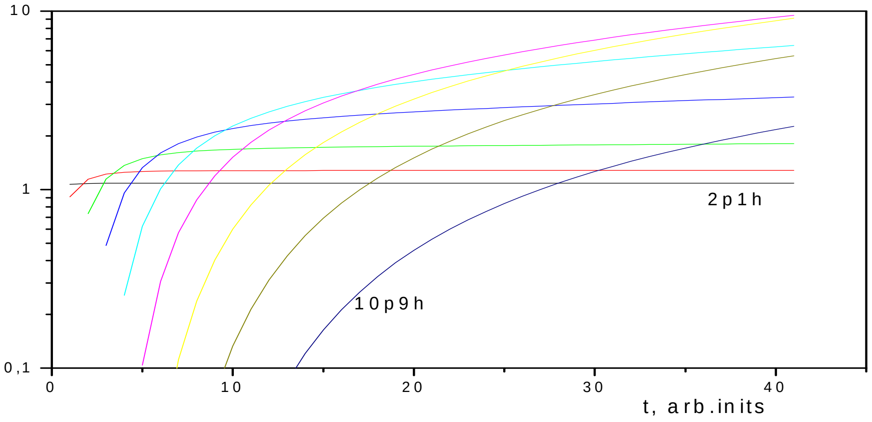

Fig. 2.2.5. Population of quasiparticle configurations as function of equilibriation time. Figures show ph values.

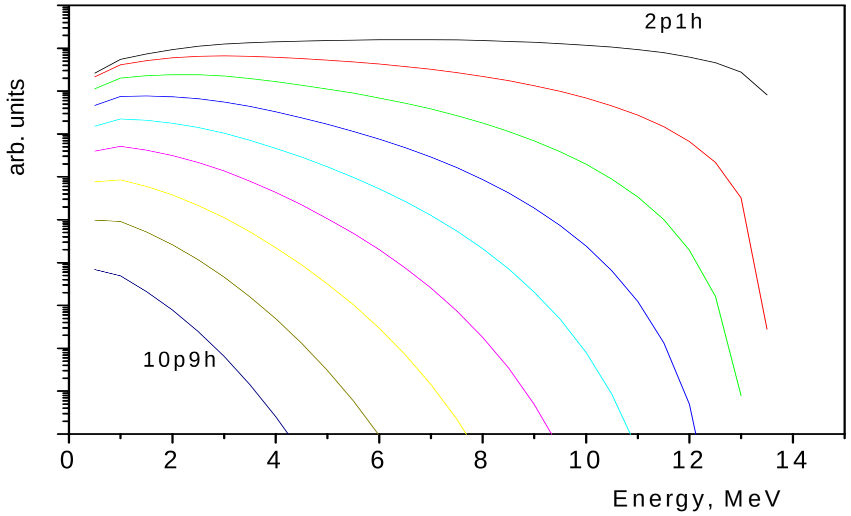

Fig. 2.2.6. Probabilities of preequilibrium neutron emission from various configurations depending on neutron energy. Figures show ph values.

It is possible to see that the more and more complicated configurations are populated during the motion to equilibrium while changes in populations of initial configuration are small. The examples of the calculated probabilities of preequilibrium neutron emission are shown in the Fig. 2.2.6 for different configurations. It can be seen that if the emission of a neutron occurs from initial ph values then the shape of a spectrum is nonequilibrium while with increase of ph quantities the neutron spectra become more and more similar to equilibrium ones. For the 2p1h configuration the spectrum looks like a plateau and for a 10p9h configuration it has the Maxwell shape.

After the solution of the equations (2.33) and calculation of P (n, t) it is possible to calculate the spectra of emitted particles in the following way:

$$S(\varepsilon) = \sum_n \int^{t_0} P(n,t) \cdot W(n,\varepsilon) dt\,, \tag{2.38}$$

where t_0 is the time of equilibration and summation is conducted on all populated configurations. The moment of time t_0 is defined from a requirement

$$\left| \sum_n P(n,t) - \sum_n P(n,t_0) \right| \Big/ \sum_n P(n,t_0) \leq 0.01 \tag{2.39}$$

i.e. the total population does not change in time and therefore the statistical equilibrium was achieved. This requirement is obviously carried out easily because time dependence of population quickly saturates (fig. 2.2.5).

This classical preequilibrium model described above was successfully used for the description of particles spectra from nucleon-induced reactions with energies up to several tens of MeV.

There are several fitting parameters of the model may serve and it causes a confusion and tangle at comparison of results and decreases the predictive opportunities of model inevitably. Therefore it is useful to use only one fitting parameter, for example, K – value in definition of the matrix elements (2.37). Research of the nucleon spectra of charge-exchange reactions for the nuclei in a wide range of mass numbers and projectile energies allows to fix this coefficient.

In the Fig. 2.2.7 some examples of the experimental neutron spectra description for the ^{90}Zr(p,xn) reaction are given at different proton energies. Calculations were carried out with the same parameters of model.

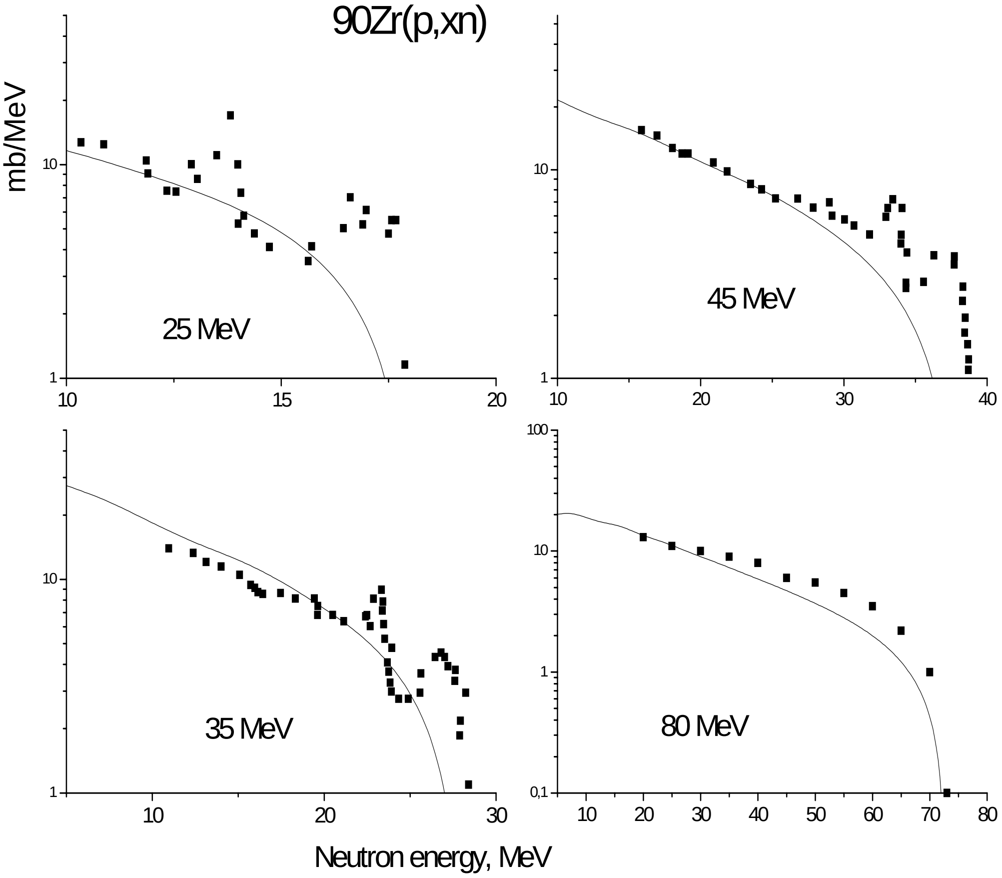

Fig. 2.2.7. Neutron spectra for ^{90}Zr (p, xn) reaction at different proton energies (25, 35, 45 and 80 MeV). The points show experimental data [9], the lines are the calculation results by the exciton model of preequilibrium decay.

For many years of the EM existence numerous attempts of its improvement, criticism and even a failure of its usage are known. One of directions of improvement is already mentioned above hybrid model and its last versions - HMS [5] and DDHMS [6]. In the DDHMS approach the opportunity of calculation of double differential cross sections is implemented using approach based on the conservation of linear moment between incoming nucleon and three quasi-particles excited during thermalization.

The development of exciton model for calculation of light cluster emission is proposed in [10,11]. Introduction of a form-factor of formation of light composite particles (deuterons, tritons and alpha-particles) and the contribution of a mechanism such as pickup has allowed to describe the spectra of the some clusters on nucleus from ^{27}Al up to ^{197}Au for the projectile energies from 29 up to 62 MeV.

The generalized exciton model [12] and its development [13] were proposed for the description of angular distribution of preequilibrium nucleons on the basis of the generalized master-equation. Here the population of n-quasiparticle states at the moment of time t is characterized by additional variable - angle of a preequilibrium nucleon emission. The quasiparticle transition probabilities have the angular dependence proportional to angular dependence of the nucleon - nucleon interactions. In this approach it was possible to describe differential cross sections of neutron inelastic scattering at 14 MeV energy on 34 targets.

The separate components of the EM models were improved too. There were numerous attempts of the modernization of the quasiparticle state density calculation methods. For example, it is proposed [14] to use the energy dependent correction on even-odd effects. Now there are tens (!) various methods of particle - hole configuration density calculations.

Despite of obvious successes in the description of nucleon spectra the EM model application for the calculation of residual equilibrated nucleus population is restricted to rather narrow projectile energy region. Really, at one nucleon emission only one residual nucleus is populated. In its population the populations of all subsequent residual nucleus is taken into account effectively. From the results analysis (Fig. 2.2.6) it is seen that nucleons are emitted mainly from initial configurations, i.e. long before approach of statistical equilibrium. It means that at sufficient excitations of residual composite system which has not reached equilibrium some amount of preequilibrium particles may be still emitted. From this point of view the emitted particle spectrum is the integrated one where all nucleons and, hence, residual nuclei are summed. It is possible to calculate the yields of all residual nuclei only taking into account preequilibrium emission of several successive emitted particles.

2.2.3 Preequilibrium multiparticle emission

The idea of multiparticle preequilibrium emission in the frameworks exciton statistical model was proposed a long time ago [15] but as far as it is known to authors was not realized till now. Its meaning is clear from the previous consideration - after the first nucleon emission to repeat the calculation of equilibration for new composite system etc.

In the proposed scheme of calculation (model MCP) the reaction cross sections for nucleons of the intermediate and high energies at a preequilibrium stage which begins with various initial excitations and configurations, residual nucleus should pass to equilibrium emitting out the nucleons.

1. At the first stage of calculations according to initial excitation energy and initial quasi-particle configuration ph of the first nucleus the list of nucleus which may be formed as a result of nucleon emission and their excitation energies E_{max} is determined. The example of such a list where nuclei with $E_{max} > 0$ are included is given in the table 2.2.1 for ^{90}Zr(p,xn) reaction at E_p=20 MeV. For this reaction at rather low energies of incoming proton the three nucleons may be emitted successively and up to seven residual nuclei may be populated as a result of emission.
2. At the second stage of calculations for all possible nuclei and their excitation energies from 0 up to E_{max} the probabilities of the nucleon emission W(n,E,ε) and the quasiparticle transition probabilities λ(n,E) are calculated. The scale of excitation energies is divided into some of equal segments with a step ΔE which is the same to all nuclei. The lists of the particle-hole configurations are formed so that the number of particles in the first configuration differed from the previous nucleus by the number of emitted nucleons. The given stage is removed from a Monte Carlo cycle to save a time of computing. The further stages are carried out the given number of times (histories).

Table 2.2.1. The list of residual nuclei for ^{90}Zr(p,xn) reaction at E_p=20 MeV. K is the value of emitted nucleons, E_{max} is the maximal energy of a nucleus, B is a binding energy of a nucleon in the given nucleus.

№	K_p	K_n	Z	A	E_{max}, MeV	B_n, MeV	B_p, MeV
1	0	0	41	91	25.16	12.05	5.16
2	0	1	41	90	13.11	10.15	5.08
3	0	2	41	89	2.96	12.71	4.24
4	1	0	40	90	20.00	11.97	8.36
5	1	1	40	89	8.03	9.31	7.86
6	2	0	39	89	11.64	11.47	7.07
7	2	1	39	88	0.17	9.36	6.71
8	3	0	38	88	4.57	11.11	10.62

3. The system of the master-equations is solved. The probabilities are calculated as:

$$P_1 = \frac{\lambda_+(n,E) + \lambda_-(n,E) + \lambda_0(n,E)}{\lambda_+(n,E) + \lambda_-(n,E) + \lambda_0(n,E) + \sum_\nu L_\nu(n,E)} \tag{2.40}$$

- quasiparticle transition probability;

$$P_2 = \frac{L_n(n,E)}{\lambda_+(n,E) + \lambda_-(n,E) + \lambda_0(n,E) + \sum_\nu L_\nu(n,E)} \tag{2.41}$$

- nucleon emission probability.

Random number $x \in (0;1)$ is used to define the type of process. If x < P_1 quasiparticle transition occurs; if P_1 < x < P_1+P_2 a neutron emission and if x > P_1+P_2 a proton emission takes place. At the given stage of the model the emission of the composite particles is not included. After the quasiparticle transition the solution of system the master-equations is prolonged and the composite system moves to equilibrium.

4. After emission of nucleon its energy is defined by the solution of the equation

$$x = \int_0^\varepsilon W(n,E,\varepsilon)\,d\varepsilon \; , \tag{2.42}$$

where x is a random number, ε is a nucleon energy.

The spectrum with weight of given state population P(n,t) at given time t is stored.

The emission of the nucleon leads to decrease of excitation energy of composite system by (ε+B_ν) as well as decrease of Z, A values and decrease of number of quasi-particles by unit. The values obtained are used as initial quantities for the following calculations. Transition to a stage 3 is carried out further and the master–equation system for new starting conditions is solved.

5. The history comes to the end if the state of equilibrium is achieved or the energy of a residual nucleus is insufficient for the nucleon emission. The nucleus population is stored at the fixed excitation energy.

Thus, at enough number of histories the spectra of preequilibrium particles and the residual nucleus population in an equilibrium state are found.

2.2.4 Calculation results and comparison with experiments available

At comparison of the calculation results with experimental data it is useful to cover as wide as possible range of projectile energies and masses of targets. The comparisons are given on fig. 2.2.8-2.2.32. Experimental data are taken from [15-27] and from EXFOR computer library. Parameters of model were the same for any case.

(n,xp) reaction. Example of rather successful use of model the comparison of the data given in the Fig. 2.2.8 and 2.2.9 for two targets and wide neutron energy range (25 - 63 MeV). Here we restricted ourselves by description of the hard part of proton spectra in these reactions only which is ordinarily begun after a break of energy spectrum. In the Fig. 2.2.8 and 2.2.9 the break of the spectrum shape is clearly seen at energies 12-13 MeV. For smaller energies of proton spectra are described by equilibrium statistical model (compound nucleus). This type of calculation is beyond this paper. Moreover there is one more reason to avoid the detailed agreement of calculations with experimental data. In the detailed description of nucleon-induced reactions the model of the intranuclear cascade is responsible for an initial stage of reaction, i.e. for formation of a particle spectrum after the first collisions inside a nucleus and for formation of the particle - hole configurations including compound nucleus. On the other hand, as it can be seen from Fig. 2.2.8 and 2.2.9 and also from the further consideration the MCP model may be used in a first approximation as self-independent model for the description of the hard part of spectra.

The systematic experimental information on the proton spectra from (n,xp) reaction is restricted by the above mentioned data. There are separate and scare measurements for energy of neutrons 14 MeV and as one would expect their results differ considerably. It is seen from Fig. 2.2.10 that for a nucleus ^{93}Nb the data [17,18] disagree considerably and it is impossible to explain this discrepancy by the difference in energies of neutrons. At the same time, the results of calculations by MCP satisfactorily describe the experimental data except for a nucleus ^{59}Co.

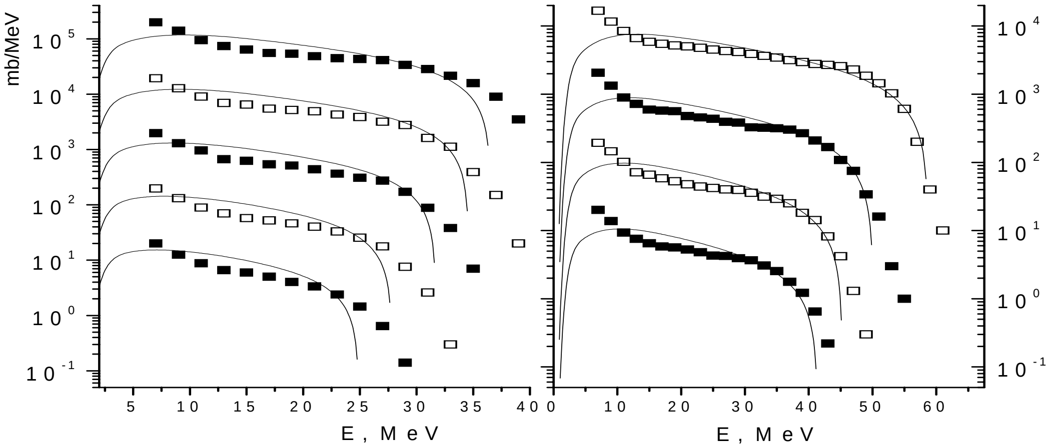

Fig. 2.2.8. Spectra of protons from ^{27}Al(n,xp) reaction at different neutron energies. On the left for 28, 31, 34, 37 and 41 MeV (from below upwards); on the right for 45, 49, 54, 63 MeV (from below upwards). The symbols show experimental data [16], the line are the results of calculations by MCP.

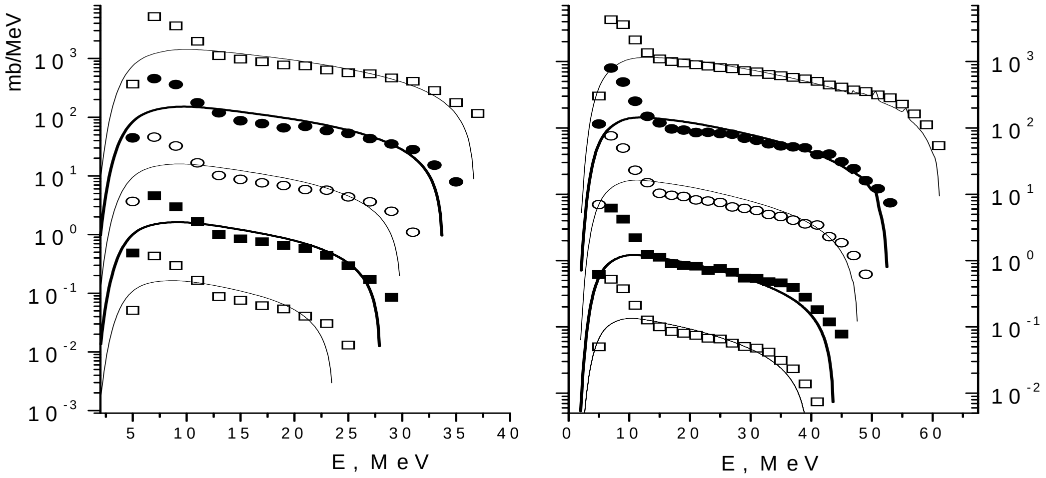

Fig. 2.2.9. The same as in the Fig. 2.5 but for ^{59}Co (n, xp).

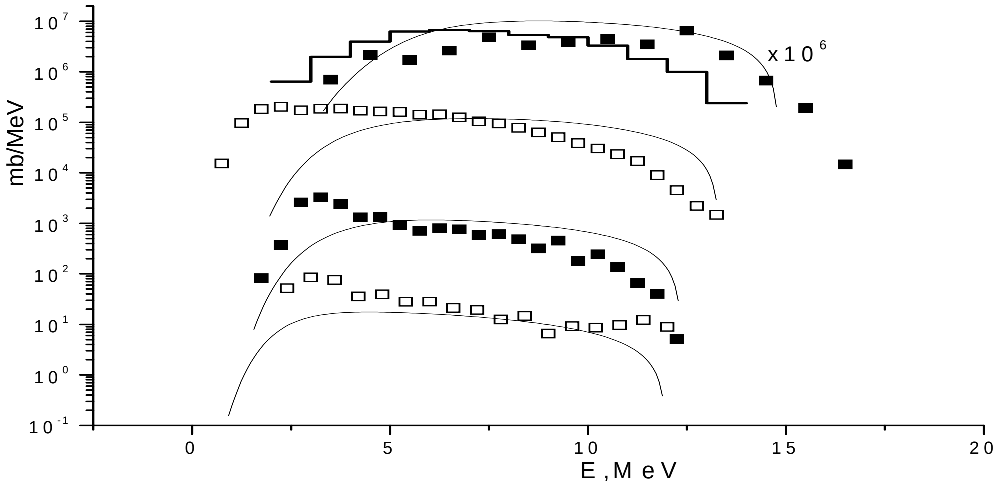

Fig. 2.2.10. Spectra of protons from (n,xp) reaction for ^{27}Al, ^{51}V, ^{59}Co and ^{93}Nb (from below upwards). Symbols show experimental data [17,18], the lines are the results MCP.

<u>(n, xn) reaction.</u> As it was already pointed above at the analysis of the basic relations of the exciton model of preequilibrium decay the shape of a nucleon spectrum and its absolute value are defined mainly by two quantities - density of the particle-hole states and matrix element of two-particle interaction. Obviously in MCP model these functions will determine a calculated spectrum too, at least for those energies where the emission of the second and the subsequent preequilibrium nucleons is forbidden. The matrix element (2.37) in a parameterization [8] depends only on mass number of a target and on an excitation energy of composite system. In the Fig. 2.2.8 and 2.2.9 we already shown that energy dependence of a matrix element is taken into account correctly. Really, for energies of a neutron from 25 up to 63 MeV the shape of spectra and their values are described with help MCP well enough.

Now we shall test a parameterization of dependence of a matrix element on a mass number at different projectile energies. Comparison of the calculation results of neutron spectra from (n,xn) reaction is given in the Fig. 2.2.11-2.2.14 for energies 8, 14, 20 and 26 MeV. It is necessary to note that the specified reaction is not so representative for testing of preequilibrium model due to presence of direct excitation of collective levels in its mechanism.

At low energies of neutrons (Fig.2.2.11) when the contribution of nonequilibrium processes to the reaction cross section is rather small there is no obvious break of the experimental spectrum shape and it is possible to conclude on applicability of MCP only qualitatively. However even in this case the description of the hard part of spectra for nuclei with mass number from 59 up to 209 is satisfactory.

As projectile neutron energy and a mass number of target increase the changes of energy dependence (Fig. 2.2.12 and 2.2.13) is visible in the experimental spectra clearly. For example, for the case of ^{51}V target (Fig. 2.2.12) energy dependence of nonequilibrium processes is practically not visible while for ^{209}Bi a distinct step for neutron energies higher 5 MeV exists. Change of projectile energy from 14 up to 20 MeV leads to clear manifestation of nonequilibrium processes in experimental data (Fig. 2.2.13). For all nuclei of Fig. 2.2.13 at energies lower 5-6 MeV there is an overestimation of experimental data because the statistical model contribution is not taken into account.

It is possible to make a conclusion from Fig. 2.2.12 on the adequacy of mass dependence of a model matrix element. Despite of some discrepancies of calculations and experments for light nuclei one can assert that mass dependence of a matrix element reflects an actual picture well enough. Correctness of the formula (2.37) from the point of view of mass dependence is also supported by analysis of Fig. 2.2.13 data where change of a mass number from 93 up to 209 practically does not influence on high quality of the description of experimental data.

The low energy (< 12 MeV) part of spectra is absent in the experimental data at 26 MeV (Fig. 2.2.14) but detailed measured spectra for energies close to the maximum energies of emitted neutrons are presented. In a energy region of 12-18 MeV the preequilibrium model gives rather satisfactory description of experimental data but at the same time for energies > 18-20 MeV the discrepancy of results of calculation with experiment is observed. If to return to Fig. 2.2.12 and 2.2.13 it is possible to see the same effect for energies 14 and 20 MeV. The pointed discrepancy has two reasons: 1) in experimental data the peak of elastic scattering presents and it is not taken into account in calculations and 2) in our calculations the direct excitation of collective levels of targets is not taken into account. The account of the second effect has allowed to achieve the simultaneous description of nucleon spectra in (n,xp) and (n,xn) reactions with the same matrix element.

To continue the analysis of correctness of matrix element function (2.37) we shall give the comparison of results of calculation with experimental data on spectra of secondary neutrons from (n,xn) reaction for two targets but for different energies from 8 up to 26 MeV (Fig. 2.2.15). The data presented in the Fig. 2.2.15 have been already discussed in connection with Fig. 2.2.11 - 2.2.14 but from the point of view of mass dependence of matrix element. From Fig. 2.2.15 it is possible to conclude that its energy dependence is well reproduced by the formula (2.37) for (n, xn) reaction as well as for (n,xp) reaction (see Fig. 2.2.8 and 2.2.9). To demonstrate the increasing of nonquilibrium part of cross section the results of total spectrum calculations are shown in the Fig. 2.2.15. At projectile energy 8 MeV the contribution of preequilibrium emission is negligible (lower parts of Fig. 2.2.15). With energy raise in the input channel of reaction this contribution is quickly increased and already at 20 MeV takes 70-80 % of cross section.

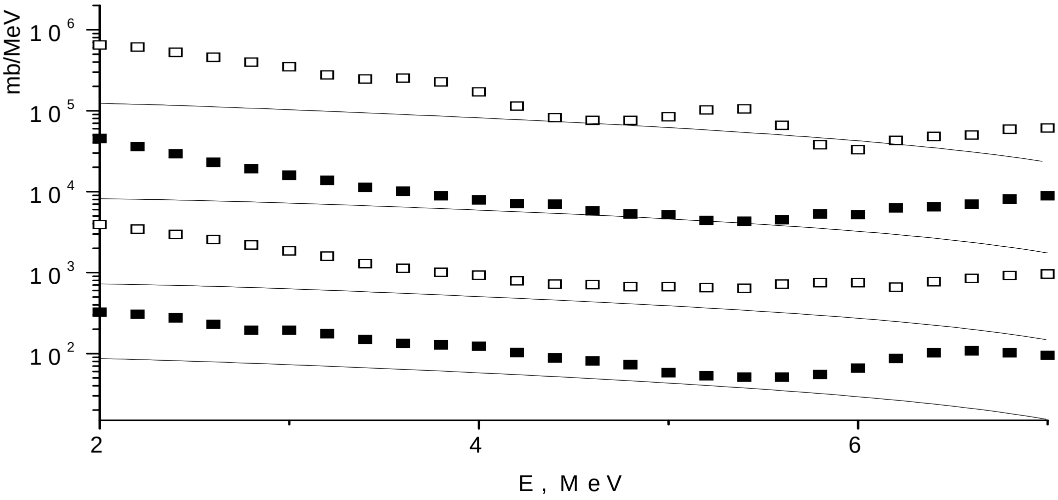

Fig. 2.2.11. Spectra of neutrons from (n,xn) reaction at projectile energy 8 MeV for ^{59}Co, ^{93}Nb, ^{181}Ta and ^{209}Bi (from below upwards). Symbols show experimental data [19], the lines are results MCP.

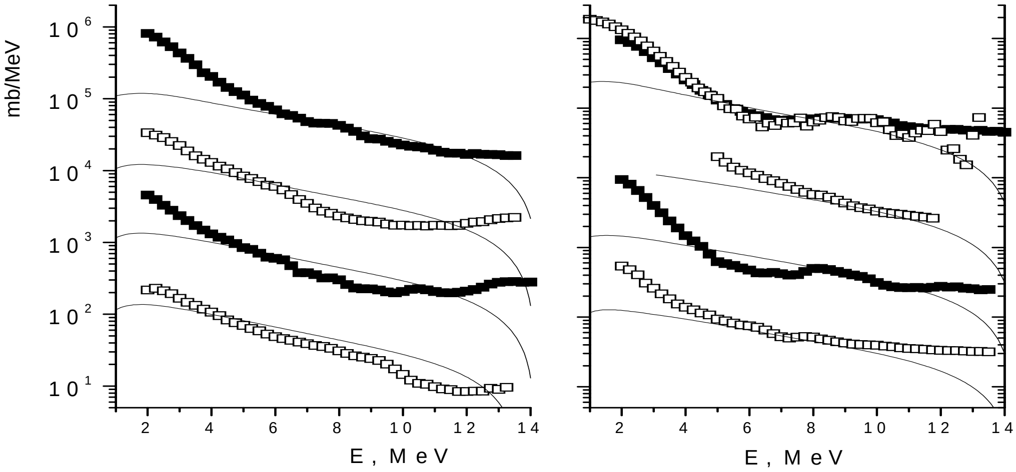

Fig. 2.2.12. Spectra of neutrons from (n,xn) reaction at projectile neutron energy 14 MeV. On the left side for ^{51}V, ^{55}Mn, ^{59}Co and ^{93}Nb (from below upwards), on the right side for ^{127}I, ^{181}Ta, ^{197}Au and ^{209}Bi (from below upwards). Symbols show experimental data [19,20], the lines are results of MCP.

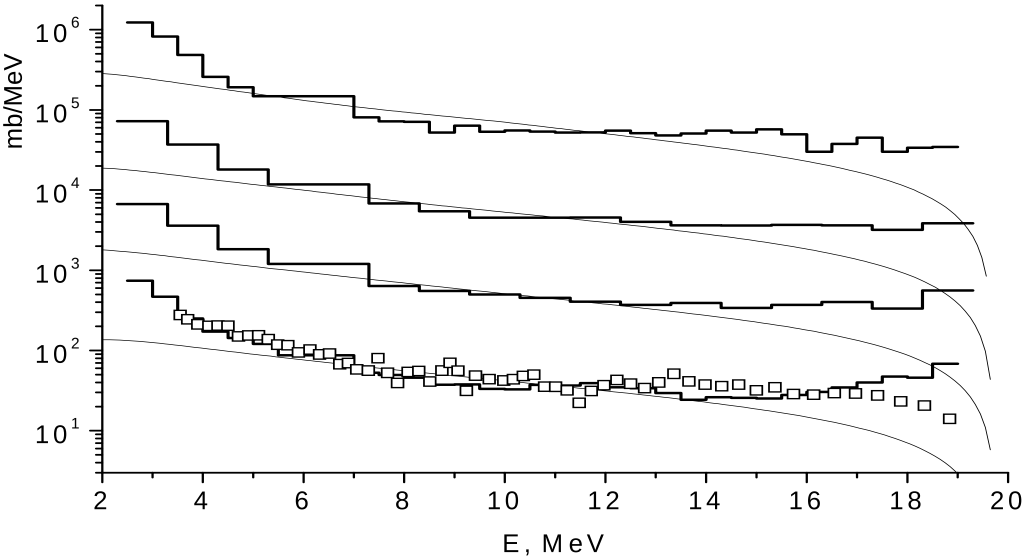

Fig. 2.2.13. Spectra of neutrons from (n,xn) reaction at projectile neutron energy 20 MeV for ^{93}Nb, ^{165}Ho, ^{181}Ta and ^{209}Bi (from below upwards). Histograms and symbols show experimental data [19,21], the lines are results MCP.

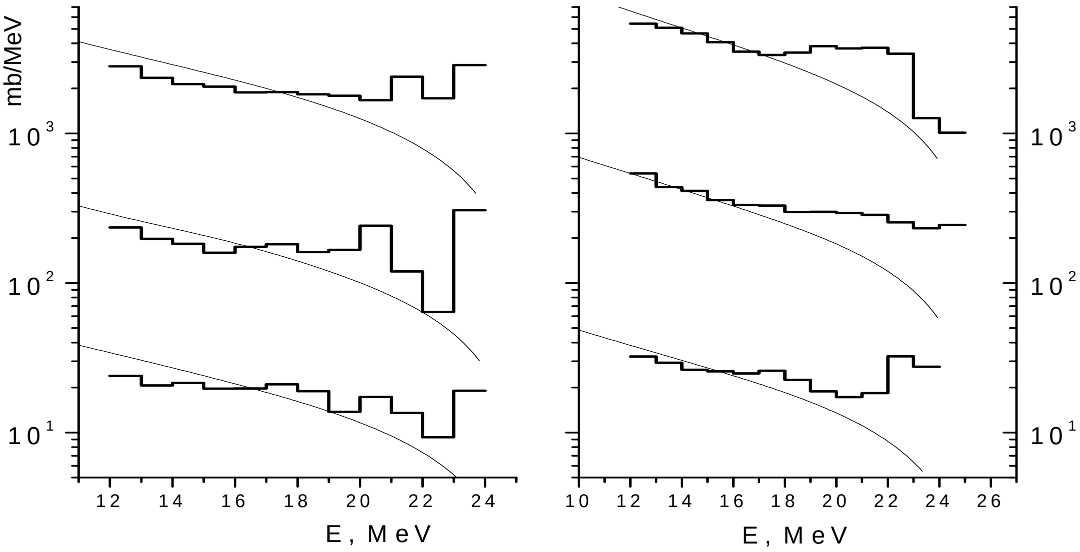

Fig. 2.2.14. Spectra of neutrons from (n,xn) reaction at 26 MeV for ^{51}V, ^{56}Fe and ^{65}Cu (from below upwards), ^{93}Nb, ^{184}W, and ^{209}Bi (from below upwards). Histograms show experimental data [21], the lines are results of MCP.

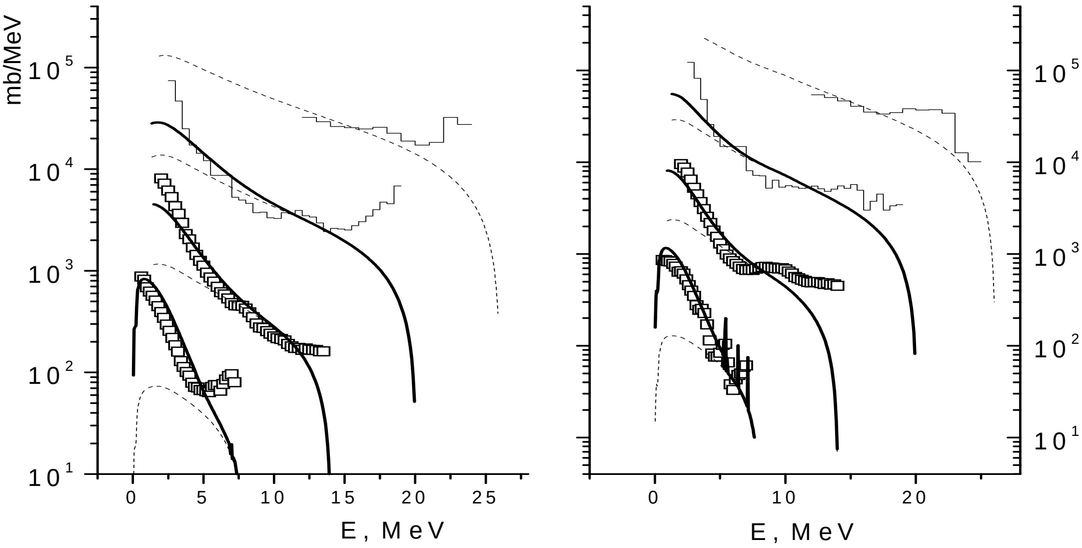

Fig. 2.2.15. Spectra of neutrons from (n, xn) reaction at the energies 8, 14 20 and 26 MeV (from below upwards) for nucleus - targets ^{93}Nb (at the left) and ^{209}Bi (on the right). Histograms and symbols show experimental data [19,20,21], continuous lines are total spectra, dashed lines are preequilibrium spectra by MCP.

(p,xn) reaction. The third reaction interested from the point of view of verification of preequilibrium model is (p,xn) reaction. The review of available experimental data testifies that there are data on neutron spectra for a plenty of targets from ^{27}Al up to ^{209}Bi and for energies of protons from 8 up to 120 MeV. This is a circumstance worthy of being noted that amount of experimental data on these reactions is the greatest of all nucleon-nucleon reactions.

It is natural to start comparison and analysis of the calculation results with experimental data from the lowest energies where the contribution of the preequilibrium mechanism begins to increase from inappreciable quantities and restrict ourselves by not very high energies (not more then 50 MeV) where intranuclear cascade has not a determining role in the nonequilibrium mechanism.

Comparison of the results of calculations on MCP model with experimental data on spectra of neutrons from (p,xn) reaction at E_p=9 MeV is given in the Fig. 2.2.16 and 2.2.17 for a plenty of targets.

The satisfactory agreement of calculation results with experimental data are achieved but in many cases unexpectedly big overestimation of the preequilibrium processes contribution in the spectra of neutrons is observed, in particular, for targets ^{113}Cd, ^{109}Ag, ^{117,119}Sn and ^{181}Ta. All of these nuclei are odd ones. Earlier in the Fig. 2.2.8-2.2.14 we did not observe similar effect. Moreover, in a charge-exchange reaction (n,xp) the effect is opposite one. In the Fig. 2.2.8 and 2.2.9 the nuclei with odd number of nucleons are presented but so-called even-odd effects were not observed. We shall discuss this situation in more detail. For demonstration of available discrepancies in the Fig. 2.2.18 and 2.2.19 the comparison of experimental data for different nuclei and the comparison of these data with results of calculations is given.

It is possible to see that distinctions of the experimental spectra for ^{107}Ag and ^{109}Ag in the region of energies of emitted neutrons up to 4 MeV is insignificant. It means the close values of level density of residual nucleus. Distinctions of spectra at E_n > 5 MeV are caused only by differences in reaction energies and as a consequence by the maximal energies of neutrons. Calculation however gives the considerable overestimated spectra for ^{109}Ag in the region of energies of nonequilibrium neutrons. A similar situation takes place for odd nuclei ^{117}Sn and ^{119}Sn (Fig. 2.2.19). In both cases calculated spectra are highly overestimated. And on the contrary, for even-even nuclei ^{120}Sn and ^{122}Sn experimental data are described by calculation well.

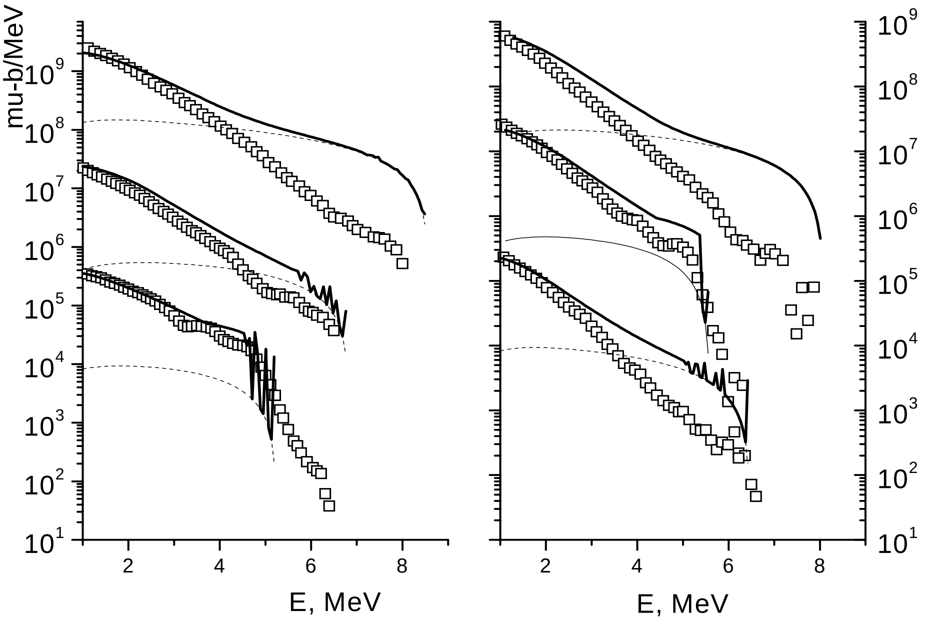

Fig. 2.2.16. Spectra of neutrons from (p,xn) reaction at projectile proton energy 9 MeV. On the left for targets ^{68}Zn, ^{107}Ag, ^{113}Cd (from below upwards); on the right for targets ^{117}Sn, ^{120}Sn, ^{181}Ta (from below upwards). Symbols show experimental data [22], solid lines are calculated total spectra, dashed lines are the preequilibrium spectra by MCP.

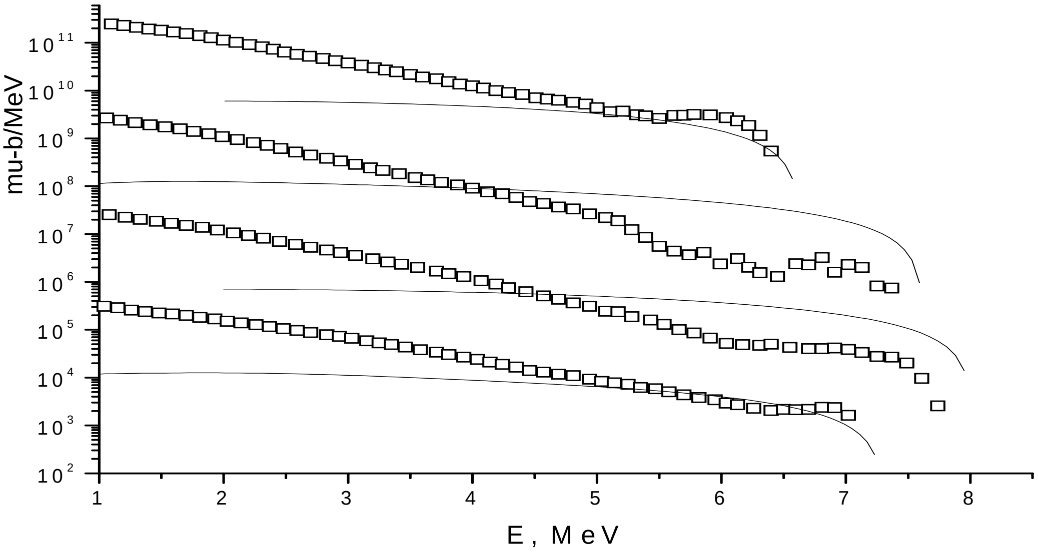

Fig. 2.2.17. Spectra of neutrons from (p,xn) reaction at 9 MeV for ^{94}Zr, ^{109}Ag, ^{119}Sn and ^{122}Sn (from below upwards). Symbols show experimental data [22], the line are the results of MCP.

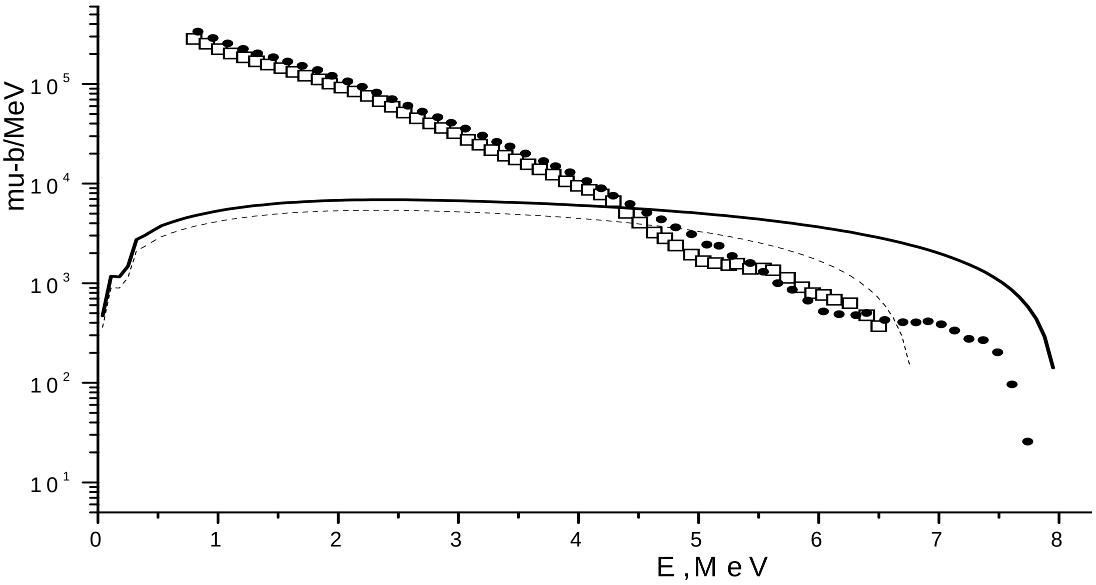

Fig. 2.2.18. Spectra of neutrons from (p,xn) reaction at 9 MeV for ^{107}Ag and ^{109}Ag. Open symbols and dashed line show the data for ^{107}Ag, by solid symbols and a line are the data for ^{109}Ag.

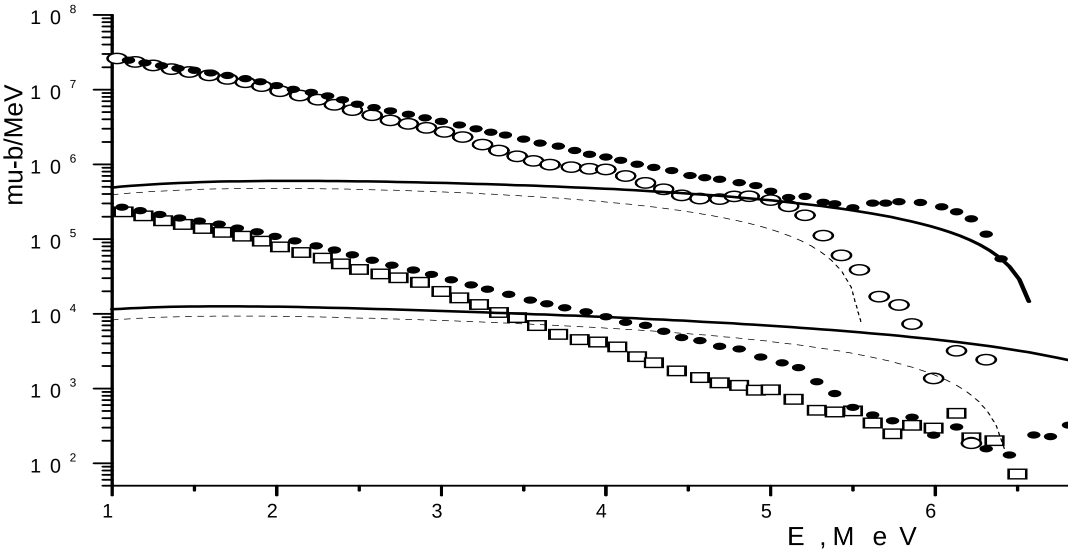

Fig. 2.2.19. Spectra of neutrons from (p, xn) reaction at 9 MeV for ^{117}Sn, ^{119}Sn (below) and ^{120}Sn, ^{122}Sn (above). Symbols are experimental data [22], the lines are the results of calculations by MCP. Open symbols and dashed lines are the data for ^{117}Sn and ^{120}Sn.

We shall continue the analysis of discrepancies between calculated and experimental spectra for the same reaction on two argentum isotopes but for higher projectile proton energies. The increase of energy does not change the character of these discrepancies for neutron-induced reactions on nuclei ^{107}Ag and ^{109}Ag (Fig. 2.2.20) in comparison with ones obtained for E_p = 9 MeV (Fig. 2.2.18). It is seen that soft parts of the experimental spectra of both nuclei are close for all energies of protons and in the field of energies of neutrons more than 6 MeV there is an appreciable excess of calculations results over experimental data.

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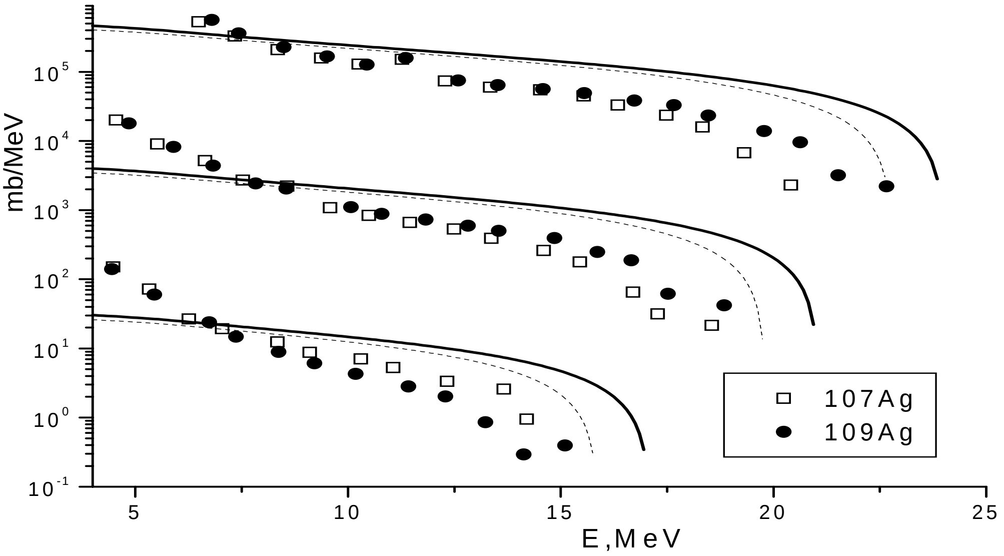

Fig. 2.2.20. Spectra of neutrons from (p,xn) reaction at energy 18, 22 and 25 MeV (from below upwards) for ^{107}Ag and ^{109}Ag. Experimental data from [23].

Let's compare spectra of neutrons from (p,xn) reaction on the next nuclei ^{103}Rh and ^{104}Pd (Fig. 2.2.21). The experimental spectra for both nuclei are close despite of different parity of number of nucleons but on other hand the description of these spectra by MCP model differs considerably. For even-even nucleus ^{104}Pd agreement of calculations and experiments is good but for odd ^{103}Rh the considerable overestimation is observed as for other odd nuclei (Fig. 2.2.17).

The situation with distinctions of calculations results for nuclei with different parity of nucleon number is reproduced in the Fig. 2.2.22 where again for odd ^{105}Pd the experimental spectrum are rather close to the neighbor even-even nucleus ^{106}Pd and results of calculations differ considerably.

The rise of proton energy for even-even targets $^{108,\ 110}$Pd and ^{120}Sn does not worsen the good description the experimental data obtained for energiy 9 MeV (Fig 2.2.16 and 2.2.17). This comparison is shown in the Fig. 2.2.23 and 2.2.24. So, for all nine cases the satisfactory description of experimental data by MCP calculation without adjustment of parameters has been achieved.

We considered above target nuclei around shell Z=50 and it is interesting now to take a look on reactions near N=50 shell.

One can see from Fig. 2.2.25 that despite of the regular overvaluation of calculation data experimental data on odd isotopes of a molybdenum are reproduced much worse than the data for the neighbor even-even isotopes. Moreover, it is obvious that systematic model adjustment (change of one model parameter on identical to all nuclei value) will give good description of the data for even-even isotopes and will not remove distinctions for odd isotopes.

Terminating the analysis of (p,xn) reaction we shall address to one more region of mass numbers - to lead isotopes. Comparison of calculation results with experimental data for four lead isotopes at energy of protons 25 MeV (Fig. 2.2.26) and isotope ^{208}Pb at energies 35 and 45 MeV (Fig. 2.2.27) shows that the good agreement is achieved. Calculations as well as in all previous cases were executed without a variation of parameters.

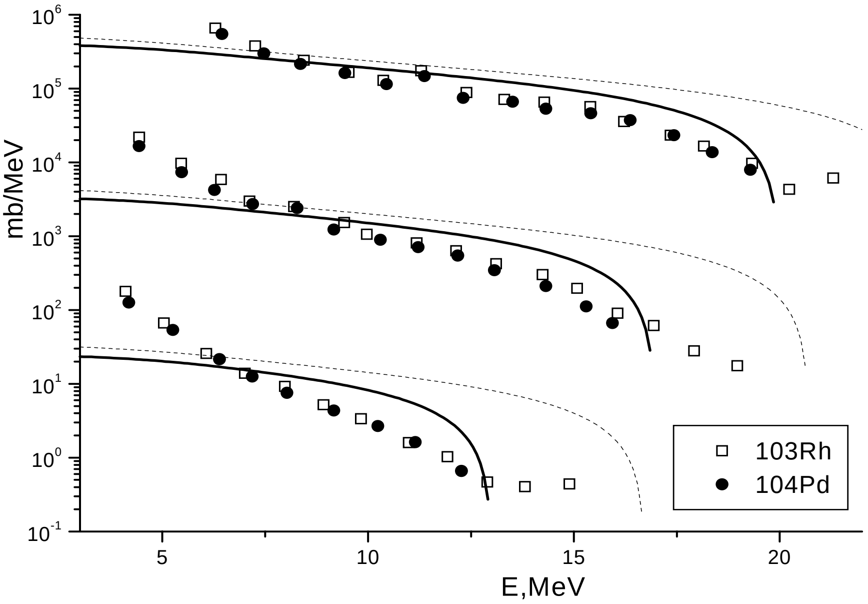

Fig. 2.2.21. Spectra of neutrons from (p,xn) reaction at 18, 22 and 25 MeV (from below upwards) for ^{103}Rh and ^{104}Pd. Experimental data from [23].

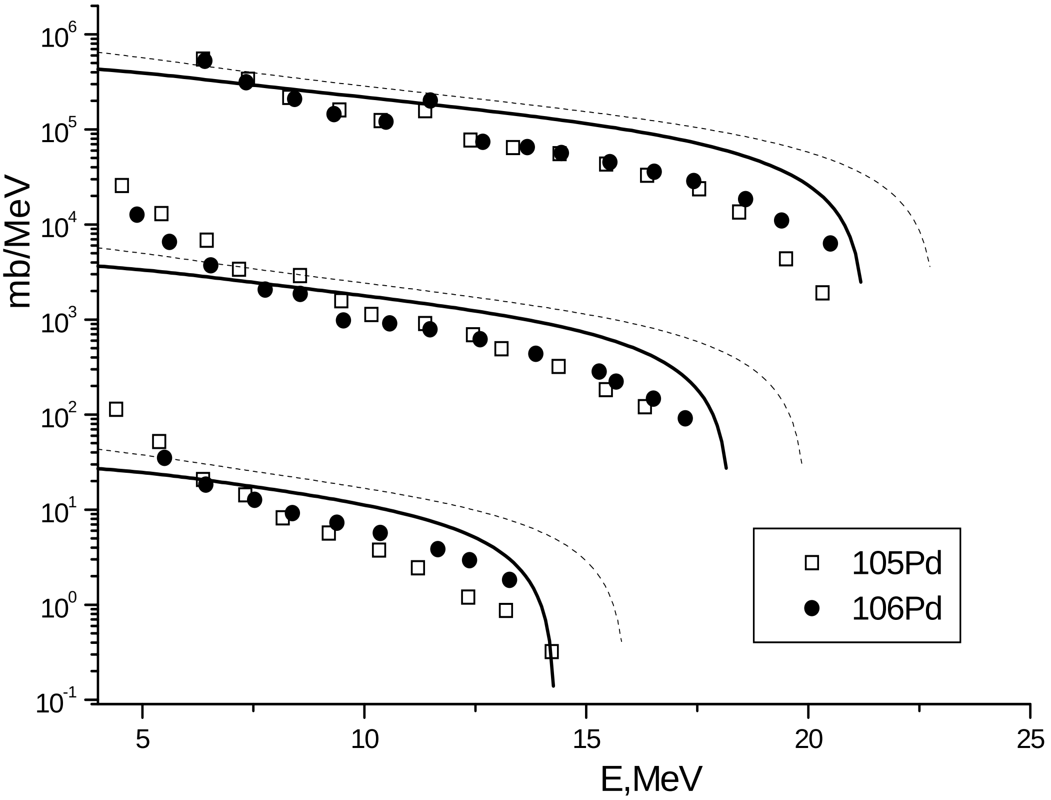

Fig. 2.2.22. Spectra of neutrons from (p, xn) reaction at 18, 22 and 25 MeV (from below upwards) for targets ^{105}Pd and ^{106}Pd. Experimental data from [23].

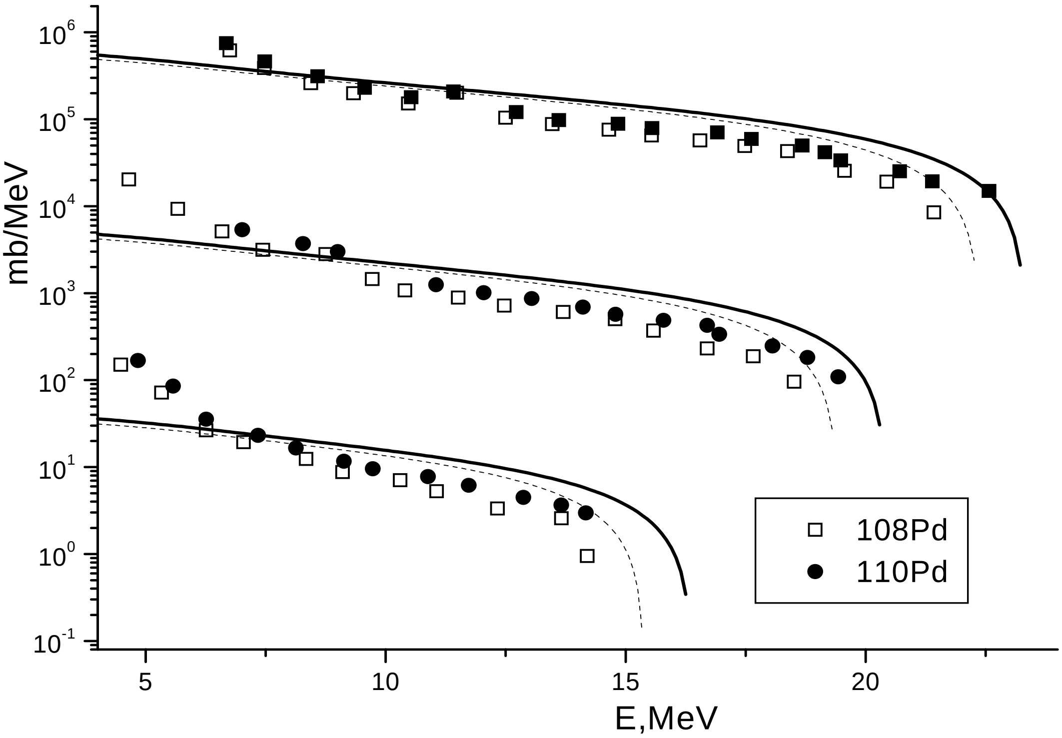

Fig. 2.2.23. Spectra of neutrons from (p,xn) reaction at 18, 22 and 25 MeV (from below upwards) for targets ^{108}Pd and ^{110}Pd. Experimental data from [23].

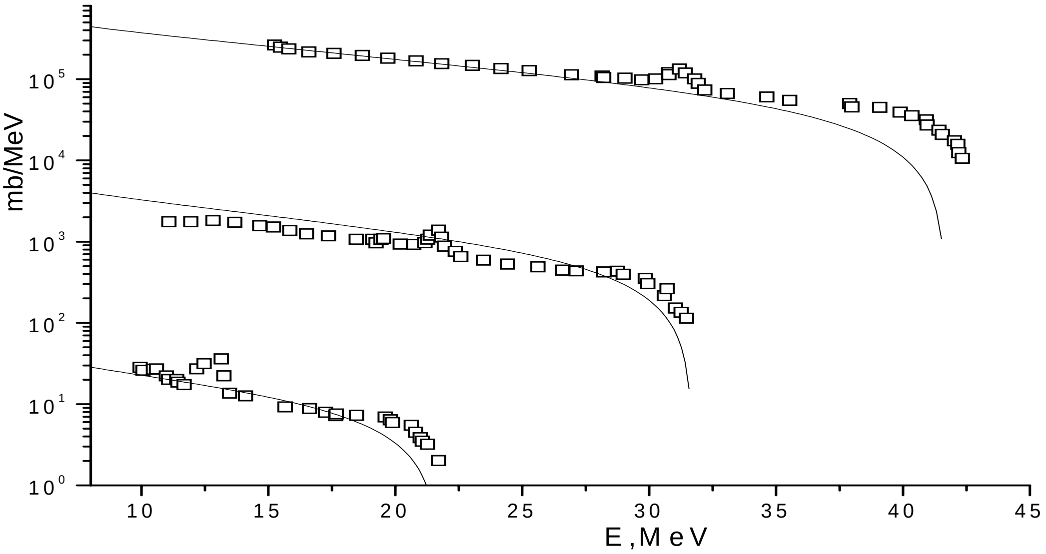

Fig. 2.2.24. Spectra of neutrons from (p,xn) reaction at energy of protons 18, 22 and 25 MeV (from below upwards) for target ^{120}Sn. Symbols show experimental data [24], the lines are results of MCP.

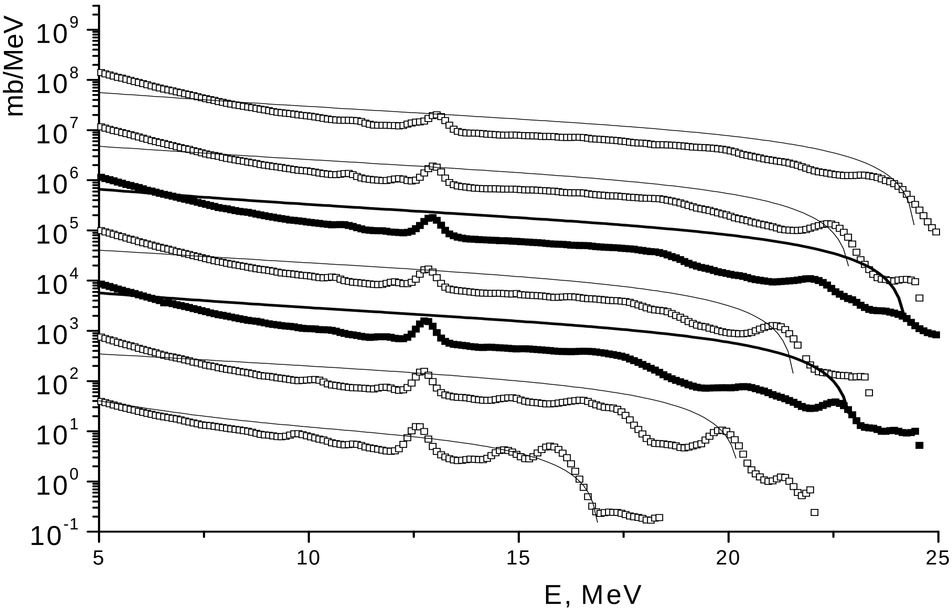

Fig. 2.2.25. Spectra of neutrons from response (p,xn) reaction at energy of protons 25 MeV for targets $^{92, 94, 95, 96, 97, 98, 100}$Mo (from below upwards). Symbols show experimental data [25], the lines are results of MCP calculations.

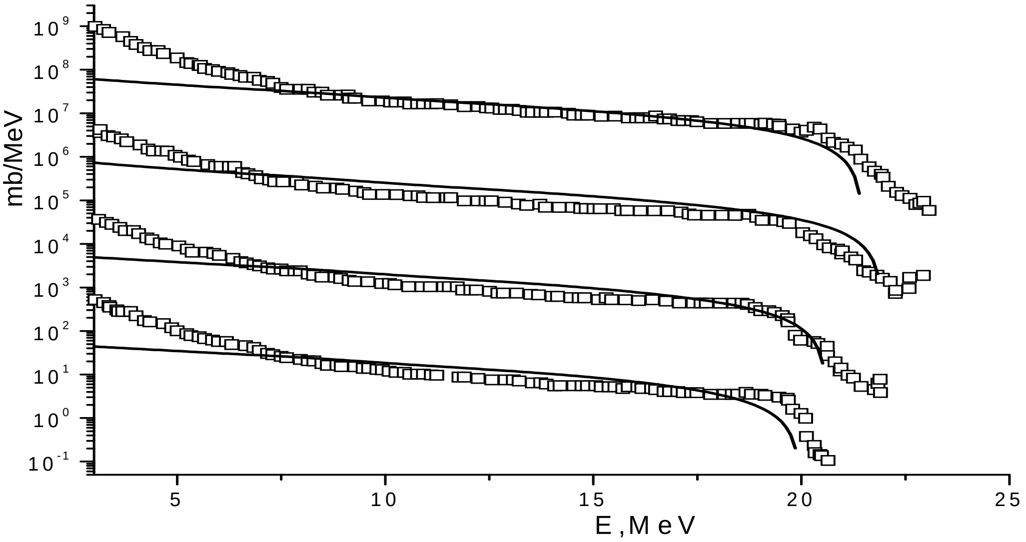

Fig. 2.2.26. Spectra of neutrons from (p,xn) reaction at energy protons 25 MeV for targets ^{204}Pb, ^{206}Pb, ^{207}Pb and ^{208}Pb (from below upwards). Symbols show experimental data [26], the lines are of MCP calculation.

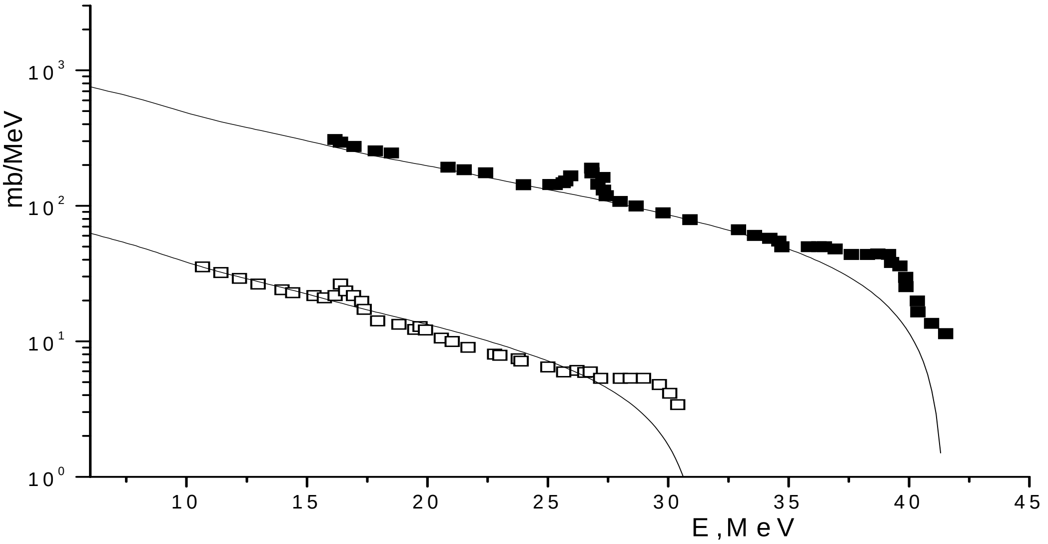

Fig. 2.2.27. Spectra of neutrons from (p, xn) reaction at 35 and 45 MeV for ^{208}Pb (from below upwards). Symbols show experimental data [24], the lines are results of calculation by MCP.

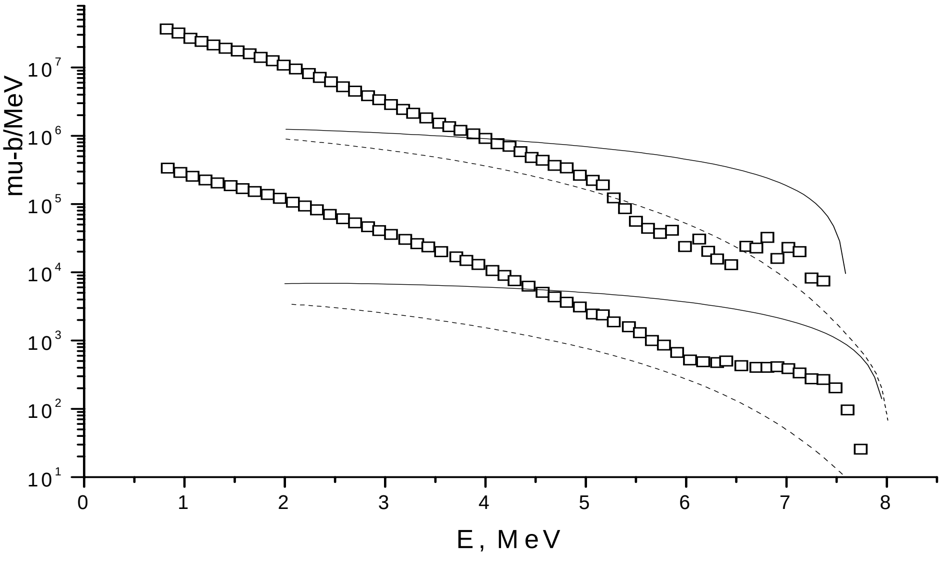

Fig. 2.2.28. Spectra of neutrons from (p xn) reaction at 9 MeV for ^{109}Ag and ^{119}Sn (from below upwards). Symbols show experimental data [23], the lines are results of calculations on MCP (solid - with an initial configuration 2p1h, dashed - with 3p2h).

(p,xp) reaction. Experimental data on spectra of protons from this reaction are rather scare as well as for previous reaction with proton emission. Only one systematic experimental research [27] has been found. Here spectra for a wide diapason of projectile proton energies (29-62 MeV) and for targets from a light nucleus ^{27}Al up to a heavy nucleus ^{209}Bi have been measured. Comparison of calculation results of proton spectra by MCP model with the specified experimental data is presented on Fig. 2.2.29-2.2.32.

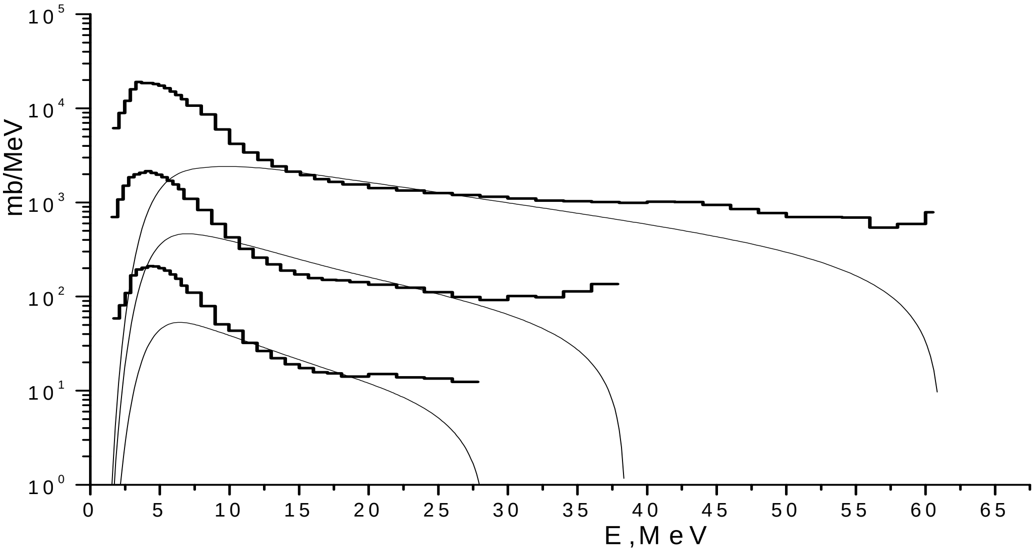

Fig. 2.2.29. Spectra of protons from (p,xp) reaction at 29, 39 and 62 MeV for a target ^{54}Fe (from below upwards). Symbols show experimental data [27], the lines are results of model MCP.

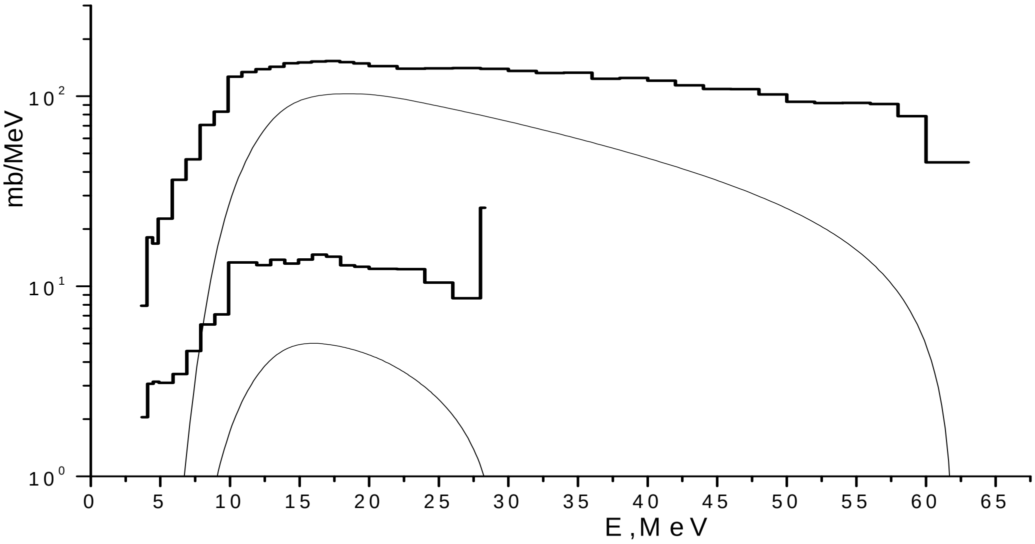

Fig. 2.2.30. Spectra of protons from (p,xp) reaction at 29 and 62 MeV for a target ^{197}Au (from below upwards). Symbols show experimental data [27], the lines are results of calculation by MCP.

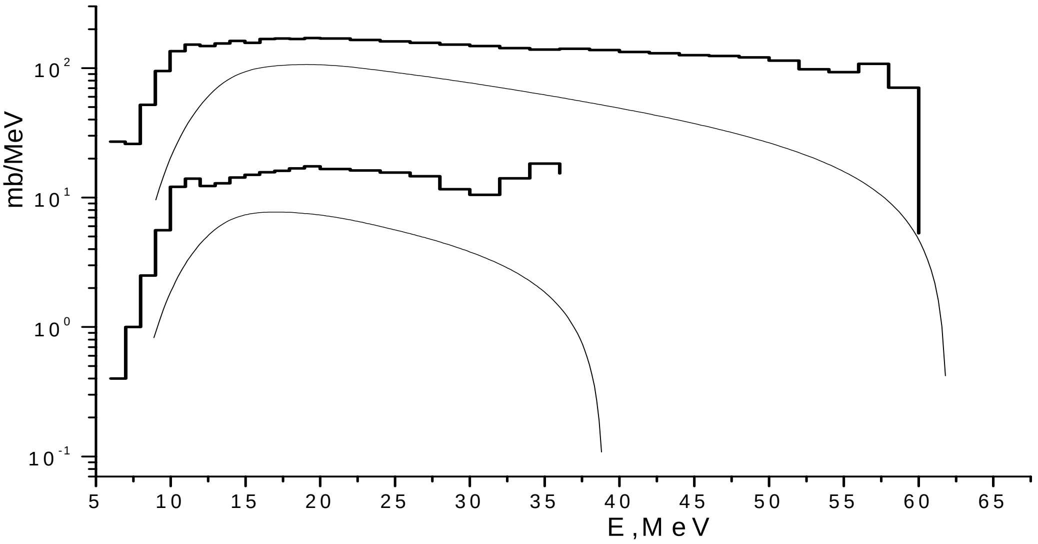

Fig. 2.2.31. Spectra of protons from (p,xp) reaction at 39 and 62 MeV for ^{209}Bi (from below upwards). Histograms show experimental datas [27], the lines are results of calculation by MCP model.

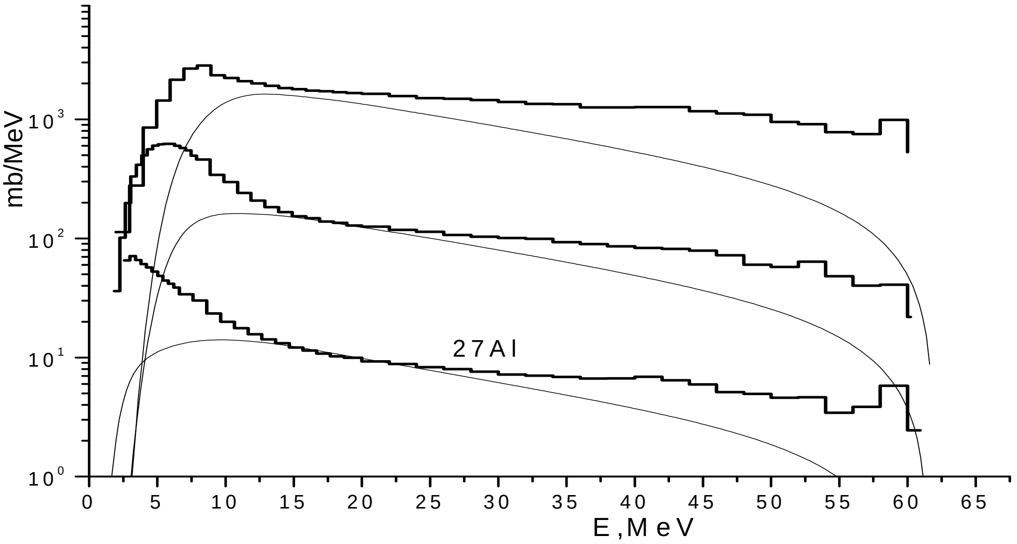

Fig. 2.2.32. Spectra of protons from (p,xp) reaction at 62 MeV for ^{27}Al, ^{89}Y and ^{120}Sn (from below upwards). Histograms show experimental data, the lines are results of calculation by MCP.

Analysis of data in the Fig. 2.2.29 shows that in accordance with inrease of energy from 29 MeV to 62 MeV the contribution of nonequilibrium part into reaction cross section is systematically risen on the one hand, and, on the other hand distinctions between calculated and experimental data are increased in the field of maximal energies of emitted protons. For example, excess of the experimental spectrum over a calculated spectrum for energy 29 MeV starts from 10 MeV before the peak energy and for 62 MeV - from 30 MeV. Here the description of the low-energy part of spectra beyond the work as well as for other cases.

At first sight, there is an exception the nuclei ^{197}Au and ^{209}Bi for where considerable discrepancy of results of calculations with the measured spectra even in that region of outgoing energies where preequilibrium model works (10-20 MeV, see Fig. 2.2.30 and 2.2.31) is observed. However, it is possible to see that if one normalizes calculations results in this energy area, the situation becomes similar to Fig. 2.2.29 in all four cases.

Unfortunately, in the EXFOR library for nuclei strongly differing on mass ^{27}Al, ^{89}Y and ^{120}Sn there are data for one energy point only, energy of projectile protons is equal to 62 MeV. Nevertheless, their comparison with calculations (Fig. 2.2.32) confirms the deductions made above.

2.2.5 Conclusions

New exciton model of preequilibrium decay (MCP) allowing to compute the spectra of multiparticle emission during the process of establishment of statistical equilibrium is proposed. Systematic comparison of calculations results with the experimental spectra of nucleons from (p, xn), (p, xp), (n, xn) and (n, xp) reaction in a wide projectile energy region from 10 up to 60 MeV for targets from ^{27}Al up to ^{209}Bi is carried out.

2.2.6 References

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2.3 Updating of a statistical model of evaporation/fission for account of a particle emission and fission from highly excited nuclear states, combination of the reaction models

2.3.1 Statistical model

The necessity of statistical model application in calculations of nuclear data for intermediate projectile energies is obvious. After cascade and preequilibrium nucleon emission the nuclei will stay at high excitations. These nuclei will undergo fission, emit nucleons etc. This last stage of reaction is described by statistical model.

Main relationships**.** The particle and gamma- spectra can be computed in statistical model by to formalism of Weiscopf-Ewing and of Hauser-Feshbach (HF). We used more rigorous HF formalism which takes into account the spin and parity conservation lows.

$$S_b(E_b) = \pi\bar{\lambda}^2 \sum_{\ell J} g_J \frac{T_{\ell j}^{J^\pi}(E_a) \sum T_b(E_b)}{N(E, J^\pi)} \rho(E - E_b - B_b, J^\pi) \qquad (2.43)$$

$$\begin{aligned} N(E, J^\pi) = {} & \sum_{J \copyright^{\pi'}} \int_0^{E-B_b} dE_b \, T_{blj}(E_b) \, \rho_b(E - B_b - E_b, J'^{\pi'}) + \\ & + \sum_{J \copyright^{\pi'}} \sum_{XL} \int_0^{E} dE_\gamma \, T_{\gamma XL}(E_\gamma)[1 + \alpha_{XL}(E_\gamma)] \, \rho(E - E_\gamma, J'^{\pi'}) \end{aligned} \qquad (2.44),$$

where E is the excitation energy of the compound nucleus, E_a, E_γ are the energies of the particles and gammas, $\rho(U,J)$ is the level density of nucleus with excitation energy U and angular momentum J, α is the electron conversion coefficient. The main values which determine the shape and absolute values of the calculated spectra are the level density $\rho(U,J)$ and transmission coefficients T_b.

The level density was calculated with phenomenological version of superfluid model [1] and its parameters were not changed.

Lorentzian function was used to calculate radiative strength functions:

$$f_{XL}(E_\gamma) = C_{XL} \left[\frac{\sigma_0 E_\gamma^2 \Gamma_0^2}{(E_\gamma^2 - E_0^2) + E_\gamma^2 \Gamma_0^2} \right] E_\gamma^{-(2L-1)} \qquad (2.45),$$

were C_{E1}=8,68x10^{-8} mb^{-1}MeV^{-2} , C_{E2}=5,22x10^{-8} mb^{-1}MeV^{-2} [2].

To calculate radiative strength functions for dipole electrical transitions the KMF method [3] based on quasiparticle fragmentation of the neutron resonances was applied. The main difference of this method from Lorentzian dependence is leading the strength function to constant value at low gamma energies. This value is determined by the giant resonance parameters E_0, Γ_0 , σ_0 and by the temperature of residual nucleus:

$$f_{E1}(E_\gamma, T) = C_{E1} \left[E_\gamma \frac{E_\gamma \Gamma\ (E_\gamma)}{(E_\gamma^2 - E_0^2) + E_\gamma^2 \Gamma(E_\gamma)^2} + \frac{0.7\Gamma_0 4\pi T^2}{E_0^5} \right] \sigma_0 \Gamma_0 \qquad (2.46),$$

$$\Gamma(E_\gamma) = \Gamma_0 \frac{E_\gamma^2 + 4\pi^2 T^2}{E_0^2} \qquad (2.47).$$

This energy dependence was proved by the experimental data [4] at the 0.2-2 MeV energy region, namely for the energies where the differences between the KMF method and Lorentz curve are the largest ones. The verification of (2.46) and (2.47) formulae was done with gamma spectra of (n,γ) reaction and averaged radiation widths and also with the isomeric ratios of the neutron reactions [5] (Fig. 2.3.1). It was shown the advantages of the KMF method for wide diapason of the nuclei. We used the parameters of GDR from [6] or from systematics [5].

2.3.2 Combination of three reaction models.

We used the three models of the reactions to calculate all reaction stages. The intranuclear cascade model was used to describe the fast processes of the nucleon-nucleon interaction, the exciton model of multiparticle preequilibrium emission (MCP) was applied to calculate intermediate stage when the equilibration of composite system takes place. The statistical model was used to describe the decay of excited compound nuclei. The main parameters of all models have to be checked correctly to avoid the misbalance of different mechanism contribution into the reaction cross sections.

The main parameter of the preequilibrium model is the matrix element value. This parameter was fixed by the fitting of calculated spectra to experimental data for the projectile energies when the cascade contribution into hard part of the spectra is negligible.

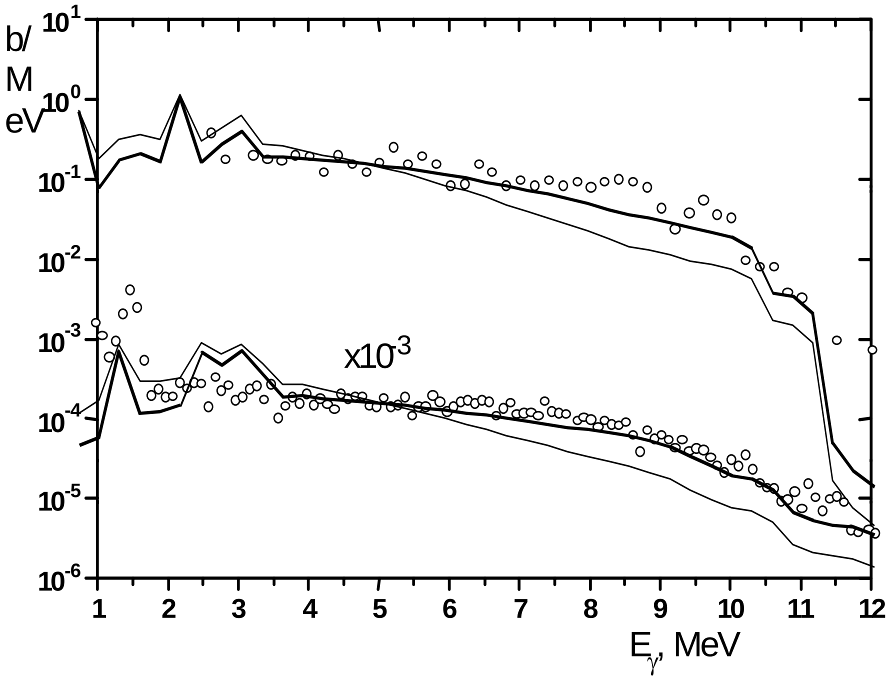

Fig. 2.3.1. Gamma spectra from (n,xγ) reaction at E_n=14 MeV on the ^{56}Fe target (top) and ^{52}Cr (bottom). The symbols are experimental data [7, 8].

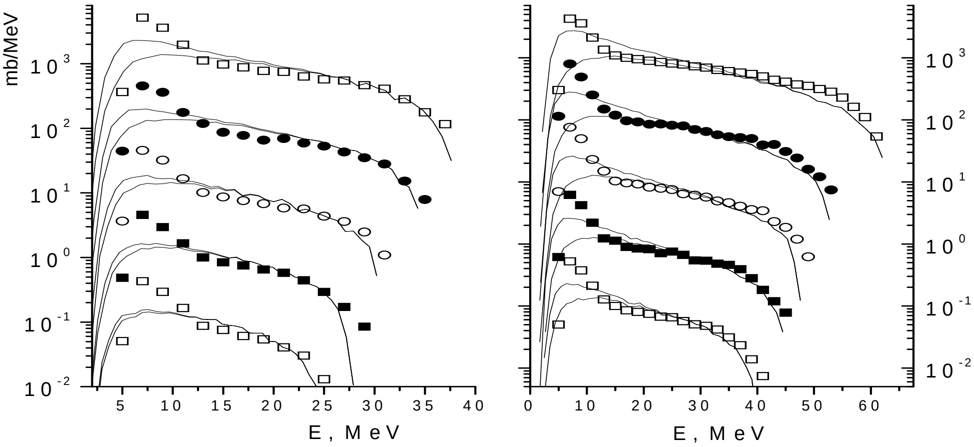

Fig. 2.3.2 The proton spectra of ^{59}Co(n,xp) reaction. The symbols are experimental data. Upper curves for each projectile energy are the sum of all preequilibrium neutrons.

The typical examples of the measured data description by the MCP model calculations are presented in fig. 2.3.2. It can be seen the good coincidence of the computed results and experimental data for the wide region of projectile energies. Fig.2.3.2 shows also the increasing of multiparticle preequilibrium contribution as the projectile energy increases. The comparison was done for all available measured data [9-21] for (p,xn), (p,xp), (n,xn) and (n,xp) reactions at the projectile energies from 10 MeV to 60 MeV for the targets from ^{27}Al to ^{209}Bi. One value of the matrix element was fixed for all cases analyzed.

The key parameter of intranuclear cascade model is the cut off energy E_{cut}. This energy is the lowest cascade particle kinetic energy. The development of the cascade processes at the energy smaller then E_{cut} is impossible. Commonly E_{cut} equals to 10-20 MeV. When the value of cut off energy is fixed the ejectile nucleon energies lower then E_{cut} are forbidden. It leads to the step-like shape of particle spectra. On the other hand, the experimental spectra are smooth. To get smooth calculated spectra we used cut off as parabolic potential barrier with fixed width and height value (fig.2.3.3).

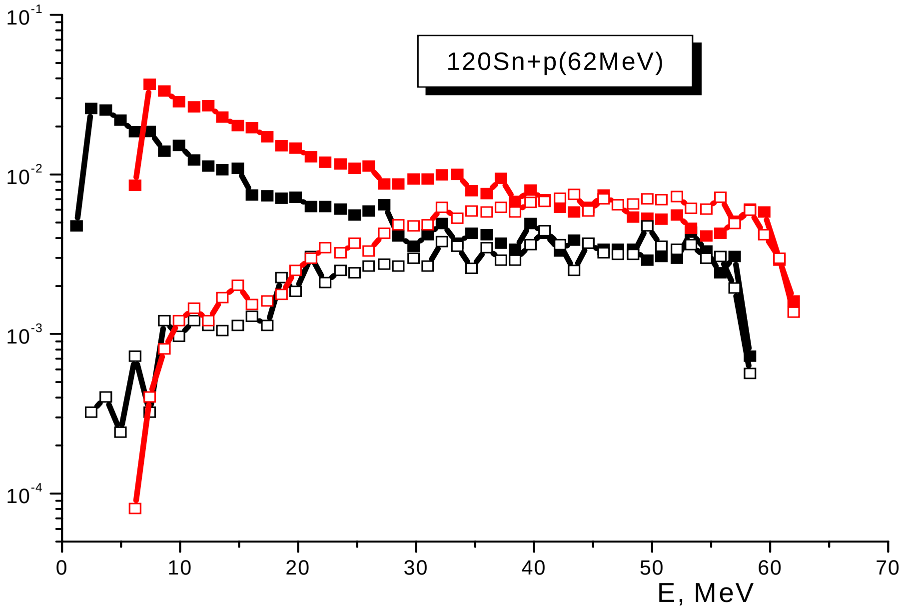

Fig. 2.3.3 The influence of cut off barrier on nucleon spectra shapes. Upper spectra were calculated with E_{cut}=0. The parabolic barrier with 50 MeV height and 10 MeV width was used for the calculations of the spectra on the bottom. The red curves are the proton spectra, black curves are the neutron spectra. The data fluctuations are from small statistics.

The fist stage of calculations with MCFx code was intranuclear cascade block. The results of this stage are the energy distributions (spectra) of the nucleons $S_{inc}(\varepsilon)$ and the residual nucleus yields Y_{inc}(Z,A,E,ph) as the function of excitation energy and particle-hole configuration. The data on particle spectra are used to final spectra modeling. The Y_{inc}(Z,A,E,ph) values are used as the input data for MCP preequilibrium model calculations. The results of this model are nucleon spectra $S_{MCP}(\varepsilon)$ and the distributions of the residual nuclei at the equilibrium states Y_{MCP}(Z,A,E). The Y_{MCP}(Z,A,E) values are the part of input data for the statistical model calculations. Other part of the input data is typical statistical model input quantities: level density parameters, discrete level information, transmission coefficients, fission barrier parameters. After the usage of Hauser-Feshbach formalism we have got a lot of information: statistical spectra $S_{HF}(\varepsilon)$; ground state nuclear distributions Y_{HF}(Z,A), fission cross sections etc..

When highly excited nucleus is in the equilibrium state it can emit *x* neutrons and *y* protons. The consequences of the nucleon emission can be quite different. All these cases have to be taken into consideration. The number of the variants of calculations is the number of combinations form (*x*+*y*) on *y*. To realize all possible consequences we used the Monte Carlo method. For each number of particles the type of nucleon was simulated. For instance, in the case of the emission of the three particles the (3p), (1n2p), (2n1p) and (3n) decays are possible. The first decay is the simple case without need to simulate consequences. Really, the (ppp) chain is possible only. The (npp), (pnp) and (ppn) chains can be realized for the (1n2p) decay. High enough number of Monte Carlo histories will generate all these cases.

The changing of proton spectrum by adding the different reaction contributions into the summary equilibrium spectrum is shown in fig. 2.3.4. It can be seen that the spectra of all reactions are approximately the same at low proton energies.

The calculated final spectrum of escaped particles is the sum of all reaction mechanism as:

$$S(\varepsilon) = S_{INC}(\varepsilon) + \sum_{Z,A}\sum_{E} Y_{INC}(Z,A,E,ph)\cdot\sum_{i} S^{i}_{MCP}(Z,A,E,\varepsilon) + \sum_{Z,A}\sum_{E} Y_{MCP}(Z,A,E)\cdot\sum_{i} S^{i}_{HF}(Z,A,U,\varepsilon) \quad . (2.48)$$

where S_{INC}(e), Y_{INC}(Z,A,E,ph) are the spectrum and the nucleus yields after intranuclear cascade; S_{MCP}(e), Y_{MCP}(Z,A,E,ph) are the spectrum and the nucleus yields after preequilibrium decay; S_{HF}(e) is the statistical spectrum.

The contributions of nonequilibrium mechanisms of the reaction into particale spectrum are presented in fig. 2.3.5. One can see the decreasing of preequilibrium part of the proton spectrum as projectile energy increases.

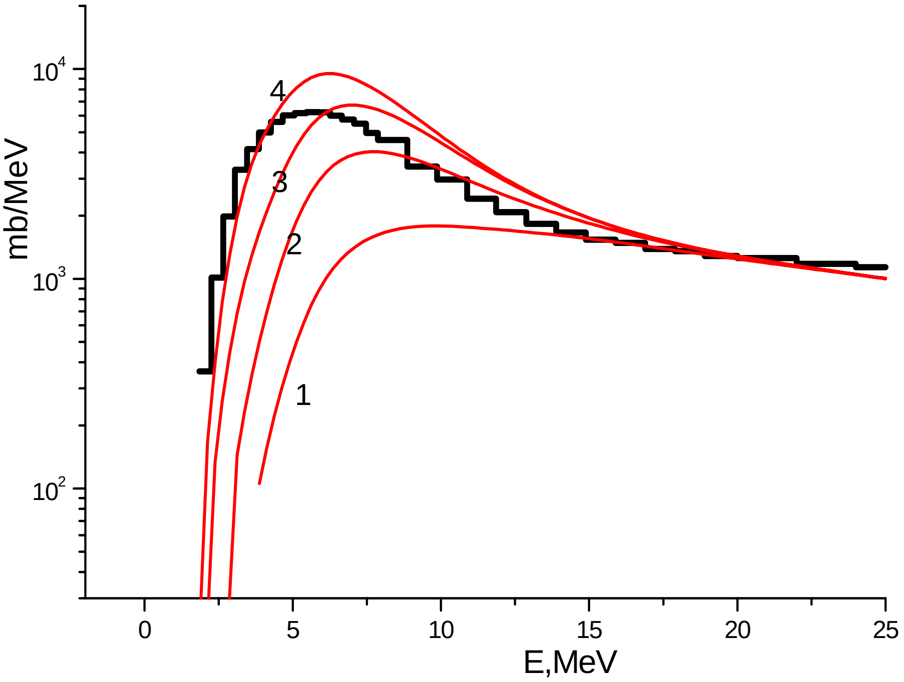

Fig. 2.3.4. The proton spectra of (p,xp) reaction at 62 MeV projectile energy on ^{89}Y. Histograms are the experimental data, curve 1 is the contribution of (p,xp) reaction, curve 2 is the sum of (p,1nxp) reaction contribution and previous one, curve 3 is the sum of (p,2nxp) reaction contribution and previous one.

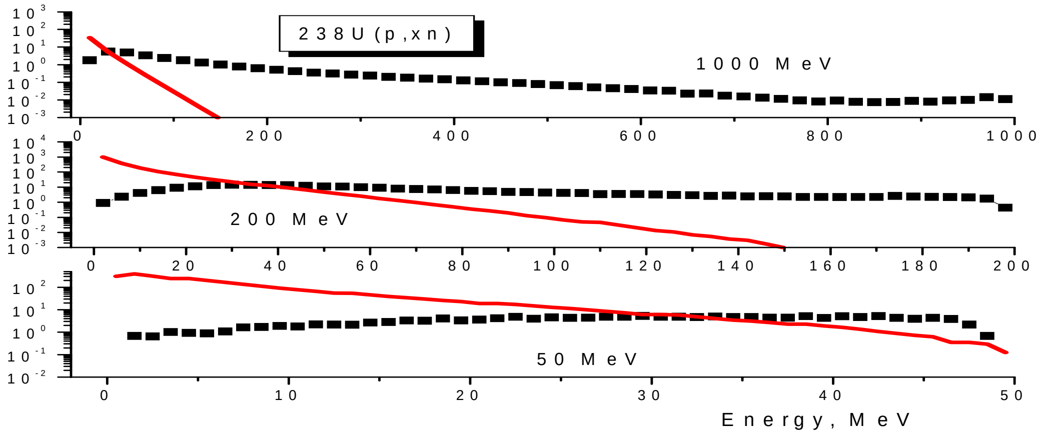

Fig. 3.5. The contributions of nonequilibrium mechanisms of the ^{238}U(p,xn) reaction at 50, 200 and 1000 MeV. The symbols are the cascade neutron spectra, the curves are the preequilibrium spectra.

2.3.3 Results of calculations

Some results of calculations are presented in figs. 2.3.6-2.3.11. The comparisons of the computed and measured neutron spectra of (p,xp) reaction on the medium and heavy mass targets for wide region of the projectile energies from 25 MeV to 160 MeV are shown in fig. 2.3.6 and 2.3.7. The experimental data for the energies up to 1 GeV are absent.

Nucleus of ^{90}Zr is interesting to verify the theoretical approach only. The second nucleus ^{208}Pb is interesting from two points of view. Firstly, it is in the list of the targets to generation of the data file of ISTC PROJECT#2524. Reasonably good description of the experimental spectra achieved is the evidence of the method reliability.

The fission cross sections of the two different types of fissile nuclei are shown in fig. 2.3.8-2.3.11. The two targets – ^{235}U and ^{238}U – have high fission probabilities. On the other hand, the fission cross sections of ^{208}Pb and ^{209}Bi are small for the projectile energies up to 1 GeV.

The calculations of fission cross sections as the function of the energy are needed not only to verify the theoretical method but also for the generation of data file in the ENDF-6 format. It is known the description of small cross sections, which are very sensitive on the competition of more strong reaction channels, is enough complicated.

The results presented in figs. 2.3.8-2.3.11 were calculated without the parameter fitting. In fact, the data comparison shows the real predictability of MCFx code and the abilities of the theoretical method developed in the frame of the project #2524. It can be seen that for ^{235}U and ^{238}U targets the experimental fission cross sections, in spite of some deviation, are described by the theoretical calculations resonably good for proton energies from 20 MeV to 1000 MeV. On the contrary, the measured fission cross sections of ^{208}Pb and ^{209}Bi targets are worse described by the calculations especially for proton energies from 200 MeV to 800 MeV. The main reason of this bad description is small values of cross sections. In this case the uncertainties in the strong reaction channels have the critical influence on the fission cross sections. For example, the errors in the parameterization of the π-meson generation cross section lead to crucial misbalance of the fission and another channels.

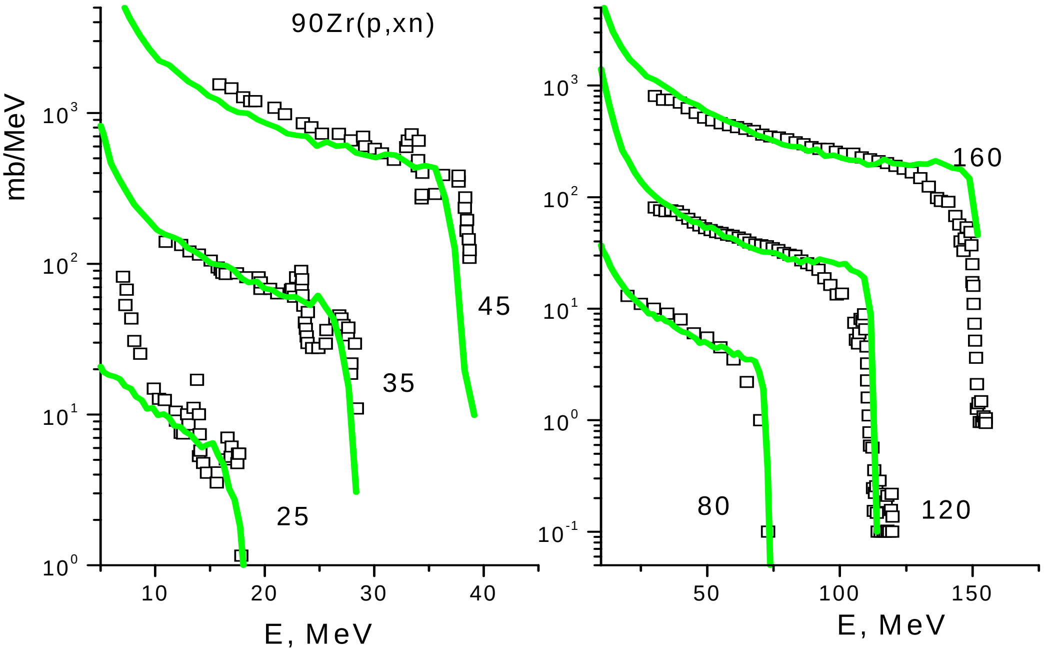

Fig. 2.3.6. The data on the neutron spectra of the ^{90}Zr(p,xn) reaction. The symbole are the measured data, the curves are the theoretical results of MCFx code.

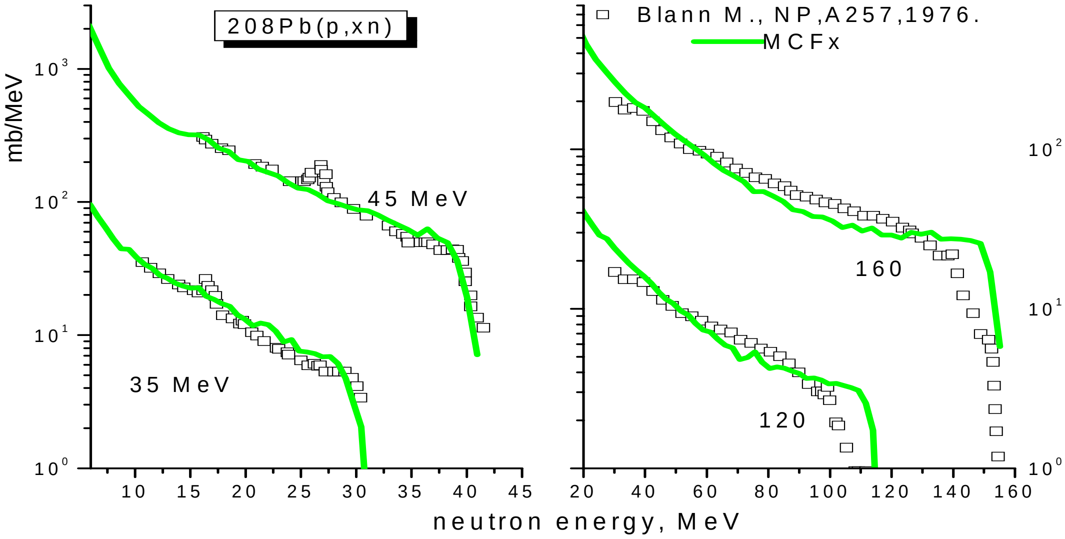

Fig.2.3.7. The same as in fig. 3.6 but for the ^{208}Pb(p,xn) reaction.

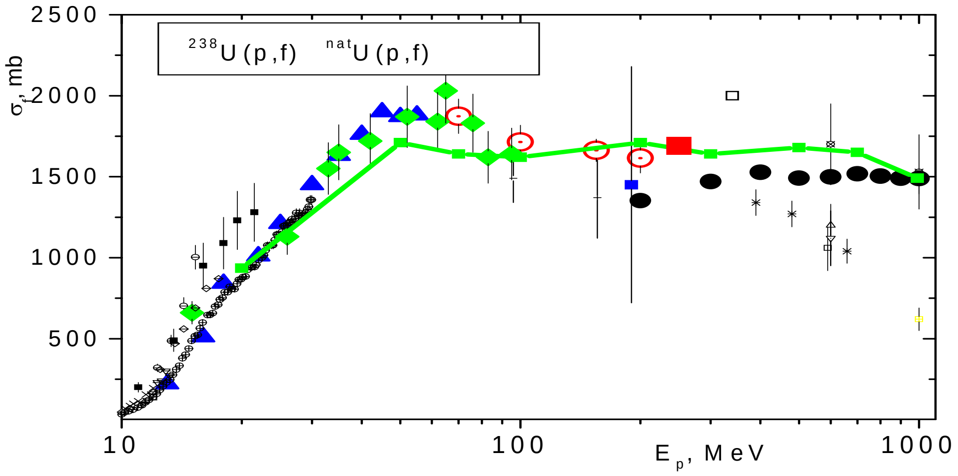

Fig. 2.3.8. The fission cross sections of ^{238}U by the protons. The symbols are measured data, the green curve is calculated results.

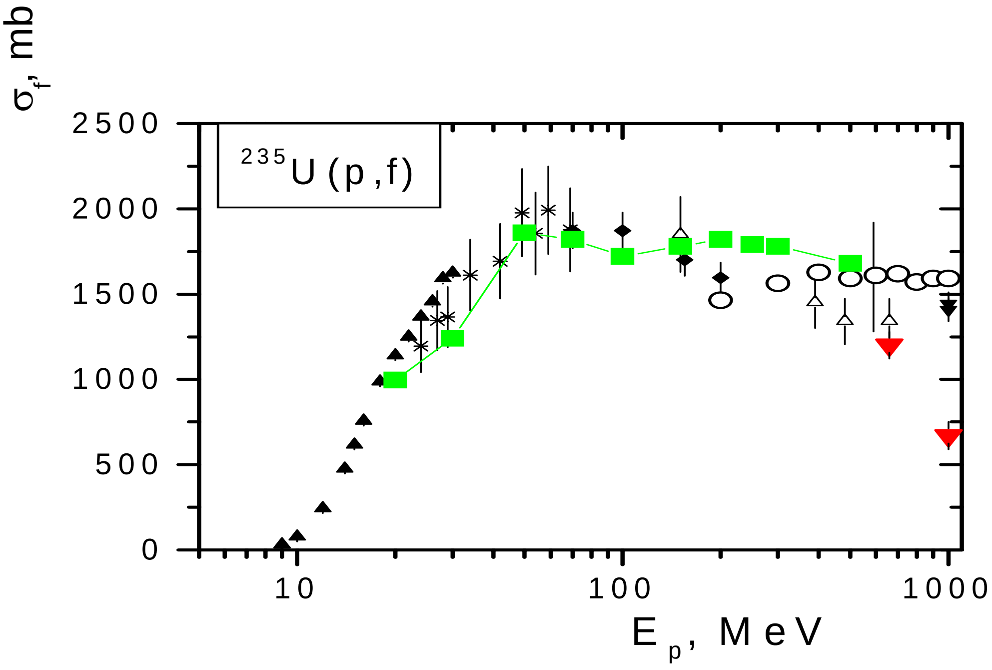

Fig. 2.3.9. The same as in fig. 3.8, but for ^{235}U.

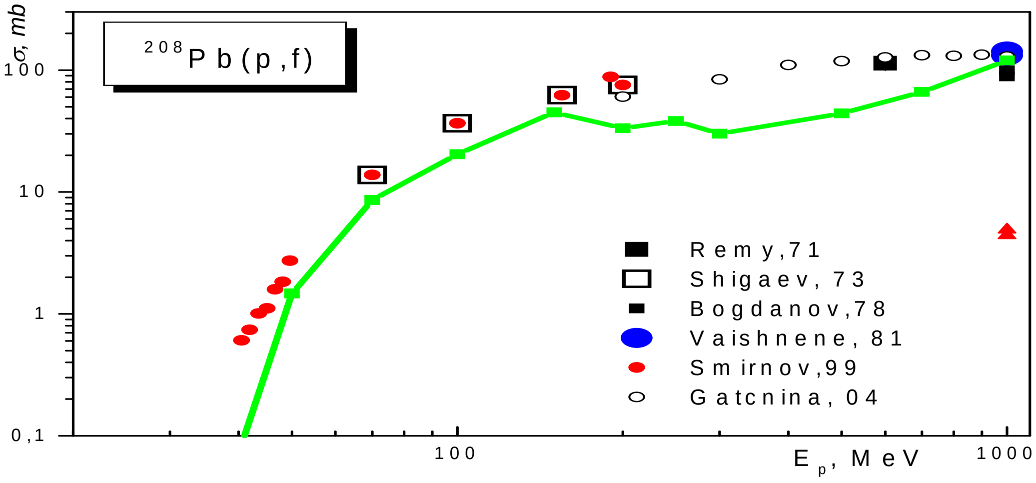

Fig.2.3.10. The same as in fig. 3.8 but for ^{208}Pb.

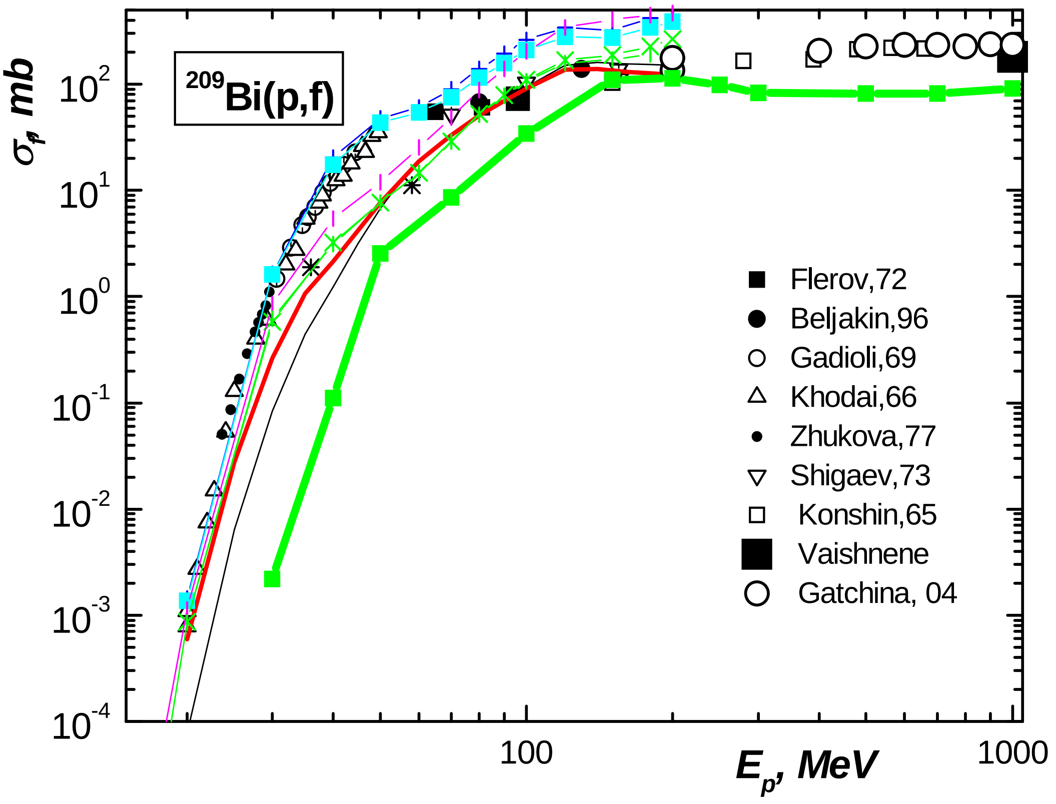

Fig. 2.3.11. The same as in fig. 2.3.8, but for ^{209}Bi. The curves for $E_p < 200$ MeV are the results of the ISTC Project#964 with the different types of the parameter fitting.

The angular distributions of the secondary particles from ^{208}Pb(p,xn) reaction are shown in fig. 2.3.12 for different projectile energies and for the different energies of secondary particle spectra. One can conclude that as the proton energy increases from 50 MeV to 1000 MeV and as the energy of emitted neutrons increases from the left part of the spectrum to the right one, the more number of the neutrons have forward direction of movement after interaction. For example, at small neutron energies the angular distributions are almost isotropic ones for the different proton energies (thin curves in fig.3.12). But for the maximal energies of the neutron angular distributions have very big values of “forward/backward” ratio. This “forward/backward” ratio value increases as projectile energy increases.

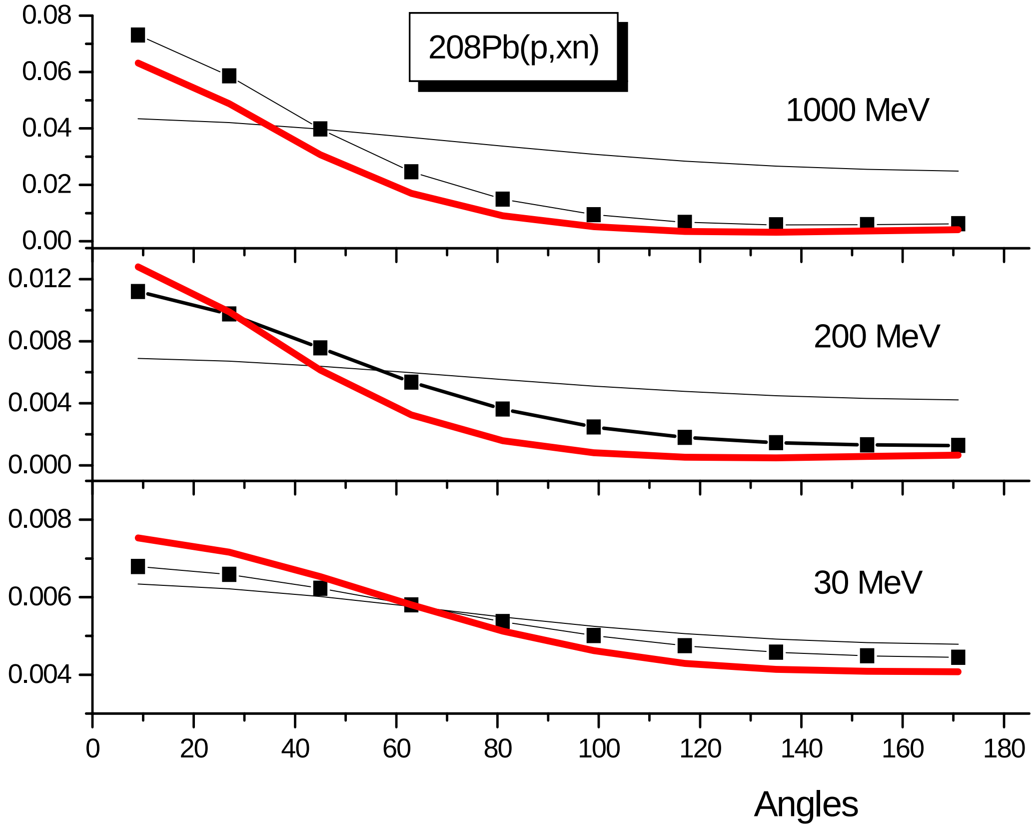

Fig. 2.3.12. The secondary neutron angular distributions of ^{208}Pb(p,xn) reaction at proton energies of 50, 200 and 1000 MeV for different neutron energies: the thin curves are for the small neutron energies (the left part of spectra); the symbols are for the middle neutron energies (the central part of spectra); the thick red curves are for the high neutron energies (the right part of spectra).

The multiplicities of the secondary neutrons and protons from (p,xnyp) and (n,xnyp) reactions were calculated by MCFx code. The Monte-Carlo simulation of all possible reaction chains was done to prepare input data for the code. The comparisons of our results for 208-Pb and LA150 [22] library data for neutrons and protons are demonstrated in fig.2.3.13. It can be concluded the good agreement for proton because statistical contribution to the value is rather small and nonstatistical models are more or less analogous. One can see that for neutrons the factor of two in multiplicities takes place. The contribution of statistical mechanism into n-multiplicities is not negligible and the reason of the differences is different parameters of the statistical model of nuclear reactions.

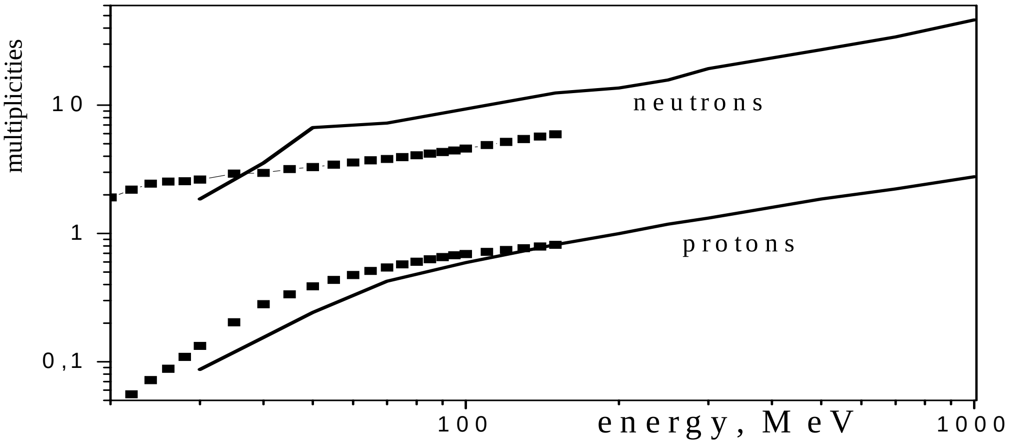

Fig. 2.3.13. Multiplicities of secondary neutrons and protons as a functions of projectile energies. Symbol are LA150 data, curves are present calculations.

2.3.4. References

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2. Development of fission fragment formation model

2.4.1 Introduction

Formation of fragments in nuclear fission is closely tied with important and still incompletely studied process of nuclear matter fragmentation for both low excited (spontaneous and thermal fission) and excited and highly excited states in the cases of intermediate and high energy nucleon-induced fission. Instability of outward fission barrier on octupole shape deformations has been noted already in the classical work [1]. However, until recently mass spectra of fission fragments were studied rather qualitatively. A number of sophisticated microscopical analyses [2-6] allowed to establish main characteristics of the process but these models are unpractical for systematical description of fragment mass spectra and nuclear data generation. Generalization of multimodal random neck rupture model to take into account nuclear temperature effects on fragment fission formation were presented in the work [7]. Results of calculation performed in this work shown a rather well description of experimental data for both low and intermediate energy fission but some ambiguities of the approach decrease its practical value. The analysis of contributions of different fission modes into the fragment mass spectra has been done in the work [9] in the framework of multimodal model, too.

It is clear at present that formation of fission fragment mass distributions is most of all connected with the properties of potential energy surface on the stage of saddle-to-scission descent. Dynamical effects are less influenced on the mass spectra and manifest itself in widths of mass distributions mainly. The model originate from a notion of nuclear shape oscillations on mass-assymetry degree of freedom in the potential well calculated with macroscopical-microscopical approach (Strutinsky' prescription) in one-center shape parameterization. Solution of one-dimensional Schrödinger equation in such a potential let us possibility to define fragment mass spectra and introduce temperature dependence of fragment yields in the natural way through temperature dependence of collective potential and population of states in the well.

2.4.2 The model

One of the important points in the study of nuclear configurations near the scission point is the choice of shape parameterization. Most of proposed methods for nuclear shape parameterization are limited by a specific shapes or small deformations near the ground state.

The method proposed by V.Pashkevich [10] for axially symmetrical configurations is free from these weaknesses. Here nuclear shape is defined in the orthogonal coordinate system where base family of coordinate surfaces is deformed Cassini ovaloids allowing to describe both oblate and prolate shapes including strongly prolate ones right up to division of nucleus on two fragments. This shape parameterization is especially suitable for fission and heavy ion reactions research but could be also applied for shapes near spherical ones.

Let us restrict the consideration by three main parameters of deformations that are $\{\alpha\} = (\alpha, \alpha_1, \alpha_4)$ where α is the lemniscate parameter, α_1 defines mirror symmetry of nuclear shape and α_4 is the parameter of hexadecapole deformations. At small values of the lemniscate parameter the shape of nucleus looks like ovaloids while values $\alpha > 0.9$ correspond to configurations with developed neck. Some examples for different sets of α, α_1, α_4 are shown in the Fig.2.4.1.

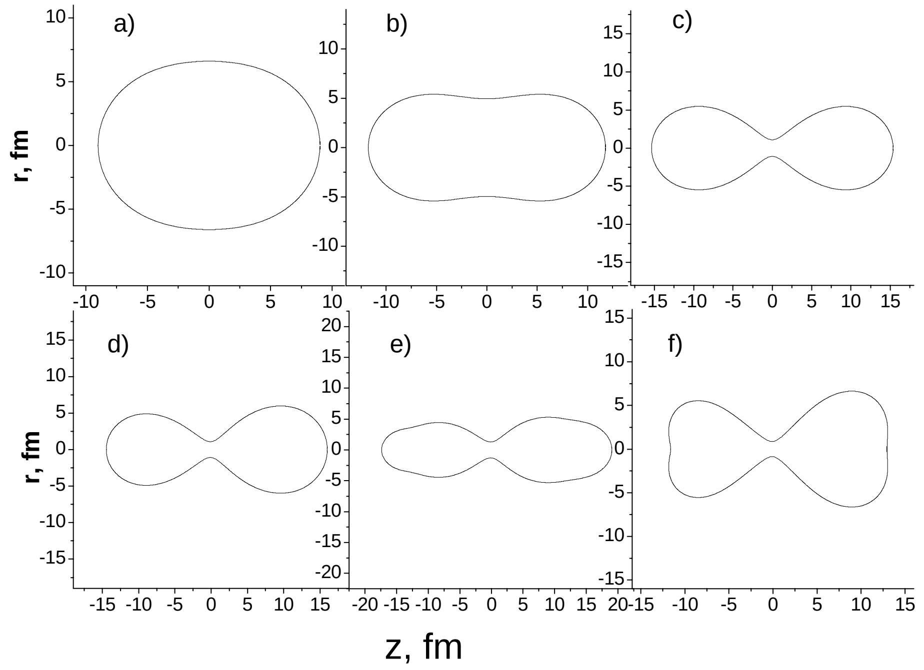

Fig. 2.4.1 Shapes of ^{236}U nucleus for different {α} sets:
a)α=0.3, α_1= α_4=0; b) α=0.7, α_1= α_4=0; c) α=0.99, α_1= α_4=0;
d) α=0.99, α_1= 0.1, α_4=0; e) α=0.3, α_1= 0.1, α_4=0.2; f) α=0.99, α_1= 0.1, α_4=-0.2.

Nuclear shape presented in the Fig. 2.4.1a corresponds to configurations near the ground state, in the Fig. 2.4.1b corresponds to shapes near the second barrier and shapes in the Fig. 2.4.1c-f correspond to the region near scission state.

Collective motion in the space of collective coordinates is defined in the common case by dynamical and static nuclear properties. Fission process as a process of movement from ground state to scission point is the large-scale nuclear process, the properties of fission depending both from the links of single particle degrees of freedom with collective coordinates which are manifested as friction, from fluctuations of an effective mass coupled with coordinate α and other effects and the structure of potential energy surface. One can expect that for formation of fragment mass asymmetry is defined mainly by properties of deformation energy near the scission because observed displacements from symmetrical fission are not very strong (about 10-15 % percents for actinides).

We use one-dimensional Schrödinger equation for description of the collective motion over mass-asymmetry coordinate:

$$\left\{-\frac{\hbar^2}{2\sqrt{B_1}}\frac{\partial}{\partial\alpha_1}\frac{1}{\sqrt{B_1}}\frac{\partial}{\partial\alpha_1}+V_T(\alpha_1;\alpha_{sc};\alpha_4^{\min})\right\}\psi_\nu(\alpha_1)=E_\nu\psi(\alpha_1). \qquad (2.49)$$

Here B_1 is the mass parameter for mass-asymmetry mode α_1, $V_T(\alpha_1;\alpha_{sc};\alpha_4^{\min})$ is the temperature dependent collective potential energy of deformation as function of α_1 at the scission point $\alpha=\alpha_{sc}$, the potential energy being minimized on the parameter of hexadecapole deformation $\alpha_4=\alpha_4^{\min}$ where $\alpha_4^{\min}$ is chosen from the condition of potential energy minima, $\psi_\nu(\alpha_1)$ are collective wave functions and E_ν is the energy spectra of collective states.

Probability to find configuration with given value of α_1 can be expressed as follows:

$$Y(\alpha_1) \propto \sum_{\nu} \left|\Psi_\nu(\alpha_1)\right|^2 e^{-E\nu/T}\, d\alpha_1, \tag{2.50}$$

while fragment mass spectra has the following form:

$$Y(A_1(\alpha_1)) \propto Y(\alpha_1)\frac{dA_1}{d\alpha_1}, \tag{2.51}$$

where A_1 is the mass number of one from the fragments.

Similar model has been proposed earlier in the work [11]. However, two-center configuration in the scission point (configuration of nascent fragments) used in [11] requires correct account of fragment interaction including nucleon exchange between fragments [12] which was not done in this work. The one-center model used in the present work is free from these weaknesses and is in natural way connected with the saddle-to-scission descent stage.

Let us define main quantities in the equation (2.49). One of the important questions here is the definition of scission point. We suggest that scission takes place when neck radius is equal to 1 fm that is about nucleon radius. Such a condition allows to fix lemniscate parameter $\alpha_{sc} \approx 0.99$ (value of α_{sc} is slightly varied in dependence of mass number of fissioning nucleus).

Dynamical nuclear properties become apparent in the behaviour of mass parameter B_1 as function of α_1. Generally microscopical calculation of effective mass as a response of nuclear system on the mean field distortions is a real challenge enclosing a number of ambiguities. In our simplified approach we used one extreme limit for mass parameter. Here one can neglect by dynamical effects and use liquid drop value for small oscillations $B_1 \propto A^{5/3}$ where A is the mass number of fissioning nucleus.

Governing value in our model is the dependence of the potential energy on α_1 near the scission point. Let us write down the potential energy as a sum of smooth liquid drop part and shell and pair corrections (V.Strutinsky, [13]):

$$V_T(\{\alpha\}) = E_{ld}(\{\alpha\}) + f(T)\delta E(\{\alpha\}), \tag{2.52}$$

where E_{ld} is a liquid drop energy, quantity δE takes into account shell correction and pair energy, $\delta E = E_{shell} + E_{pair}$ and function $f(T)$ reflects dumping of nuclear structure effects with nuclear temperature increase. We used Woods-Saxon form of function $f(T)$, $f(T) = 1\big/(1+\exp(T-T_{cr})/a)$, where T_{cr} and a are model parameters. Single particle spectra which are necessary to calculate shell corrections and pair energies have been calculated with DIANA code [14], the nuclear shape has being taken in the lemniscate coordinate and mean field potential was as deformed Woods-Saxon potential. Parameters of potential and pair interaction have been chosen in the ordinary way according [15].

2.4.3 Results of calculations

The potential surface for ^{236}U fission is shown in the Fig.2.4.2 for region from the second well up to scission. Energy of deformation calculated accordingly (2.52) for unexcited nucleus as function of deformation parameters α, α_1 and α_4 and minimized on the hexadecapole mode α_4. Results presented in the Fig.2.4.2 show that the potential well on the mass-asymmetry mode starts development at the descent stage from the saddle point ($\alpha \approx 0.66$), the form of the well and its components being shown in the scission point vs. mass number of nascent fragment in the Fig.2.4.3.

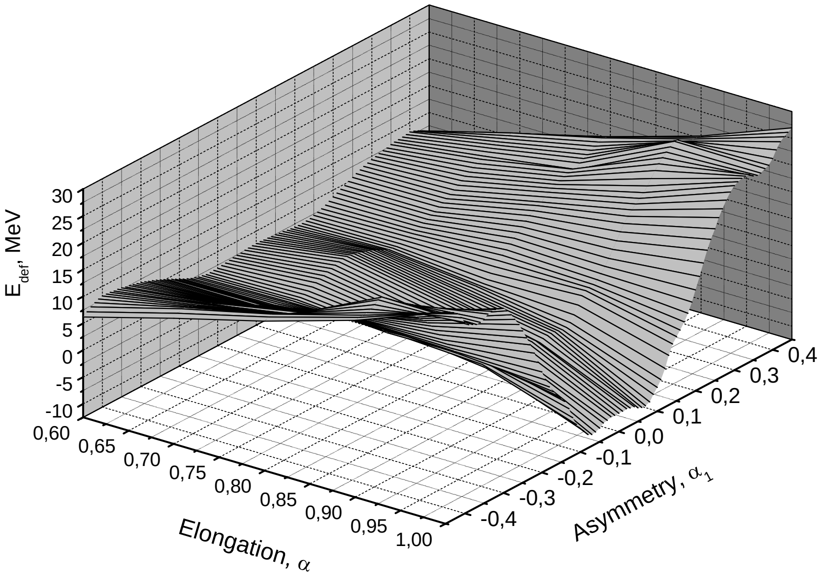

Fig. 2.4.2 Potential energy surface for the fission of ^{236}U vs. elongation and asymmetry of nuclear shape.

Calculations have been done at zero nuclear temperature and link between asymmetry parameter α_1 and fragment mass was found as the following integral:

$$A_1 = 2\pi \frac{A}{V} \int_{z_{\min}}^{z_1} r^2(z)dz, \tag{2.53}$$

where A_1 is the mass number of one of fragments, A and V is the mass number and volume of fissioning nucleus, correspondingly, $r(z)$ is the surface equation in cylindrical coordinates (r, z), z_{min} is the value of z coordinate in the point with the minimal value of neck radius, and z_1 is the value of z at edge of nucleus.

It is seen from the Fig.2.4.3 that results of our calculations shows clear minimum in the potential energy near fragment mass 140 a.u. in accordance with well-known property of fragment mass distributions of actinides.

The similar picture takes place for all actinides. The results of the potential energy calculations for other nuclei are shown in the Fig. 2.4.4.

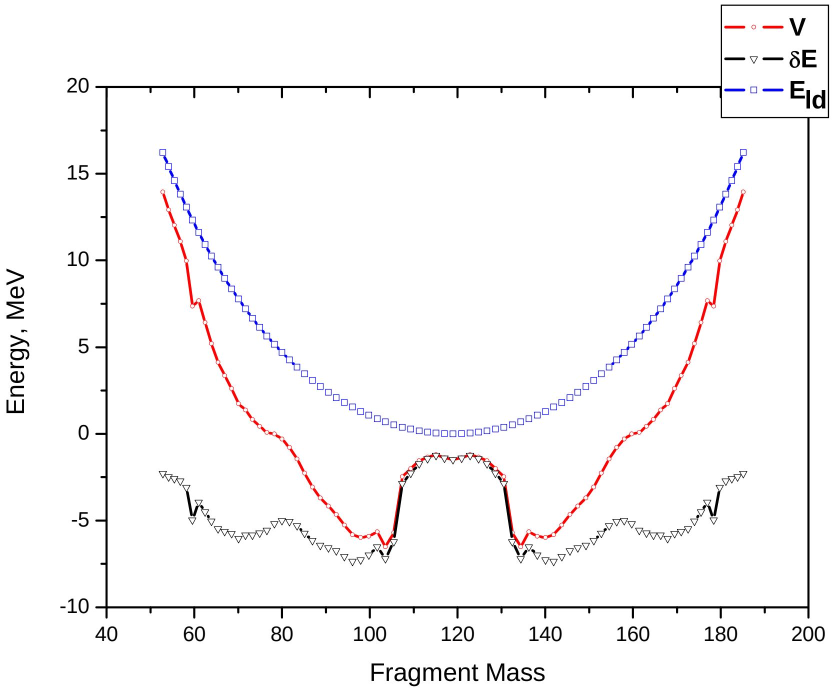

Fig. 2.4.3 Potential energy of deformation and its components in the scission point for the case of 236-U fission as function of nascent fragment mass number for zero nuclear temperature.

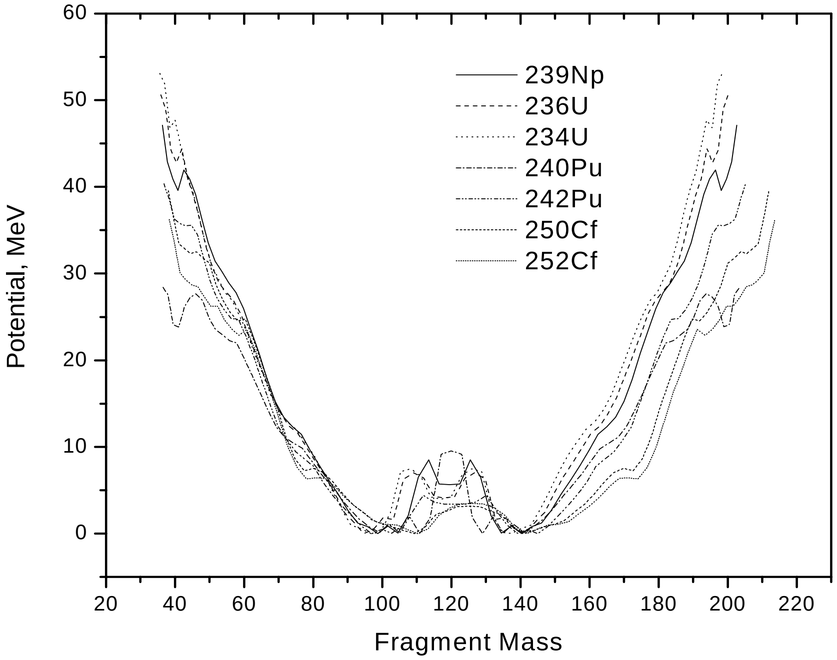

Fig.2.4.4. The dependence of the potential energy on the fragment mass for nuclei from U to Cf

The solution of eq. (2.49) has been found as series expansion on the oscillator basis. Some results for low-energy fission fragment mass distributions are presented in the Fig.2.4.5-2.4.7.

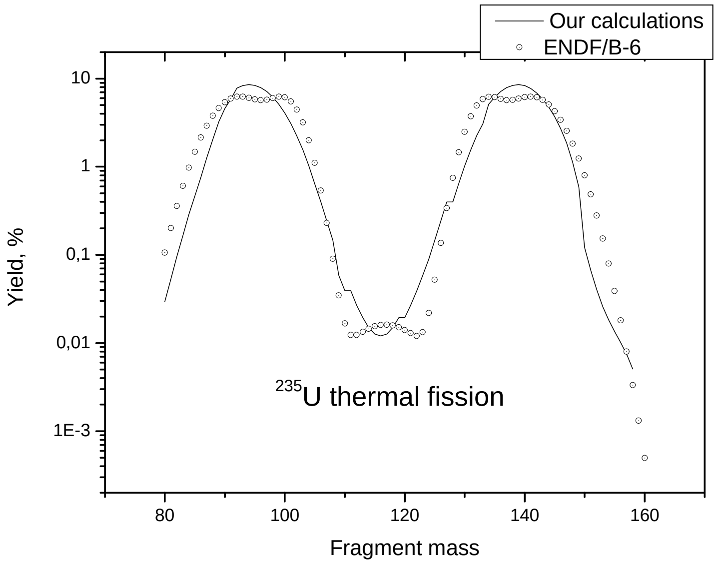

Fig. 2.4.5 Fission fragment mass distribution for thermal fission of 235-U

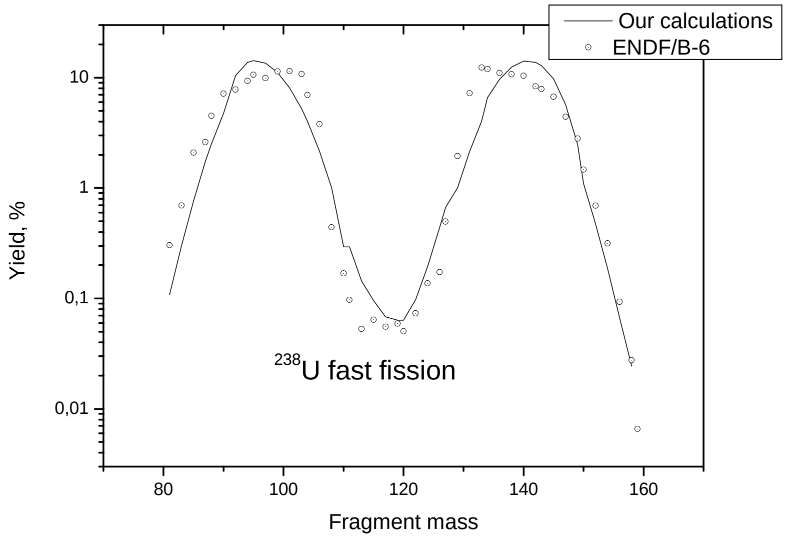

Fig. 2.4.6 Fission fragment mass distribution for fast fission of 238-U

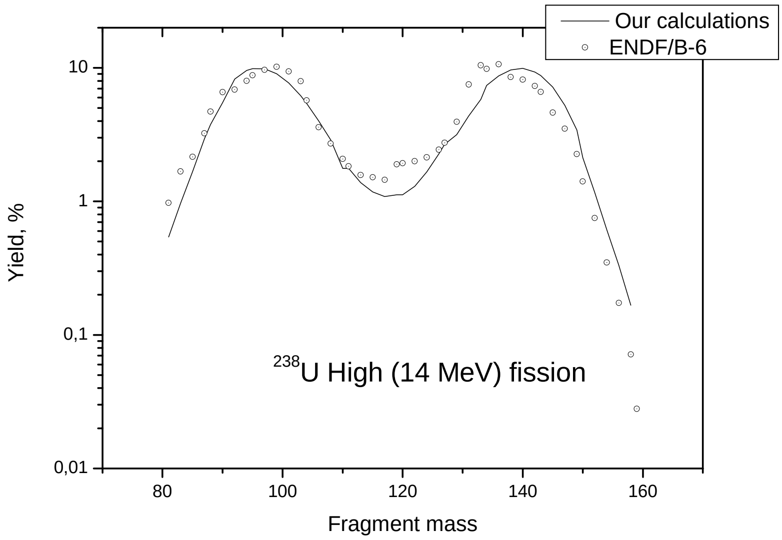

Fig. 2.4.7 Fission fragment mass distribution for 14-MeV fission of 238-U

In all cases the neutron emission from fission fragments has been approximates by sawtooth function based on the experimental data [17] and presented in the Fig. 2.4.8.

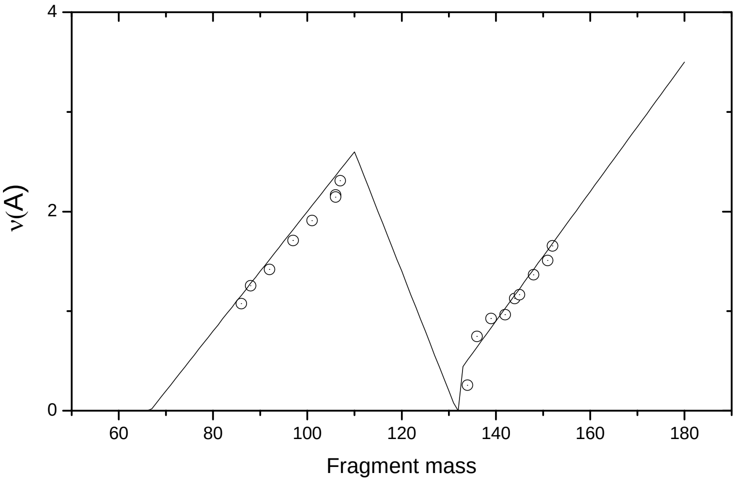

Fig.2.4.8 Fission fragment neutron multiplicity vs. fragment mass

For intermediate-energy fission one should take into account the formation of wide distribution of fissioning nuclei on mass and charge numbers and excitation energies A_f, Z_f, E_f^* due to prefission particle emission at each stage of nucleon-induced reaction, i.e. at direct, preequilibrium and equilibrium (multichance fission) stages. The final fragment mass distribution could be found as a superposition of fragment yields for each nucleus with corresponding weight $W(A_f, Z_f, E_f^*)$ defined by the reaction mechanism:

$$Y \propto \sum_{A_f, Z_f, E_f} W(A_f, Z_f, E_f^*) Y_f, \tag{2.54}$$

The example of weight distribution is shown in the Fig.2.4.9 for the case of 475 MeV proton-induced fission of ^{209}Bi. The calculations have been done with the developed code MCFx.

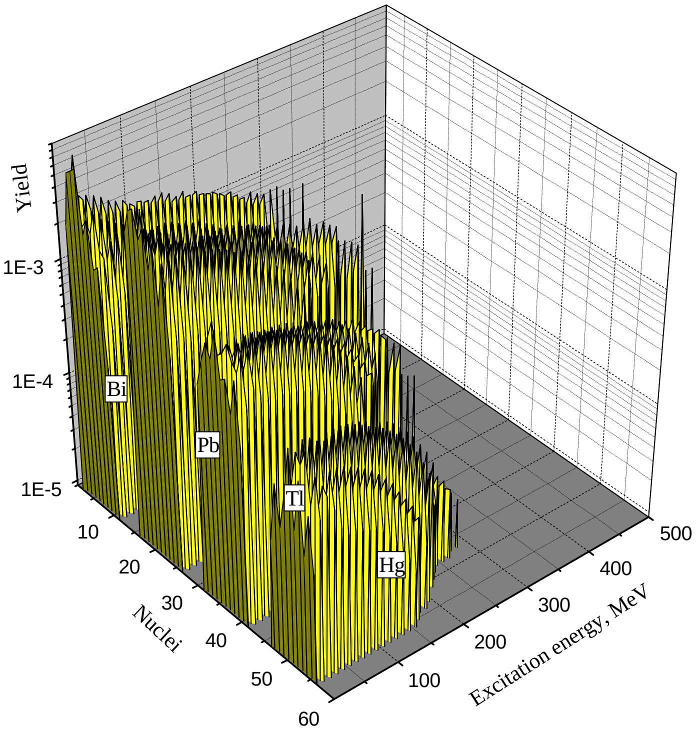

Fig.2.4.9. Yields of residual nuclei in the reaction 209-Bi+n with 475 MeV neutron energy

Calculated fission fragment mass distributions (eq. (2.54) are shown in the Fig.2.4.10 for the reaction ^{209}Bi(p,f) at energy 475 MeV and in Figs. 2.4.11-15 for ^{238}U(n,f) for neutron energies from 20 to 450 MeV in the comparison with experimental data. It is necessary to note that the experimental data on the fission fragment yields for energies higher 14 MeV are very scarce and not very reliable. Nevertheless, one can see that in these cases our results reproduce experimental data rather well. So, we can conclude that the model developed in link with MCFx code can be used for data file generation on the fission fragment mass distributions at low- and intermediate energy fission.

The calculated isotopic mass distributions are presented in the Fig. 2.4.16 for ^{238}U neutron-induced fission with different neutron energies. Isotopic distribution was found from isobaric distribution which is defined by Gaussian function [17]

$$Y_A(Z) \propto \exp\left(\frac{(Z-\overline{Z}_A)^2}{2\sigma_Z^2}\right) \tag{2.55}$$

with average value of fragment charge Z calculated with UCD hypothesis [17], $\overline{Z}_A = \frac{Z_f}{A_f} A$, Z_f, A_f are charge and mass numbers of the fissionning nucleus, A is the mass number of the fragment, correspondingly, and with $\sigma_Z^2 = 0.4$ ch.u.^{2} taken from experimental data [17].

Results presented in the Fig. 2.4.16 show clear shift and broadening of the distributions, the effect being completely caused by reaction mechanism and increasing of fissionning nuclei number with the increase of beam energy.

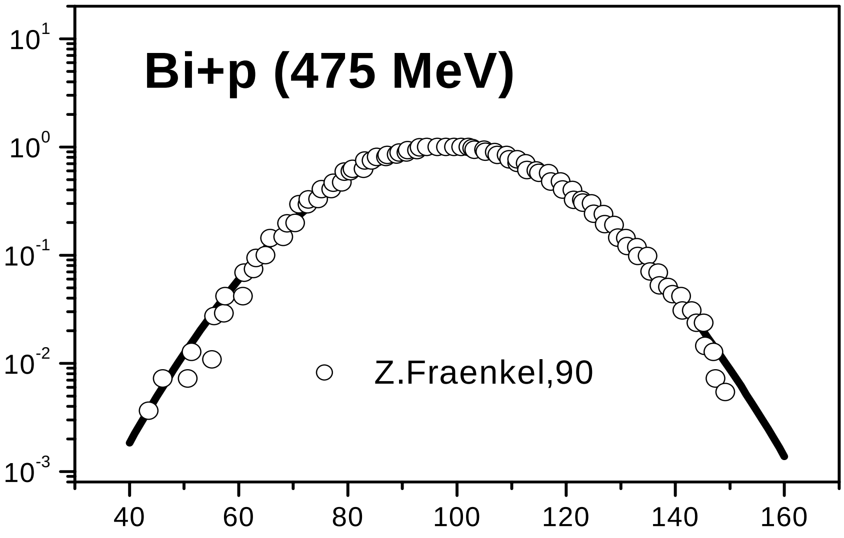

Fig. 2.4.10 Fission fragment yields for ^{209}Bi(p,f). Experimental data were taken from work [19].

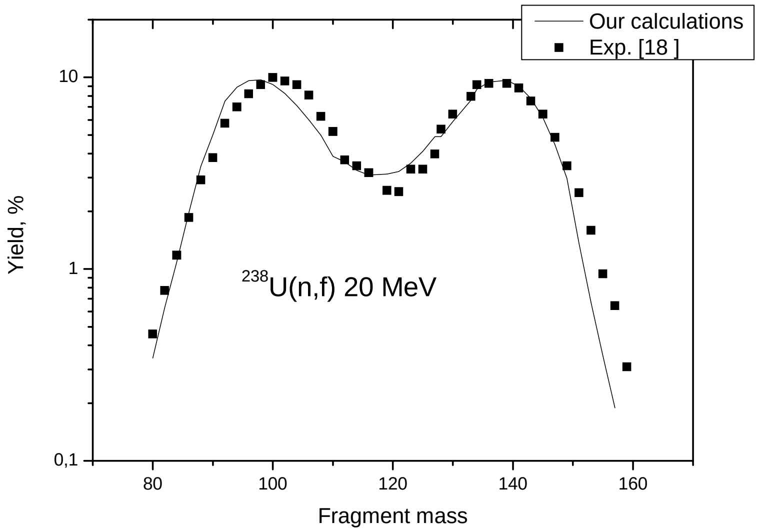

Fig. 2.4.11 Fission fragment yields for ^{238}U(n,f), E_n=20 MeV. Experimental data were taken from work [18].

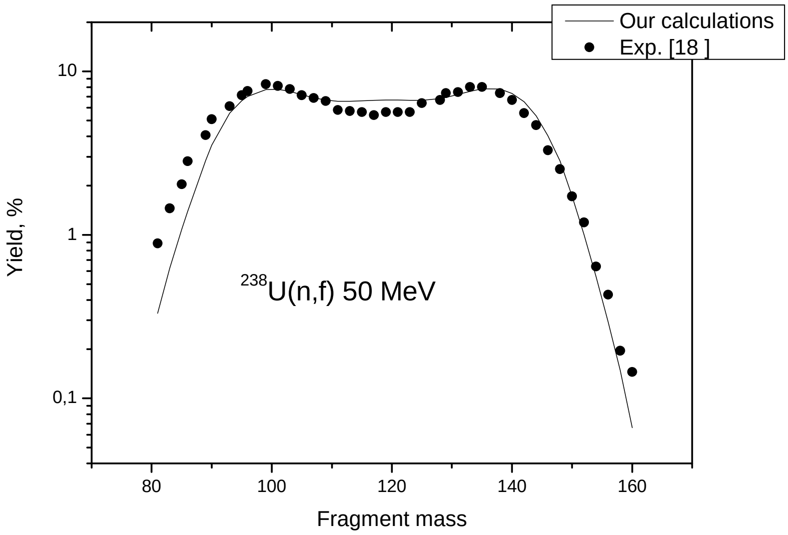

Fig. 2.4.12 Fission fragment yields for ^{238}U(n,f), E_n=50 MeV. Experimental data were taken from work [18].

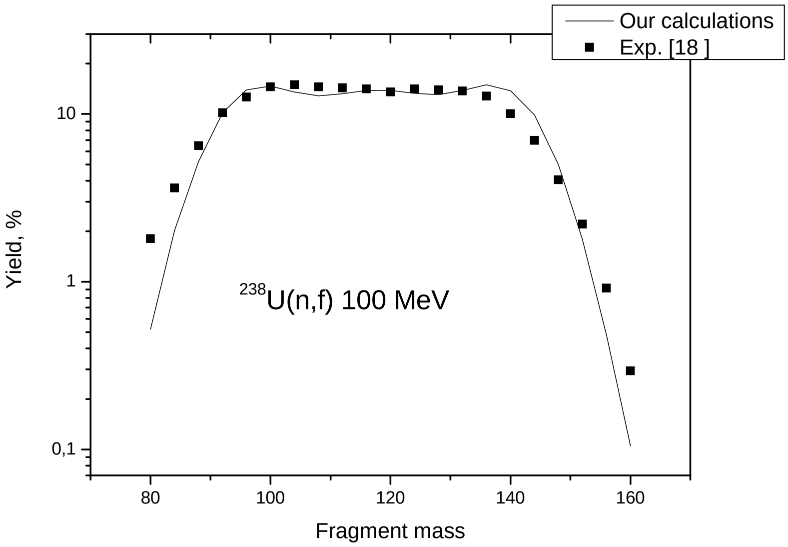

Fig. 2.4.12 Fission fragment yields for ^{238}U(n,f), E_n=100 MeV. Experimental data were taken from work [18].

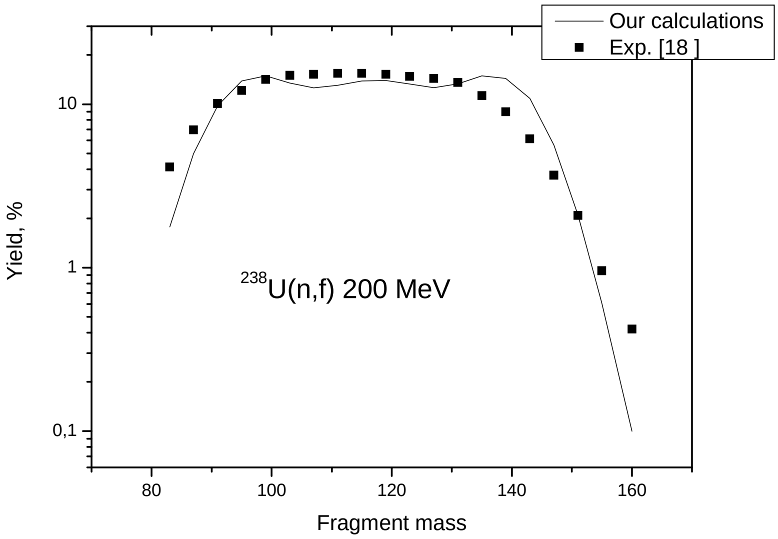

Fig. 2.4.13 Fission fragment yields for ^{238}U(n,f), E_n=200 MeV. Experimental data were taken from work [18].

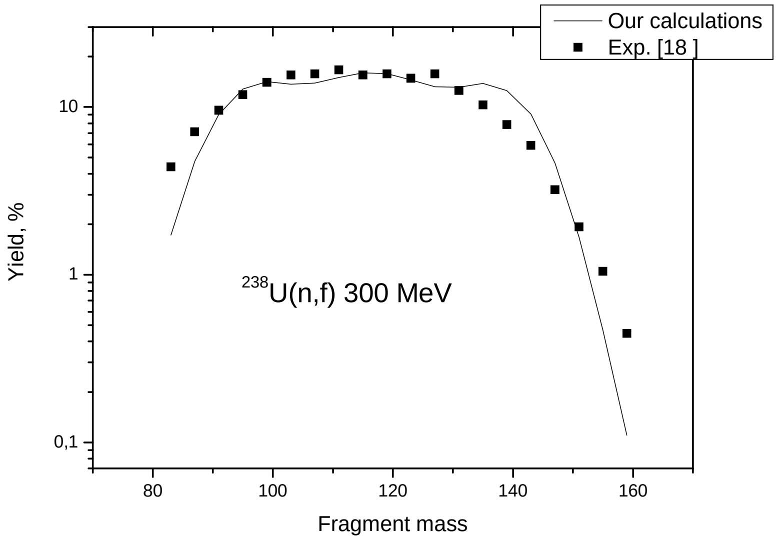

Fig. 2.4.14 Fission fragment yields for ^{238}U(n,f), E_n=300 MeV. Experimental data were taken from work [18].

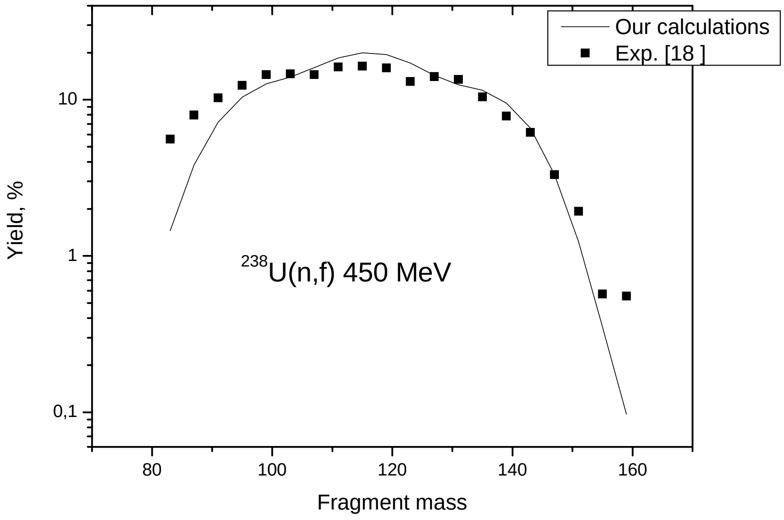

Fig. 2.4.15 Fission fragment yields for ^{238}U(n,f), E_n=450 MeV. Experimental data were taken from work [18].

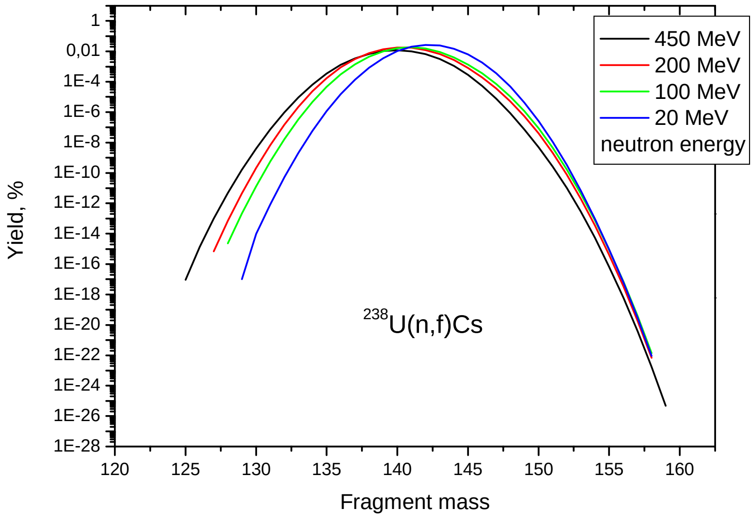

Fig. 2.4.16 Yields of Cs isotopes in 238-U(n,f) reaction for different neutron energies

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2.5. Development of fission barriers library

2.5.1 Introduction

The models of fission fragment formation in the nucleon-induced reactions at low and intermediate energy region as well as for calculations of fission barrier were proposed at previous stages of the project performance. The models are based on the properties of potential energy in the space of collective coordinates defining nuclear shape in lemniscate coordinates (see sect.2.4). It was necessary during this work to introduce the nuclear stiffness relative to mass-asymmetrical oscillations as a model parameter. The rather well agreement between theoretical and experimental data on fission fragment yields confirmed the adequacy of the model for description of main fission characteristics for both cold and heated nuclei. However, the development of fission barrier data library for nuclei formed in reactions with intermediate energy nucleons far from the stability where the data on the fission barriers are absent raised a question on the model parameter specification. With this goal the known approaches for the calculations of collective potential energy were analyzed and it was concluded on the necessity of taking into account of the curvature energy especially in vicinity of the saddle point where fissionning nucleus is deformed strongly.

Conception of curvature energy E_{cur} was introduced into the nuclear physics as early as the fifties of the last century as extension of the classical model of liquid drop used for the estimation of fission barriers and nuclear masses. Already in 1953 Hill and Wheeler [1] deduced from Fermi-gas model that there should exist a curvature-dependent term in the liquid drop potential energy. Other approaches to the curvature energy where further proposed in works [2-4]. The common feature of all models mentioned is the proportionality rule $E_{cur} \propto A^{1/3}$ where *A* is the mass number of the nucleus.

Similar calculations were performed recently in the framework of new version of liquid drop model by Pomorski and Dudek [5]. Calculation results show on significant improvement of experimental data description in comparison with traditional model. However, neglect by shell corrections and mass-asymmetry deformations reduce the predictive power of the model especially for the calculations of actinide low-energy fission.

Research of nucleon-induced fission at intermediate nucleon energies meets need of inclusion to the calculation scheme of fission barrier dependence on excitation energy. At present practically there is no detailed investigations of this kind of dependence as well as influence of barrier temperature dependence on the description of main integral fission characteristics as, for example, fission cross-sections. It is clear qualitatively that increase of excitation energy (of nuclear temperature) results in the transition from double-humped to one-humped barriers in the actinide region caused by shell corrections melting. For lead-bismuth region this effect leads to the change of the barrier height and width.

In the given work the semimicroscopical approach to the calculations of fission barriers with taking into account all items enumerated, *i.e.* curvature energy, shell corrections, mass-asymmetrical deformations, and temperature dependence.

2.5.2 The model and results

Governing value in our model is the dependence of the potential energy on α_1 near the scission point. Due to Strutinsky prescription the potential energy could be presented as a sum of smooth liquid drop part and shell and pair corrections (see eq. 2.52).

In the classical liquid drop model the smooth part of energy is as follows:

$$E_{ld} = b_s(T)S + b_c(T)B_{coul}\,, \tag{2.55}$$

where b_s and S are surface tension and area and b_c , B_{coul} are coulomb energy coefficient and coulomb energy, correspondingly, T is the nuclear temperature connected with nuclear excitation energy

$$E^* = a_{ld} T^2 , \tag{2.56}$$

a_{ld} is the level density parameter, $a_{ld} = A/10$. We use the standard Myers-Swiatecki model [6] as a "classical" liquid drop model.

The temperature dependence of coefficients in (2.56) was presented in [7] in the following way:

$$b_s(T) = b_s^0 \left(1 - (\beta - \frac{2}{3}\alpha) T^2 \right), \tag{2.57}$$

$$b_c(T) = b_c^0 \left(1 - \frac{1}{3}\alpha T^2 \right), \tag{2.58}$$

where b_s^0, b_c^0 are parameter values at zero temperature, $\alpha = 0.0032$ MeV^{-2}, $\beta = 0.00114$ MeV^{-2}.

Let us introduce to the liquid drop model the curvature-dependent term, $E_{ld} = E_{surf} + E_{coul} + E_{curv}$. Following to [4] the curvature energy has the form as follows

$$E_{cur} = b_{cur} \int dS (\frac{1}{R_1} + \frac{1}{R_2}) , \tag{2.59}$$

where R_1, R_2 are principal curvature radii of the surface-sheet element dS.

In cylindrical coordinates (r, z) expression (2.59) has a form (relative to the energy of spherical shape nucleus):

$$E_{cur} = b_{cur} \pi \int_{z_1}^{z_2} \frac{r(z) r''(z)}{1 + r'^2(z)} dz . \tag{2.60}$$

Here $r(z)$ is the surface equation and integration is carried out between poles z_1, z_2 defined by condition $r(z_1) = r(z_2) = 0$. Coefficient b_{cur} is the model parameter and it could be found from fit to the experimental values of fission barriers.

Example of the potential energy surface for 236-U was presented in the Fig. 2.4.2 in the previous section.

It is necessary to carry out further minimization of energy on α_1 parameter in order to define fission barriers. The example of such a calculation is presented in the Fig. 2.5.1 for ^{236}U fission with and without curvature energy.

As results presented show the account of the curvature energy leads to the decrease of outer fission barriers in agreement with experimental data.

Constituents of the deformation energy, *i.e.* smooth part and shell+pair corrections are shown in the Fig. 2.5.2 for two cases also. It is seen from the figure that the decrease of outer barrier is caused by liquid drop part of the energy while some variation of shell part are connected with different (α_1, α_4) values obtained in the energy minimization procedure for these two cases.

The behavior of asymmetry parameter α_1 along fission path is shown in the Fig. 2.5.3. Positions of the ground state (G.S.), first and second barriers (B I, II), and second mimimum (MIN II) are indicated by arrows. Results presented are in good accordance with the modern knowledge on the potential energy structure. It is seen that nuclear shape comes to mass-asymmetrical shapes near the saddle point only and the height of the second barrier is strongly depended from the correct choice of mass asymmetry. In the vicinity of the scission point our calculations give the mean value of the heavy fragment $\overline{A}_H \approx 140$ in agreement with well-known property of fission fragment mass distribution for low-energy fission of actinides (see insert).

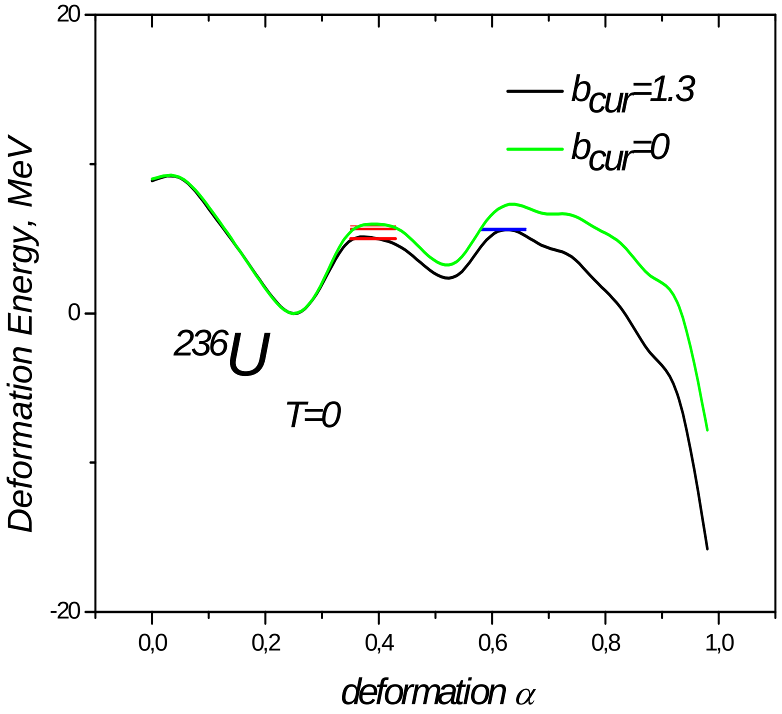


Fig. 2.5.1 Deformation energy for ^{236}U fission with (black line) and without (green line) curvature energy. Red lines are indicated the interval of experimental values for the height of the inner barrier and blue ones – for the outer barrier. Experimental data are taken from works [8-10].

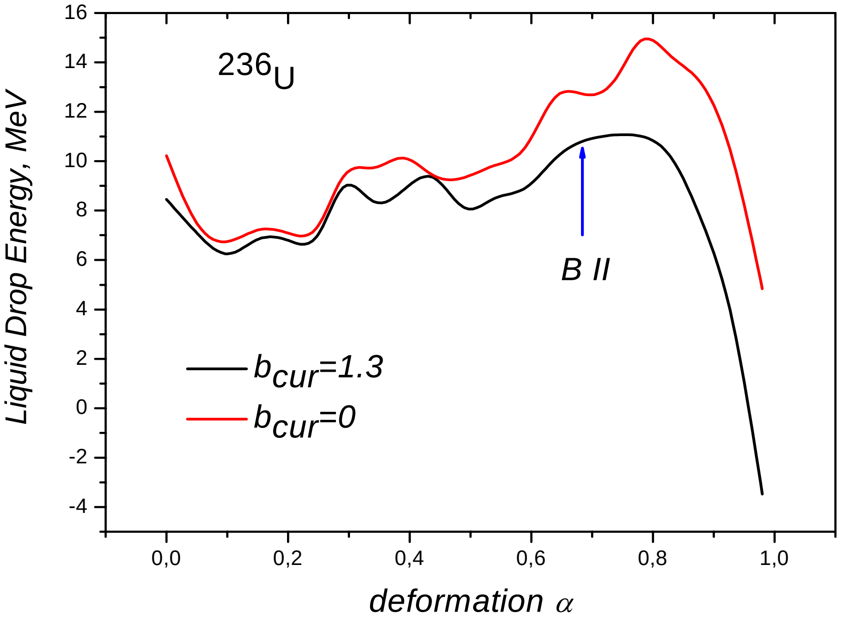


Fig. 2.5.1 Liquid drop part of deformation energy for ^{236}U fission. Blue arrow indicates the position of the outer fission barrier.

The same results were obtained for ^{240}Pu fission (see Figs. 2.5.5-2.5.6). So, the model for the calculations of fission barriers with taking into account of possible mass asymmetry of fissionning nucleus and curvature energy is able to reproduce main experimental features of fission barriers and future fragment masses at least in the actinide region.

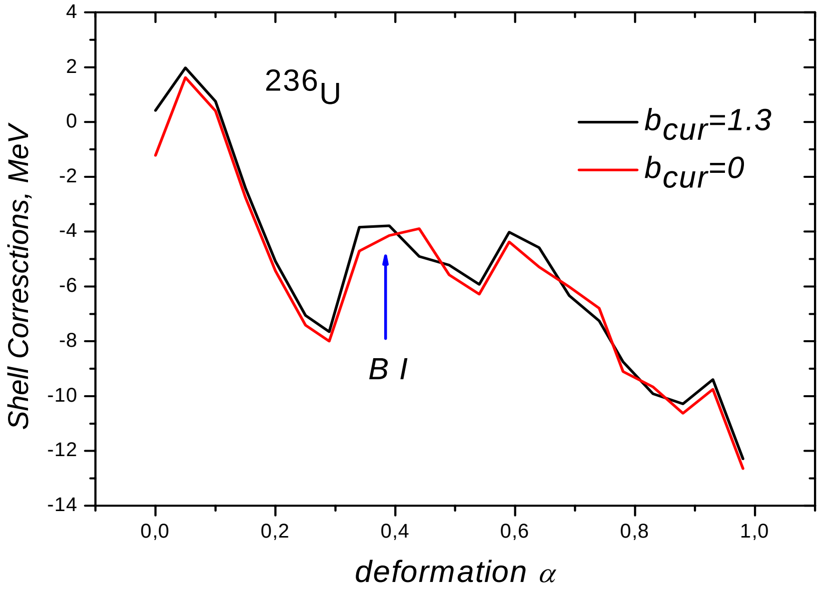


Fig. 2.5.2 Shell+pair part of deformation energy for ^{236}U fission. Blue arrow indicates the position of the inner fission barrier.

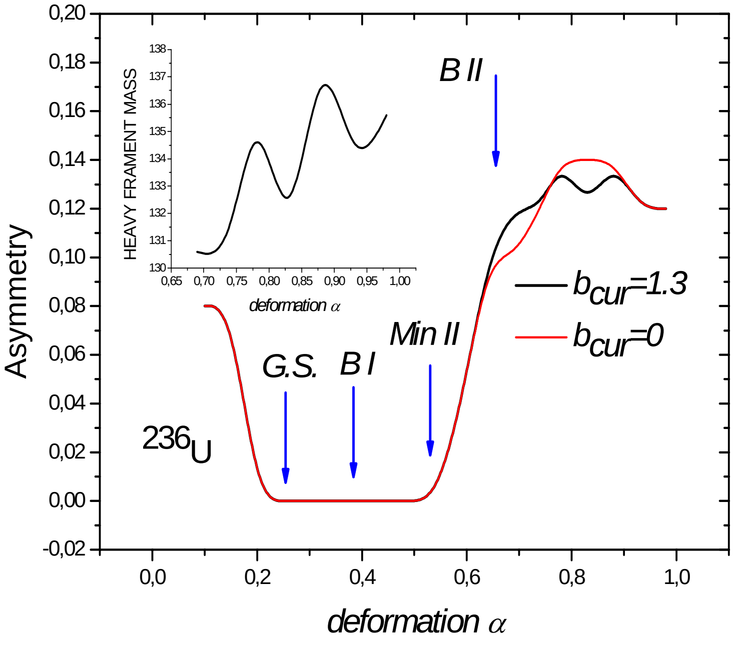


Fig. 2.5.3 Parameter of asymmetry α_1 *vs.* elongation parameter α for ^{236}U fission See text for figure legend.

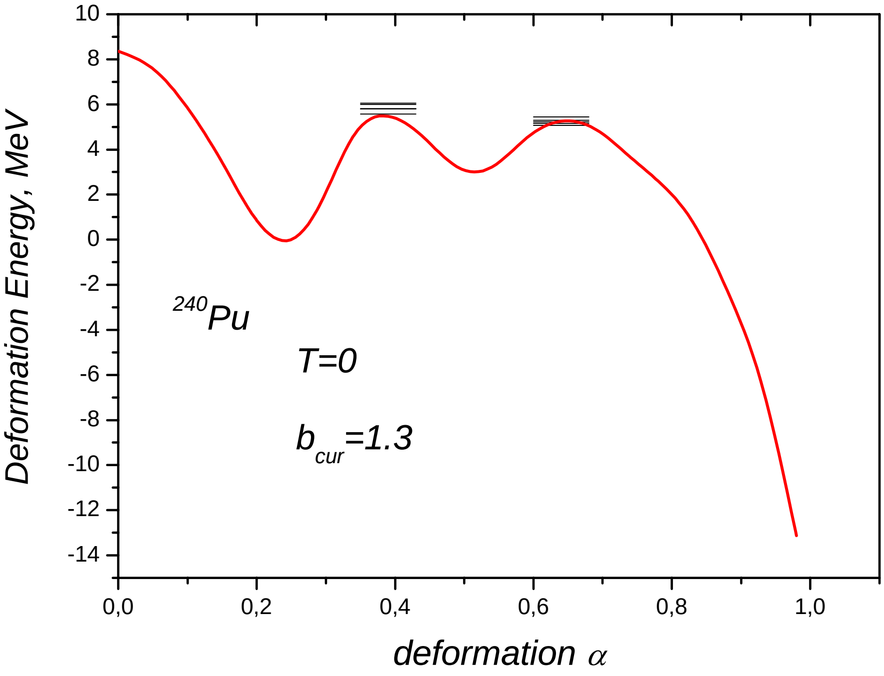


Fig. 2.5.4 The same as in Fig. 2.5.1 but for ^{240}Pu fission

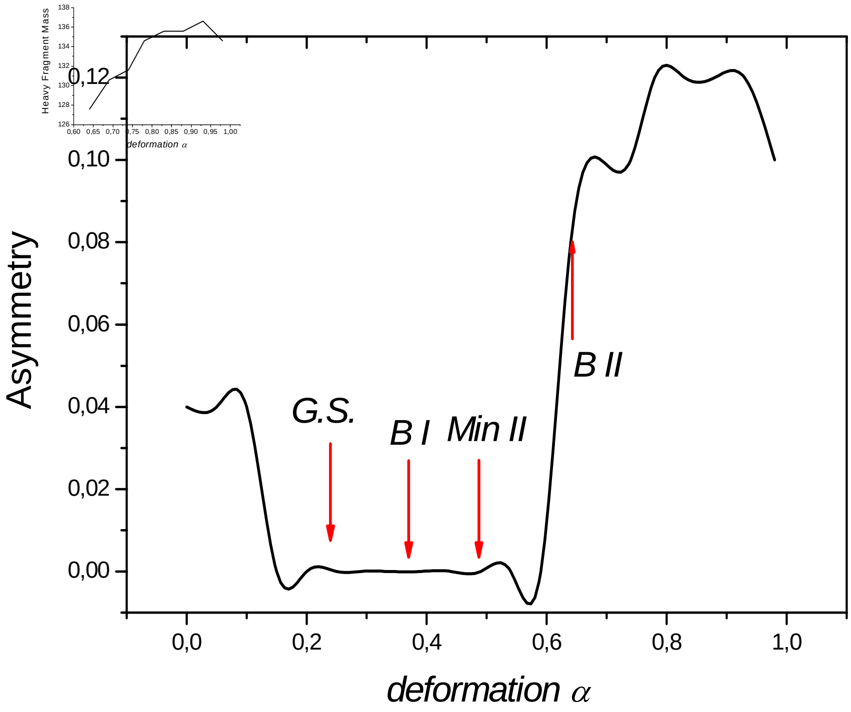


Fig. 2.5.5 The same as in Fig. 2.5.3 but for ^{240}Pu fission

The expression (2.52) for nuclear potential energy allows to include the melting of nuclear structure effects for higher excitation energies in the natural way. The dependence of the potential energy at different excitation energies is shown in the Fig. 2.56. Calculations were done at typical values of $f(T)$ parameters in (1), $T_{cr} = 1\,\text{MeV}$ and $a = 0.1$. It is seen that with increase of excitation energy the double-humped barriers transforms to one-humped one with simultaneous reduce of barrier height.

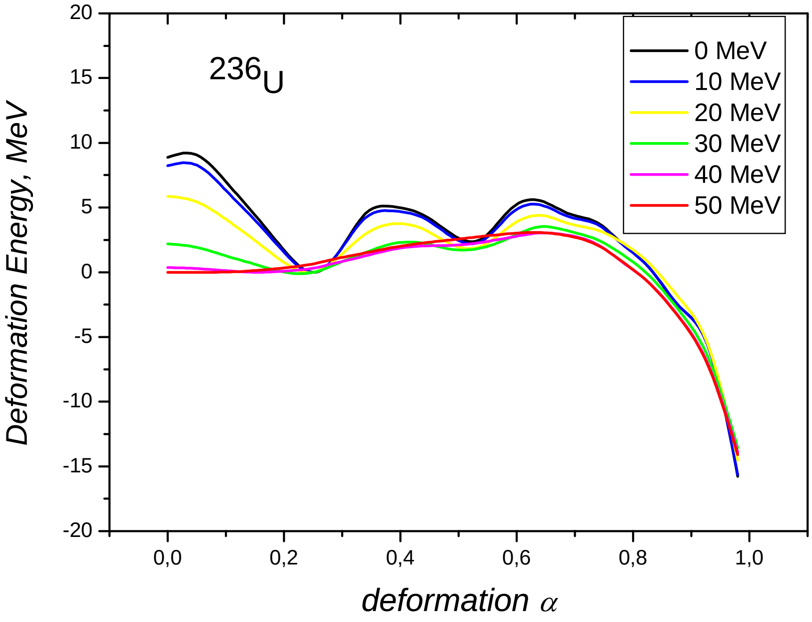


Fig. 2.5.6. Deformation energy for ^{236}U fission for different excitation energies.

Another closely connected and important question is the influence of barrier temperature dependence on the fission cross-section calculations. It is used to calculate in the statistical models the fission transmission coefficient (or fission width) in the following way [1,11]:

$$\Gamma = \int dE' \frac{\rho(E'-B)}{1+\exp\left(-2\pi(E'-B)/\hbar\omega\right)} . \tag{2.61}$$

Here ρ is the level density, B is the barrier height, $\hbar\omega$ is the typical fission frequency ($\hbar\omega \approx 0.6$ for actinides). In the case of the double-humped barrier the fission width is

$$\Gamma = \frac{\Gamma_1 \Gamma_2}{\Gamma_1 + \Gamma_2} , \tag{2.62}$$

where $\Gamma_{1,2}$ are the transmission coefficients for 1st and 2nd barriers, correspondingly.

Results of fission width calculations for ^{236}U fission as function of excitation energy are presented in the Fig. 2.57 for two cases. In the first case (black line) barriers were calculated at zero temperature and did not depend from excitation energy. For the second case (red line) the barrier heights were defined by corresponding maximums of potential energy function presented in the Fig. 2.56. The Fermi gas model was used for the level density. Results presented show practically identity of the variants. This result seems to be quite natural because at excitation energies in the overbarrier region the fission width is completely defined by the behavior of the level density over fission barrier. The same result was obtained for fission of ^{240}Pu (Fig. 2.58).

So, our results of fission width calculations show that there is no necessity to complicate calculations and include in the traditional statistical calculations any temperature dependence of fission barriers

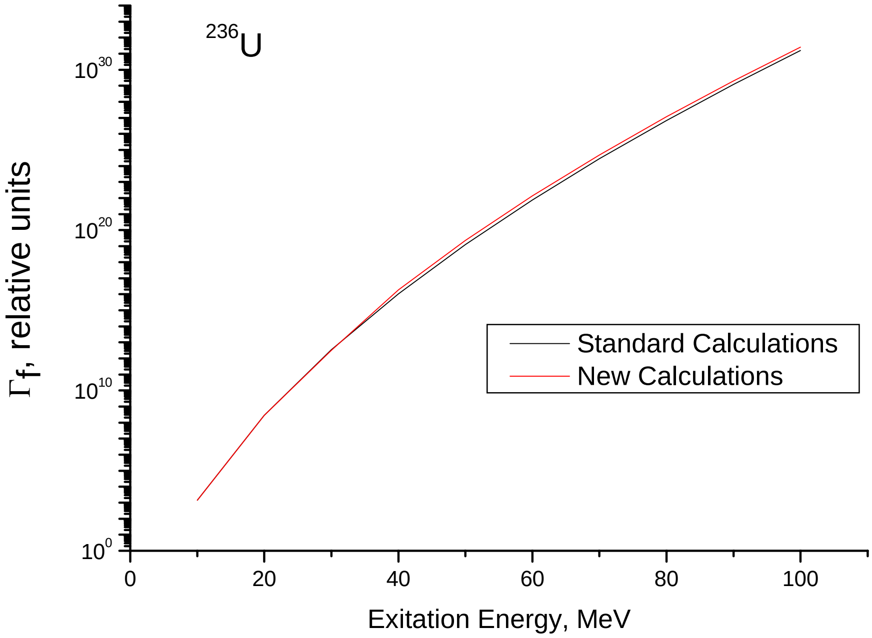


Fig. 2.5.7 The dependence of fission width on the excitation energy for ^{236}U fission.

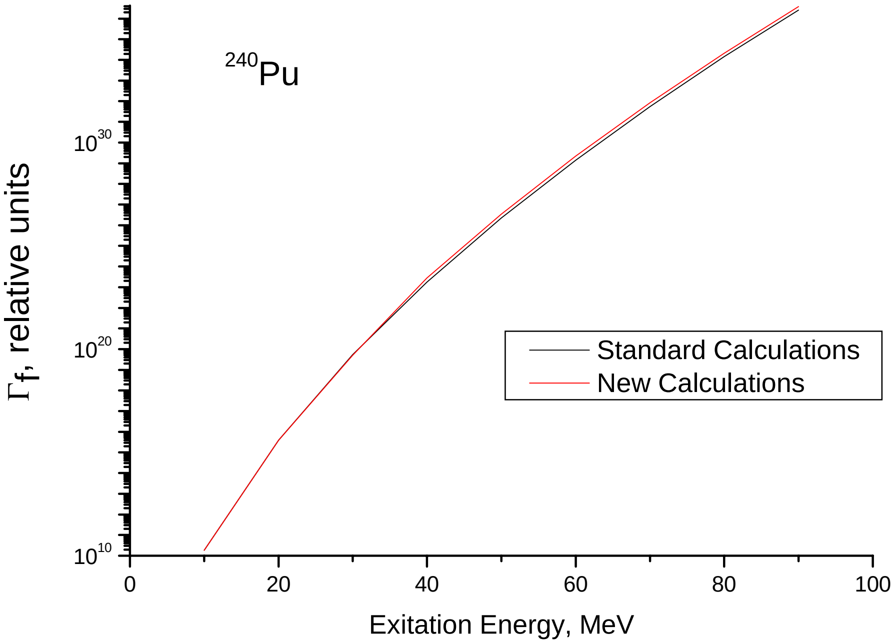


Fig. 2.5.8 The dependence of fission width on the excitation energy for ^{240}Pu fission.

2.5.3 Fission barrier library

Results of our results comparison with the data of the systematics [ ] are shown in the Figs. 2.5.9-2.5.10 separately for nuclei with one-humped barriers and for the case of the first and second barriers for actinides.

Fission barriers were defined as

$$B_f^{1,2} = E_{def}^{1,2} - E_{GS} - E_{vib}^0 \tag{2.63}$$

where $B_f^{1,2}$ is the height of the 1st (2nd) barrier (1st and 2nd maxima of the deformation energy curve), E_{GS} is the ground state energy (minimum of the deformation energy) and E_{vib}^0 is the energy of the zero-point vibrations, $E_{vib}^0 = 0.5-0.6$ MeV for actinides and $E_{vib}^0 = 0.8-1.4$ MeV for preactinides with the maximum near the double-magic nucleus 208-Pb with large stiffness to deformation.

Curvature parameters defined from the comparison with systematics [8-10] are equal

$b_{cur} = -1.5\left(1 + 26.7\left[\frac{N-Z}{A}\right]^2\right)$ for preactinides and $b_{cur} = -3.25\left(1 + 24.6\left[\frac{N-Z}{A}\right]^2\right)$ for transactinide nuclei.

Calculation results and comparison with systematics [8-10] are presented in the Figs. 2.5.9-2.5.10. The average deviation of our results from systematics [10] is equal 0.13 MeV for preactinides with r.m.s. error 0.7 MeV and 0.1 MeV and 0.77 MeV for transactinides and systematics [9], correspondingly. Because the data on the fission barriers in the systematics are not strictly experimental ones and may be varied slightly in the calculation of the fission characteristics, the accuracy achieved is enough for the practical application.

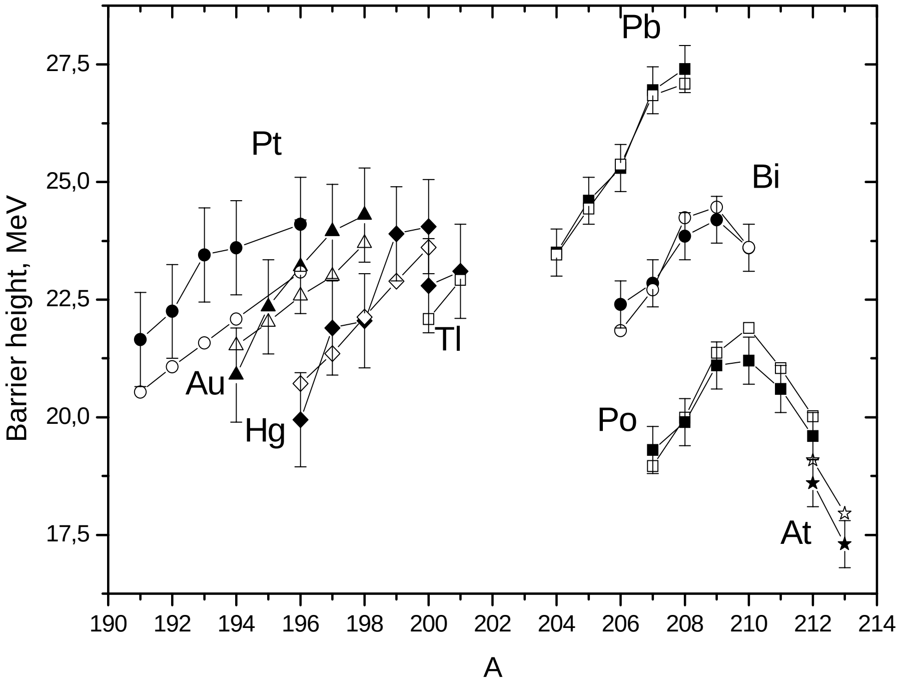
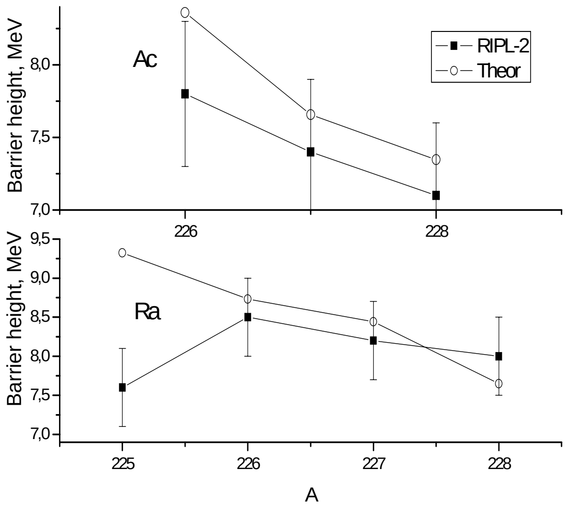


Fig. 2.5.9. Comparison of the fission barrier height calculation results with the data from systematics [10].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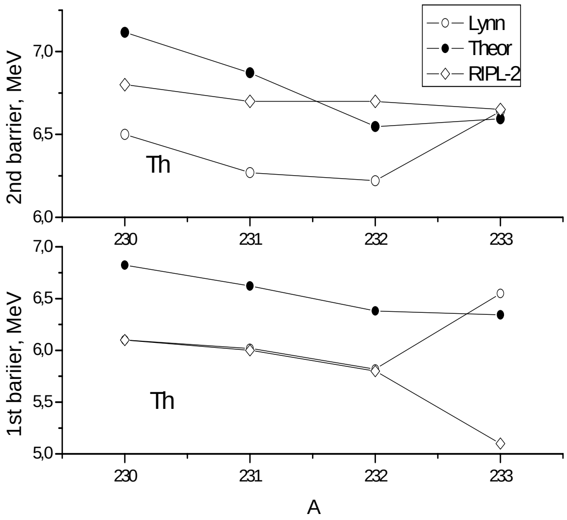
A


Lynn
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Th
2nd barrier, MeV
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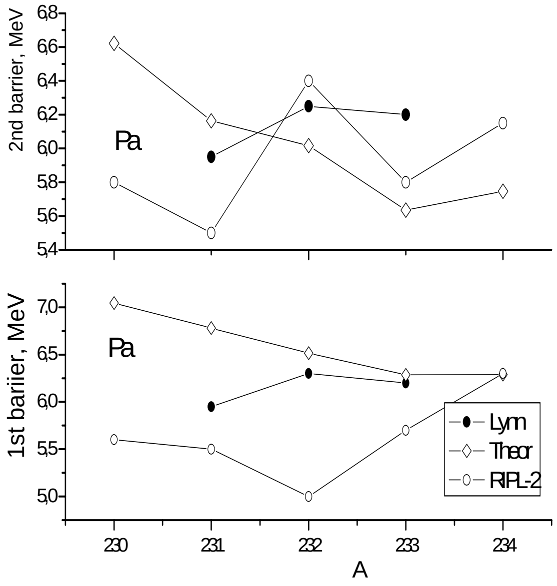
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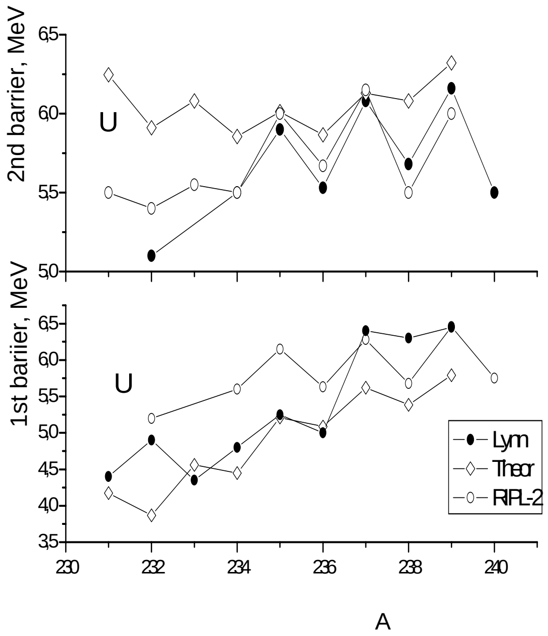
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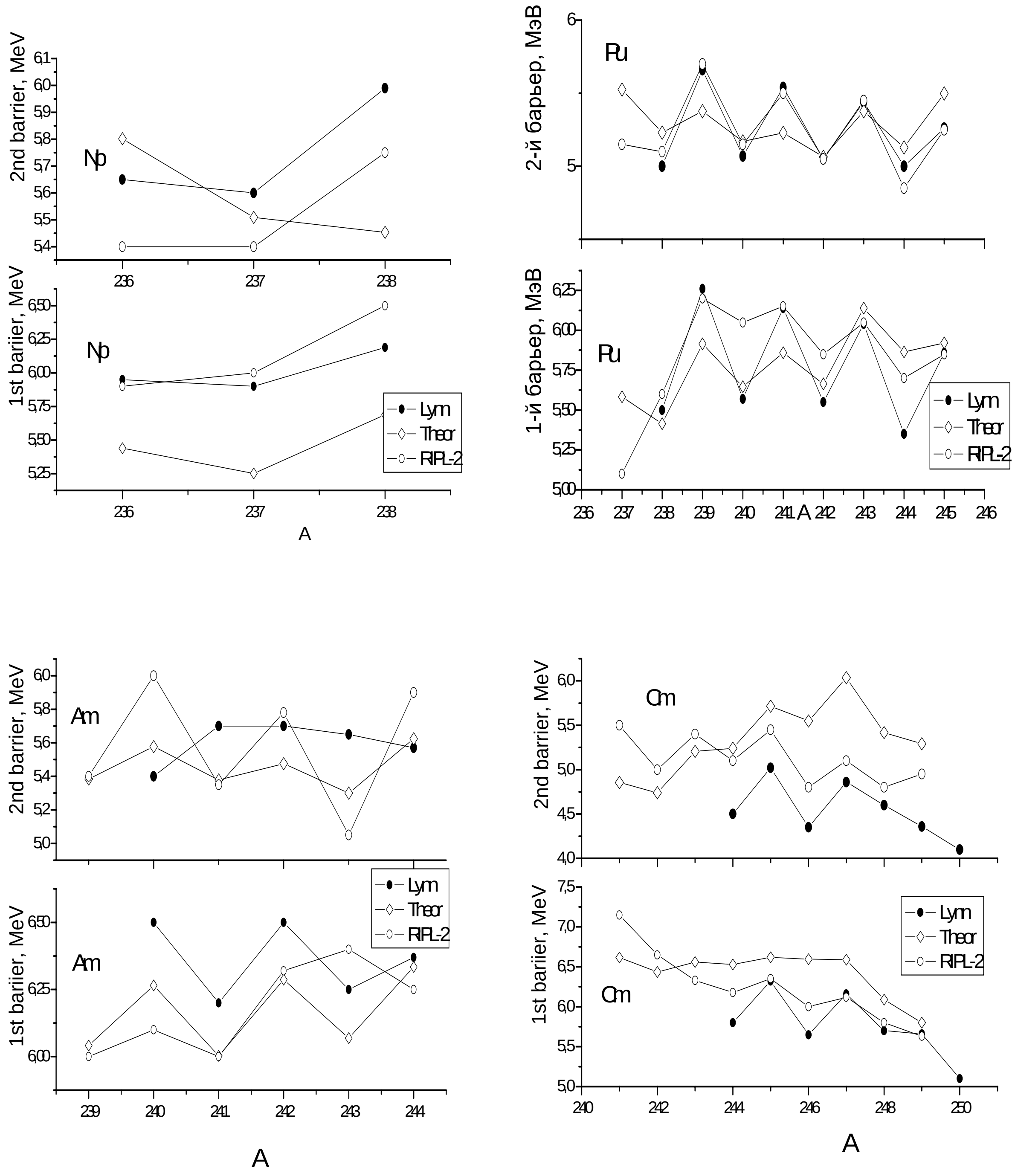

Fig. 2.5.10. Comparison of the fission barrier heights calculation results with the data from systematics: Lynn - [8], RIPL2 – [9].

2.5.4 Conclusions.

The semimicroscopical model for fission barrier calculations based on the properties of potential energy of fissionning nucleus is proposed. It is shown that with taking into account of mass-asymmetry deformations and curvature energy the model is able to reproduce known experimental features of fission barriers and fragment mass distributions for actinide region. It is also shown that account of excitation energy in fission barrier calculations does not change fission widths and could be omitted in the scheme of fission cross-section calculations based on the traditional statistical model. The model developed let us possibility to construct fission barrier library for nuclei far from the line of β-stability which will be further used for calculations in the interests of the project.

2.5.5 References

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3. Results

Main result of the project is the development of nuclear data files relevant for perspective nuclear technologies and first at all for accelerated driven system (ADS). There are two groups of the data necessary for design of the subcritical reactor driven by the accelerator of charged particles. The first one is destined for nuclides of ADS Pb-Bi neutron generating target irradiated by the beam of high energy protons, and the second group includes nuclides of subcritical blanket, *i.e.* isotopes of uranium and probably plutonium (for MOX fuel) and nuclides to be transmuted of minor actinides group (neptunium, americium, curium).

The transport files library involves 18 files for 9 nuclei irradiated by neutrons and protons with energy 20-1000 MeV. The list of nuclei may be extended in new evaluations and following projects.

Contents of the library KRIT1000 (Khlopin Radium Institute 1000 MeV):
Targets:
208-Pb, 209-Bi, 232-Th, 235-U, 238-U, 237-Np, 239-Pu, 241-Am, 243-Cm

For the information representation we used three files of complete file according to ENDF-6 manual recommendations.

- File 1 contains general information where in brief style the methods of data evaluation are described.
- File 2 was not prepared because neutron projectile energies of our evaluations starts from 20 MeV. We believe it is better to insert different complete files into transport calculation separately instead of compilation one data file for energy from 10^{-5} eV to 1 GeV.
- File 3 contains cross sections as a functions of incoming energy: i) total reaction cross section, ii) elastic scattering cross section, iii) fission cross section and iv) cross section of neutron/proton production. Some small corrections of calculated fission cross sections were done to reproduce measured data better.
- The energy-angle distributions of secondary neutrons/protons and the multiplicities of these particles are included into File 6. We used Kalbach-Mann approach [1] of the data presentation to save the file volume.

The example of the data file for 208-Pb+p reaction, 20-1000 MeV, is presented in the Attachment 4.

Another data type prepared in the ENDF-6 format is data on fission fragment yield. The example of the data file containing independent fission fragment yields is shown in the Attachment 5.

The important result obtained during the project performance is the new library of fission barrier parameters presented in the Attachment 6.

Reference to section 3.

[1] C. Kalbach, Phys.Rev.C 37, 2350 (1988); C. Kalbach and F. M. Mann, Phys.Rev.C 23, 112 (1981)

4. Conclusions

The nuclear data problem on the nucleon-induced reaction characteristics in the over and above traditional reactor energy region is the important and practically not solved issue governing development of the modern nuclear technologies based on the application of middle and intermediate energy neutron and proton beams. The development of external files in the format necessary for carrying out of facilities design works, the estimation of the structural materials activation and shielding (ENDF-6 format) is the important step to the solution of issues indicated. Moreover the study of nuclear reaction mechanism induced by intermediate energy mechanism gives us valuable information on the properties of nuclear matter at high excitation energy, interplay between different intranuclear processes governing the reaction, the fragment formation in the fission of excited and highly excited nuclei and so on.

In the given work the new code MCFx has been developed for calculations of main characteristics of nuclear reactions induced by nucleons on heavy nuclei including cross-sections of main processes, that are total cross-sections, reaction cross-sections and cross-sections of the elastic scattering, fission cross-section, multiplicities and spectra of secondary nucleons, fission fragment yields. Novelty of the code is defined by the development of the algorithm which affords ground for description in the unified way the entire reaction mechanism with energies of incoming nucleons from few tens MeV to few GeV by detailed consideration of all reaction stages including entrance channel, cascade stage and stages of preequilibrium and equilibrium (statistical) nuclear decay. The use of modern nuclear models and development of new models based on the well-studied nuclear properties let us possibility to fix main parameters of the approach and to raise thereby the predicting power on the new model code.

The large volume of calculations performed on the base of the code developed and comparison of the results obtained with the experimental data allows making a conclusion on the adequacy of the approach to the description of the reactions induced by middle and intermediate energy nucleons and applying the code for nuclear data generation.

The complete transport files of neutron and proton data in the energy region 20-1000 MeV for main nuclides used in ADS facilities, that are data for lead and bismuth (neutron-generating target), fuel nuclides of the subcritical reactor (Th, U, Pu isotopes) and some nuclides to be transmuted (Np, Am, Cm), have been developed in the framework of the project. Moreover the data files on the fission fragment yields in the 238-U+n with energies up to 450 MeV were created at the first time. The libraries of the main reaction parameters such as new fission barrier library have self-dependent value and can be used by other experts independently.

The three articles have been published in the Russian scientific journals and nine presentations on the international conferences were done.

Attachment 1: List of published papers with abstracts

1. *Yu. Martirosyan “Modeling of the multiparticle preequilibrium nucleon emission” – Izvestiya Vuzov, Yadernaya Energetika, 2006, N3, p.48-53*

New exciton model of preequilibrium decay (MCP), that allows to compute the spectra of multiparticle emission during the establishment of statistical equilibrium, is proposed. Testing of the offered model in comparision with results of calculations on the basis of classical exciton model for the one preequilibrium nucleons – neutron and/or proton is executed. Reliability of multiparticle preequilibrium emission spectra is qualitatively estimated.

2. *Yu. Martirosyan “Calculation of multiparticle preequilibrium emission spectra” – Izvestiya Vuzov, Yadernaya Energetika, 2006, N3, p.54-59*

Systematic comparision of the results of calculations on the basis of exciton model of multiparticle preequilibrium decay with the experimental spectra of nucleons from (p,xn), (p,xp), (n,xn) and (n,xp) reactions in a wide projectile energy region from 10 up to 60 MeV for targets from ^{27}Al up to ^{209}Bi was carried out.

3. *V.G.Vinogradova, O.T.Grudzevich, S.G.Yavshits ‘Exciton model of the multiparticle preequilibrium decay’ // VANT, 2005, ser. Yadernye Konstanty, vyp. 1-2, pp.26-39.*

New exciton model of preequilibrium decay (MCP), allowing to compute the spectra of multiparticle emission during an establishment of statistical equilibrium is proposed. Systematic comparison of results of calculations with the experimental spectra of nucleons from (p, xn), (p, xp), (n, xn) and (n, xp) reactions in a wide projectile energy region from 10 up to 60 MeV for targets from ^{27}Al up to ^{209}Bi is carried out.

Attachment 2: List of presentations at conferences and meetings with abstracts

1. *S.Yavshits, O.Grudzevich "Description of fission yields in the nucleon induced fission reactions" // Proc. of Int. Conference on Nuclear Data for Science and Technology, Apr. 22-27, 2007, Nice, France. Book of summaties, p.218.*

The potential model for the fission fragment mass distributions and simplified approach for the isobaric charge distribution are proposed for the description of fission yields (FY). The intermediate energy reaction code MCFx was used for the calculation of the fissionning nuclei distribution after fast (cascade), preequlibrium and statistical reaction stages. Formation of the mass distributions is considered as a result of oscillations on mass asymmetry degree of freedom in the potential well calculated with the temperature dependent shell correction method. The comparison of calculation results with the experimental data on FY for both low and intermediate energy fission show a good agreement of the data and let us conclude that the approach proposed may be useful for FY evaluations for experimentally unknown fission yields data in the case of the intermediate energy nucleon-induced fission.

2. *Grudzevich O.T., Martirosyan J.M., Yavshits S.G. 'Complete files of neutron- and proton-induced nuclear data to 1 GeV for 208Pb target ' // Proc. of Int. Conference on Nuclear Data for Science and Technology, Apr. 22-27, 2007, Nice, France. Book of summaties, p.102.*

Nuclear data for high projectile energies are needed to design an Accelerator Driven System (target, material activation, heating, shielding etc.). The files of evaluated neutron and proton nuclear data were created in ENDF-6 format for the projectile particle energies from 20 MeV to 1000 MeV. The evaluated data of the files are based mainly on the modern theoretical model calculations with MCFx code. Three mechanism of nuclear reaction were modeled in computing: i) intranuclear cascade; ii) preequilibrium exciton multiparticle emission and iii) statistical decay of excited nuclei. The experimental data available were used to benchmark of the model calculation results. The data on neutron total and reaction cross sections were used to create and to check the set of the optical model parameters in wide energy region. The experimental spectra of 208Pb(p,xn) reaction for projectile energies up to 160 MeV were described with one set of the model parameter. The measured fission cross sections of 208Pb by protons and neutrons were described without fitting practically. The files contain total cross sections, fission cross sections, elastic scattering cross sections and angular distributions, proton- and neutron energy-angular distributions.

3. *Grudzevich O.T., Martirosyan J.M., Vinogradova V.G. "Use of the Monte Carlo Method for modeling of the preequilibrium multiparticle nucleon spectra" - Proc. of the XIII International Seminar on Interaction of Neutrons with Nuclei (ISINN-13). – Dubna, 2005. – pp.160-165*

The calculation scheme of the preequilibrium multiparticle nucleon emission is realized with the Monte Carlo method. In calculations the emission of ten neutrons and ten protons is taken into account as a function of composite system energy. Nucleons are emitted at the stage of system transition into statistical equilibrium state. In the framework of one history of the statistical test method (Monte Carlo method) the competition of nucleon emission process (neutron or proton) and the complication of particle-hole configuration is played. If the choice has fallen on the nucleon emission, the energy of the given nucleon is chosen by means of random number. Accumulation of nucleon spectrum is produced taking into account the order of the particle emission. The given history is being continued for the following residual nucleus. The number of particles decreases by unity, and number of holes does not vary, because the nucleon above the Fermi energy is emitted. The energy of the following composite system is reduced in appropriate way. Consideration of the branching processes is finished in two cases:

1. If the nucleus energy is not sufficient for the nucleon emission.
2. If the statistical equilibrium state is achieved.

Testing the proposed method (MCP) is performed as compared to the calculation results with the classical exciton model for the first nucleons.

4. *Martirosyan J.M., Grudzevich O.T., Yavshits S.G. "Modeling of the multiparticle preequilibrium nucleon emission and nucleon spectra" -/ Proc. of the XIV International Seminar on Interaction of Neutrons with Nuclei (ISINN-14). – Dubna, 2006. – pp. 235-242*

New exciton model of preequilibrium decay (MCP), allowing to compute the spectra of multiparticle emission during an establishment of statistical equilibrium is proposed. Testing the offered model is executed in comparison with results of calculations on classical exciton models for the one preequilibrium nucleons – neutron and/or proton. Reliability of multiparticle preequilibrium emission spectra is qualitatively evaluated.

5. *Martirosyan J.M., Grudzevich O.T., Yavshits S.G. Calculation of temperature-dependent fission barriers and fission fragment yields.// Proc. of the XIV International Seminar on Interaction of Neutrons with Nuclei (ISINN-14). – Dubna, 2006. – pp. 75-84*

The model for temperature-dependent fission barrier and fragment mass distributions and results of calculations for low and intermediated energy fission is presented. The values of fission barrier heights are calculated accordingly to Strutinsky' prescription with taking into account the curvature energy of nucleus. Formation of mass distributions is considered as a result of oscillations on mass asymmetry degree of freedom in the potential well calculated in the macroscopic-microscopic approach. Temperature dependence is treated as a result of shell effects dumping. For intermediate energy nucleon induced fission the distribution of fissioning nuclei is taken into account with MCFx code developed by us earlier for detailed description of reaction stages.

6. *Martirosyan J.M., Grudzevich O.T., Yavshits S.G. "Complete files of neutron- and proton-induced nuclear data to 1 GeV for Bi-209, U-235 and U-238 target" - Proc. of the XV International Seminar on Interaction of Neutrons with Nuclei (ISINN-15). – Dubna, 2007. – Abstracts, p. 28*

Nuclear data for high projectile energies are needed to design an Accelerator Driven System (target, material activation, heating, shielding etc.). The files of evaluated neutron and proton nuclear data were created in ENDF-6 format for the projectile particle energies from 20 MeV to 1000 MeV. The evaluated data of the files are based mainly on the modern theoretical model calculations with MCFx code. Three mechanism of nuclear reaction were modeled in computing: i) intranuclear cascade; ii) preequilibrium exciton multiparticle emission and iii) statistical decay of excited nuclei. The experimental data available were used to benchmark of the model calculation results. The data on neutron total and reaction cross sections were used to create and to check the set of the optical model parameters in wide energy region. The measured fission cross sections of ^{208}Pb, ^{209}Bi, ^{235}U and ^{238}U by protons and neutrons were described without fitting practically.

7. *Grudzevich O.T., Yavshits S.G. "Nonequilibrium nucleon spectra from reactions at intermediate energies"// Proc. of Tenth Symposium on Neutron Dosimetry,* Uppsala, June 12-16, 2006. *Radiat. Prot. Dosimetry,* 2007 - *Neudos-10 Special Issue*; 0: ncm021v1-3

A new exciton model of pre-equilibrium decay (*M*onte *C*arlo *P*re-equilibrium) to compute spectra of multiparticle emission during an establishment of statistical equilibrium in the composite system is proposed. The MCP stage of the calculation was included into the standard scheme of the nucleon spectra calculation between the intranuclear cascade stage and statistical model stage. A systematic comparison of calculation results with experimental spectra of nucleons from (p,xn), (p,xp), (n,xn) and (n,xp) reactions in a wide projectile energy region from 10 up to 160 MeV for targets from ^{27}Al up to ^{209}Bi has been carried out. A short description of the MCP model and results obtained are presented.

8. *Grudzevich O.T., Yavshits S.G. "Calculation of fission fragment yields at low and intermediate energy fission" // Proc. of 3rd Int. Workshop on Nuclear Fission and Fission Product Spectroscopy, Cadarache, France, May 11-14, 2005, p.373-375.*

The model for fission fragment mass distributions and results of calculations for low and intermediated energy fission is presented. Formation of mass distributions is considered as a result of oscillations on mass asymmetry degree of freedom in the potential well calculated in the macroscopic-microscopic approach. Temperature dependence of mass spectra is treated as a result of shell effects melting and occupation of higher collective levels in the well. For intermediate energy nucleon induced fission the distribution of fissioning nuclei is taken into account with MCFx code developed earlier [1] for detailed description of reaction stages.

[1] S.Yavshits *et al.*; Proc. of the 9 th International Conference on Nuclear Reaction Mechanisms, ed. by E. Gadioli, Varenna, June 5-9, 2000, 219

9. *Grudzevich O.T., Yavshits S.G "Calculations of emission neutrons and fission fragment yields for intermediate energy nucleon-induced reactions" // Proc. of Int. Conference on Nuclear Data for Science and Technology, Sept. 26 – Oct.1, 2004, Santa Fe, USA. Vol.2, p.1221-1226.*

The code system MCFx developed earlier [1] on the base of extended cascade-evaporation model for description of fission cross-sections was adapted to calculations of emission neutron and fission fragment yields in reactions on heavy nuclei induced by neutrons and protons of intermediate energies.

Model of fission fragment mass distribution originated from the properties of deformation energy surface near the scission point has been evolved and incorporated into the MCFx code. Calculations for ^{209}Bi(p,x) and ^{238}U(p,x) reactions in 100-500 MeV energy region have been carried out.

Results of fission fragment calculations are in good agreement with experimental data [2] as well as mean number and spectra of prefission neutrons emitted by a number of excited nuclei at the final stage of reaction. The agreement of averaged fission fragment mass indicates that nonequilibrium stage of reaction is described in the proper way (cascade and preequlibrium reaction stages).

References

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2. Z. Fraenkel e.a., Phys. Review, C41(3),1990, p.1050.

Attachment 3: Information on patents and copy rights

No

Attachment 4. Transport file 208-Pb+p, 20-1000 MeV

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                                      -1 0  0    0
 8.22080+04 2.06190+02        -1         1         0        18237 1451    1
 0.00000+00 1.00000+00         0         0         0        68237 1451    2
 9.98620-01 1.00000+09         0         0     10010         18237 1451    3
 0.00000+00 0.00000+00         0         0        87        78237 1451    4
 82-Pb-208 KRI-RUS    EVAL-DEC06 YAVSHITS S.G.,    GRUDZEVICH O.T.8237 1451    5
                      MARTIROSAYN Y.M.              8237 1451    6
                 DIST-FEB07 REV0-              070101     8237 1451    7
--- KRI-TF          MATERIAL8237                          8237 1451    8
-----INCIDENT PROTON DATA.                                  8237 1451    9
------ENDF-6 FORMAT                                     8237 1451   10
==================================================================8237 1451
11
MF=3   REACTION CROSS SECTIONS                              8237 1451   12
******************************************************************8237 1451   13
 This high energy transport file serves for transport,           8237 1451   14
  damage, heating and shielding calculations and               8237 1451   15
  covers energy range 20-1000 MeV.                       8237 1451   16
 The evaluations are based on the code MCFx [Ya01] unified        8237 1451   17
  the optical model, intranuclear cascade,                     8237 1451   18
  preequlibrium model and statistical Hauser-Feshbach model.      8237 1451   19
 The optical model with relativistic corrections                8237 1451   20
  was used for reaction cross sections calculations             8237 1451   21
  and  calculations of energy-angle distributions of            8237 1451   22
  electically scattering nucleons based on the ECIS             8237 1451   23
  code [Ra94] with new global optical model potential [SY01].     8237 1451   24
  OMP parameters were fitted to experimental data on the total,   8237 1451   25
  reaction and elastic scattering cross sections.               8237 1451   26
 The description of exp.data on angular distribution of          8237 1451   27
  elastic scatted nucleons for wide range of projectile energies  8237 1451   28
  and for targets from Pb to U was analyzed too.                 8237 1451   29
 The intranuclear cascade model [Gu83] and new preequlibrium      8237 1451   30
  exciton model with multiple particle emission [Gr04]           8237 1451   31
  have been applied for description of energy and               8237 1451   32
  angle distributions of fast particles.                   8237 1451   33
  STAPRE code [Uh76] with fission barriers derived              8237 1451   34
  from fission probabilities were used for                    8237 1451   35
  fission/evaporation calculations of fission                 8237 1451   36
  cross-sections and low-energy part of energy-angle            8237 1451   37
  distributions.                                      8237 1451   38
 The MCFx code results of the nucleon spectra calculations were   8237 1451   39
  benchmarked against measured values up to 300 MeV             8237 1451   40
  projectile energy [Gr06].                             8237 1451   41
     MT=1  TOTAL CROSS SECTION                              8237 1451   42
            ECIS CALCULATIONS                          8237 1451   43
     MT=2 ELASTIC SCATTERING                               8237 1451   44
            ECIS CALCULATIONS                          8237 1451   45
     MT=5 TOTAL-ELASTIC-FISSION=NUCLEON PRODUCTION XS           8237 1451   46
            MCFx CALCULATIONS                           8237 1451   47
     MT=18   TOTAL FISSION                             8237 1451   48
 HAUSER-FESHBACH CALCULATIONS BASED ON FISSION BARRIERS          8237 1451   49
==================================================================8237 1451
50
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MF=6    PRODUCT ENERGY-ANGLE DISTRIBUTION                  8237 1451   51
*****************************************************************8237 1451   52
   MT=2   ELASTIC SCATTERING                             8237 1451   53
 Distribution of elastic scattering                   8237 1451   54
   MT=5   Neutron and Proton                           8237 1451   55
 Neutron and proton distribution                      8237 1451   56
=================================================================8237 1451
57
     REFERENCES                                  8237 1451   58
=================================================================8237 1451
59
 [Ya01] S.Yavshits, V. Ippolitov, A. Goverdovskii, O. Grudzevich 8237 1451   60
  Proc. of  the International Conference on Nuclear Data for    8237 1451   61
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                                                 8237 1451   65
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                                                 8237 1451   68
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                                                 8237 1451   75
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     2004, Santa Fe, USA. Vol.2, p.1221;                  8237 1451   78
   V.G.Vinogradova, O.T.Grudzevich, S.G.Yavshits, Voprosy      8237 1451   79
   Atomnoi Nauki i Techniki, ser. Yadernye Constanty,         8237 1451   80
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                                                 8237 1451   85
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 Sweden, 2006. Radiation Protection, Oxford Press,2007,p 1-3.    8237 1451   88
=================================================================8237 1451
89
            DICTIONARY                           8237 1451   90
=================================================================8237 1451
91
                1       451        98          18237 1451   92
                3         1         9         18237 1451   93
                3         2         9         18237 1451   94
                3         5         9         18237 1451   95
                3        18         9          18237 1451   96
                6         2       582           18237 1451   97
                6         5       987           18237 1451   98
                                                 8237 1  099999
                                                 8237 0  0    0
 8.22080+04 2.06190+02          0          0          0          08237 3  1    1
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         18          2          0          0          0          08237 3  1    3
 2.00000+07 2.37800+00 3.00000+07 3.30100+00 3.50000+07 3.50300+008237 3  1    4
 4.00000+07 3.64200+00 4.50000+07 3.70700+00 5.00000+07 3.74900+008237 3  1    5
 7.00000+07 3.80200+00 1.00000+08 3.93900+00 1.50000+08 3.77700+008237 3  1    6
 2.00000+08 3.39700+00 3.00000+08 2.99300+00 4.10000+08 2.86600+008237 3  1    7
 5.00000+08 2.83400+00 6.60000+08 2.81500+00 7.01000+08 2.81200+008237 3  1    8
 7.90000+08 2.80400+00 9.00000+08 2.79100+00 1.00000+09 2.77900+008237 3  1    9
                                                                  8237 3  099999
 8.22080+04 2.06190+02          0          0          0          08237 3  2    1
 0.00000+00 0.00000+00          0          0          1        188237 3  2    2
         18          2          0          0          0          08237 3  2    3
 2.00000+07 9.73800-01 3.00000+07 1.46800+00 3.50000+07 1.58100+008237 3  2    4
 4.00000+07 1.65700+00 4.50000+07 1.69300+00 5.00000+07 1.71500+008237 3  2    5
 7.00000+07 1.82900+00 1.00000+08 2.13400+00 1.50000+08 2.01900+008237 3  2    6
 2.00000+08 1.64300+00 3.00000+08 1.23000+00 4.10000+08 1.08800+008237 3  2    7
 5.00000+08 1.04600+00 6.60000+08 1.01200+00 7.01000+08 1.00500+008237 3  2    8
 7.90000+08 9.90400-01 9.00000+08 9.71700-01 1.00000+09 9.56900-018237 3  2    9
                                                                  8237 3  099999
 8.22080+04 2.06190+02          0          0          0          08237 3  5    1
 0.00000+00 0.00000+00          0          0          1        188237 3  5    2
         18          2          0          0          0          08237 3  5    3
 2.00000+07 1.40420+00 3.00000+07 1.83300+00 3.50000+07 1.92199+008237 3  5    4
 4.00000+07 1.98483+00 4.50000+07 2.01252+00 5.00000+07 2.03078+008237 3  5    5
 7.00000+07 1.95669+00 1.00000+08 1.76577+00 1.50000+08 1.68412+008237 3  5    6
 2.00000+08 1.67713+00 3.00000+08 1.68512+00 4.10000+08 1.66121+008237 3  5    7
 5.00000+08 1.66167+00 6.60000+08 1.65820+00 7.01000+08 1.66663+008237 3  5    8
 7.90000+08 1.66698+00 9.00000+08 1.65256+00 1.00000+09 1.70865+008237 3  5    9
                                                                  8237 3  099999
 8.22080+04 2.06190+02          0          0          0          08237 3 18    1
 2.00000+08 0.00000+00          0          0          1        188237 3 18    2
         18          2          0          0          0          08237 3 18    3
 2.00000+07 1.27920-15 3.00000+07 2.71920-07 3.50000+07 1.25400-058237 3 18    4
 4.00000+07 1.72920-04 4.50000+07 1.47520-03 5.00000+07 3.21580-038237 3 18    5
 7.00000+07 1.63130-02 1.00000+08 3.92250-02 1.50000+08 7.38840-028237 3 18    6
 2.00000+08 7.68740-02 3.00000+08 7.78830-02 4.10000+08 1.16790-018237 3 18    7
 5.00000+08 1.26330-01 6.60000+08 1.44800-01 7.01000+08 1.40370-018237 3 18    8
 7.90000+08 1.46620-01 9.00000+08 1.66740-01 1.00000+09 1.13450-018237 3 18    9
                                                                  8237 3  099999
                                                                  8237 0  0    0
 8.22080+04 2.06190+02          0          2          1          08237 6  2    1
 1.00100+03 9.98620-01          0          2          1          28237 6  2    2
          2          2          0          0          0          08237 6  2    3
 2.00000+07 1.00000+00 1.00000+09 1.00000+00                      8237 6  2    4
 0.00000+00 0.00000+00         12          2          1        188237 6  2    5
         18          2          0          0          0          08237 6  2    6
 0.00000+00 2.00000+07         12          0        182          918237 6  2    7
-1.00000+00 1.46400+00-9.99391-01 1.48800+00-9.97564-01 1.56000+008237 6  2    8
-9.94522-01 1.67700+00-9.90268-01 1.83700+00-9.84808-01 2.03500+008237 6  2    9
-9.78148-01 2.26800+00-9.70296-01 2.52500+00-9.61262-01 2.80000+008237 6  2   10
-9.51056-01 3.08200+00-9.39693-01 3.35900+00-9.27184-01 3.62100+008237 6  2   11
-9.13545-01 3.85800+00-8.98794-01 4.05900+00-8.82948-01 4.22000+008237 6  2   12
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1.81700+08 6.02502-10 2.58420-01 1.97500+08 5.21002-10 2.58420-018237 6  5  914
2.13300+08 4.53362-10 2.58420-01 2.29100+08 3.99333-10 2.58420-018237 6  5  915
2.44900+08 3.53444-10 2.58420-01 2.60700+08 3.21060-10 2.58420-018237 6  5  916
2.76500+08 2.83287-10 2.58420-01 2.92300+08 2.54956-10 2.58420-018237 6  5  917
```

```
3.08100+08 2.30674-10 2.58420-01 3.23900+08 2.08551-10 2.58420-018237 6  5  918
3.39700+08 1.94522-10 2.58420-01 3.55500+08 1.79413-10 2.58420-018237 6  5  919
3.71300+08 1.62956-10 2.58420-01 3.87100+08 1.46498-10 2.58420-018237 6  5  920
4.02900+08 1.37055-10 2.58420-01 4.18700+08 1.23566-10 2.58420-018237 6  5  921
4.34500+08 1.13044-10 2.58420-01 4.50300+08 1.04680-10 2.58420-018237 6  5  922
4.66100+08 9.76655-11 2.58420-01 4.81900+08 9.14602-11 2.58420-018237 6  5  923
4.97700+08 8.28268-11 2.58420-01 5.13500+08 7.90497-11 2.58420-018237 6  5  924
5.29300+08 7.41934-11 2.58420-01 5.45100+08 6.69090-11 2.58420-018237 6  5  925
5.60900+08 6.47506-11 2.58420-01 5.76700+08 6.09735-11 2.58420-018237 6  5  926
5.92500+08 5.98943-11 2.58420-01 6.08300+08 6.04339-11 2.58420-018237 6  5  927
6.24100+08 6.12433-11 2.58420-01 6.39900+08 6.36714-11 2.58420-018237 6  5  928
6.55700+08 6.55600-11 2.58420-01 6.71500+08 7.09559-11 2.58420-018237 6  5  929
6.87300+08 7.58122-11 2.58420-01 7.03100+08 8.17476-11 2.58420-018237 6  5  930
7.18900+08 8.63341-11 2.58420-01 7.34700+08 8.84925-11 2.58420-018237 6  5  931
7.50500+08 9.01113-11 2.58420-01 7.66300+08 9.46977-11 2.58420-018237 6  5  932
7.82100+08 7.47330-11 2.58420-01 7.97900+08 0.00000+00 0.00000+008237 6  5  933
0.00000+00 9.00000+08          0          1        156        528237 6  5  934
0.00000+00 0.00000+00 0.00000+00 9.00000+06 1.10713-09 2.63364-018237 6  5  935
2.70000+07 3.00296-08 1.16851-01 4.50000+07 8.33968-09 1.98417-018237 6  5  936
6.30000+07 3.75663-09 2.37665-01 8.10000+07 2.23161-09 2.54018-018237 6  5  937
9.90000+07 1.56960-09 2.60613-01 1.17000+08 1.19247-09 2.62683-018237 6  5  938
1.35000+08 9.42300-10 2.63206-01 1.53000+08 7.66905-10 2.63332-018237 6  5  939
1.71000+08 6.29640-10 2.63357-01 1.89000+08 5.20324-10 2.63362-018237 6  5  940
2.07000+08 4.47809-10 2.63364-01 2.25000+08 3.80318-10 2.63364-018237 6  5  941
2.43000+08 3.29746-10 2.63364-01 2.61000+08 2.93634-10 2.63364-018237 6  5  942
2.79000+08 2.62344-10 2.63364-01 2.97000+08 2.32978-10 2.63364-018237 6  5  943
3.15000+08 2.11558-10 2.63364-01 3.33000+08 1.88693-10 2.63364-018237 6  5  944
3.51000+08 1.70642-10 2.63364-01 3.69000+08 1.52832-10 2.63364-018237 6  5  945
3.87000+08 1.41760-10 2.63364-01 4.05000+08 1.29967-10 2.63364-018237 6  5  946
4.23000+08 1.16008-10 2.63364-01 4.41000+08 1.03733-10 2.63364-018237 6  5  947
4.59000+08 9.62720-11 2.63364-01 4.77000+08 8.97736-11 2.63364-018237 6  5  948
4.95000+08 8.61634-11 2.63364-01 5.13000+08 7.48515-11 2.63364-018237 6  5  949
5.31000+08 6.95565-11 2.63364-01 5.49000+08 6.59463-11 2.63364-018237 6  5  950
5.67000+08 6.08920-11 2.63364-01 5.85000+08 5.77632-11 2.63364-018237 6  5  951
6.03000+08 5.17462-11 2.63364-01 6.21000+08 4.93394-11 2.63364-018237 6  5  952
6.39000+08 4.66919-11 2.63364-01 6.57000+08 4.52478-11 2.63364-018237 6  5  953
6.75000+08 4.35631-11 2.63364-01 6.93000+08 4.28410-11 2.63364-018237 6  5  954
7.11000+08 4.35631-11 2.63364-01 7.29000+08 4.47665-11 2.63364-018237 6  5  955
7.47000+08 4.71733-11 2.63364-01 7.65000+08 5.22275-11 2.63364-018237 6  5  956
7.83000+08 5.72818-11 2.63364-01 8.01000+08 6.42615-11 2.63364-018237 6  5  957
8.19000+08 7.14819-11 2.63364-01 8.37000+08 7.91837-11 2.63364-018237 6  5  958
8.55000+08 8.37566-11 2.63364-01 8.73000+08 9.00143-11 2.63364-018237 6  5  959
8.91000+08 7.00379-11 2.63364-01 9.09000+08 0.00000+00 0.00000+008237 6  5  960
0.00000+00 1.00000+09          0          1        156        528237 6  5  961
0.00000+00 0.00000+00 0.00000+00 1.00000+07 2.21309-09 2.98872-018237 6  5  962
3.00000+07 2.12566-08 1.23760-01 5.00000+07 6.53353-09 2.58719-018237 6  5  963
7.00000+07 3.92408-09 2.92917-01 9.00000+07 2.76003-09 2.97970-018237 6  5  964
1.10000+08 2.06787-09 2.98752-01 1.30000+08 1.59804-09 2.98858-018237 6  5  965
1.50000+08 1.25769-09 2.98870-01 1.70000+08 1.01643-09 2.98872-018237 6  5  966
1.90000+08 8.27711-10 2.98872-01 2.10000+08 6.72454-10 2.98872-018237 6  5  967
2.30000+08 5.91150-10 2.98872-01 2.50000+08 4.87693-10 2.98872-018237 6  5  968
2.70000+08 4.32273-10 2.98872-01 2.90000+08 3.73159-10 2.98872-018237 6  5  969
3.10000+08 3.39538-10 2.98872-01 3.30000+08 2.98158-10 2.98872-018237 6  5  970
3.50000+08 2.70078-10 2.98872-01 3.70000+08 2.40891-10 2.98872-018237 6  5  971
3.90000+08 2.13920-10 2.98872-01 4.10000+08 1.97294-10 2.98872-018237 6  5  972
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4.30000+08 1.76973-10 2.98872-01 4.50000+08 1.66628-10 2.98872-018237 6  5  973
4.70000+08 1.50372-10 2.98872-01 4.90000+08 1.33746-10 2.98872-018237 6  5  974
5.10000+08 1.28574-10 2.98872-01 5.30000+08 1.16012-10 2.98872-018237 6  5  975
5.50000+08 1.04558-10 2.98872-01 5.70000+08 1.08253-10 2.98872-018237 6  5  976
5.90000+08 9.31050-11 2.98872-01 6.10000+08 9.19966-11 2.98872-018237 6  5  977
6.30000+08 7.94348-11 2.98872-01 6.50000+08 7.68486-11 2.98872-018237 6  5  978
6.70000+08 7.09371-11 2.98872-01 6.90000+08 7.35234-11 2.98872-018237 6  5  979
7.10000+08 6.53952-11 2.98872-01 7.30000+08 6.13311-11 2.98872-018237 6  5  980
7.50000+08 6.17005-11 2.98872-01 7.70000+08 6.17005-11 2.98872-018237 6  5  981
7.90000+08 5.98532-11 2.98872-01 8.10000+08 6.17005-11 2.98872-018237 6  5  982
8.30000+08 7.38928-11 2.98872-01 8.50000+08 7.27845-11 2.98872-018237 6  5  983
8.70000+08 9.31050-11 2.98872-01 8.90000+08 1.06036-10 2.98872-018237 6  5  984
9.10000+08 1.17490-10 2.98872-01 9.30000+08 1.38180-10 2.98872-018237 6  5  985
9.50000+08 1.51111-10 2.98872-01 9.70000+08 1.57022-10 2.98872-018237 6  5  986
9.90000+08 1.29312-10 2.98872-01 1.01000+09 0.00000+00 0.00000+008237 6  5  987
                                                                  8237 6  099999
                                                                  8237 0  0    0
                                                                     0 0  0    0
                                                                    -1 0  0    0
```

Attachment 5. Independent fission fragment yields file, 238-U+n, 300 MeV.

```
9.2238E+04 2.3601E+02          -1          1          2          0 3546 1451    1
 0.0000E+00 1.0000E+00          0          0          0          6 3546 1451    2
 1.0000E+00 0.0000E+00          0          0         11         31 3546 1451    3
 0.0000E+00 0.0000E+00          0          0         36          3 3546 1451    4
        92-U - 238   KRI-RUS EVAL-APR07 YAVSHITS S., GRUDZEVICH 0. 3546 1451    5
                     DIST - MAY07   070505              3546 1451    6
        ----KRIYF   REV 0.0         MATERIAL 3456              3546 1451    7
        ----NEUTRON INDUCED FISSION PRODUCT YIELDS              3546 1451    8
        ----ENDF-6 FORMAT                                3546 1451    9
        ********************************************************* 3546 1451   10
        Theoretical independent (pre-neutron) yield library        3546 1451   11
        No ternary fission or isomeric splitting included         3546 1451   12
        REFERENCES:                                     3546 1451   13
        1.- O.Grudzevich, S.Yavshits, Proc. of  Int. Conference on 3546 1451   14
        Nuclear Data for Science and Technology, Sept. 26, Oct.1,  3546 1451   15
            2004, Santa Fe, USA. Vol.2, p.1221;                3546 1451   16
        2.- S.Yavshits, O.Grudzevich, Proc. of 3rd Int. Workshop   3546 1451   17
        on Nuclear Fission and Fission Product Spectroscopy,       3546 1451   18
        Cadarache, France, May 11-14, 2005, p.373               3546 1451   19
                                                      3546 1451   20
                             1          451          22          3546 1451   21
                             8          454          23          704 3546 1451   22
 0.0000E+00 0.0000E+00          0          0          0          0 3546    0    0
 9.2238E+04 2.3601E+02         -1          1          2          0 3546 8454    1
 3.0000E+08 0.0000E+00          1          0       3936        984 3546 8454    2
 2.5080E+04 0.0000E+00 4.5111E-24 0.0000E+00 2.6080E+04 0.0000E+003546 8454    3
 4.6174E-18 0.0000E+00 2.6081E+04 0.0000E+00 4.3956E-20 0.0000E+003546 8454    4
 2.6082E+04 0.0000E+00 2.8965E-22 0.0000E+00 2.6083E+04 0.0000E+003546 8454    5
 2.5371E-25 0.0000E+00 2.7080E+04 0.0000E+00 3.4491E-13 0.0000E+003546 8454    6
 2.7081E+04 0.0000E+00 8.2685E-15 0.0000E+00 2.7082E+04 0.0000E+003546 8454    7
 1.3829E-16 0.0000E+00 2.7083E+04 0.0000E+00 1.5840E-18 0.0000E+003546 8454    8
 2.7084E+04 0.0000E+00 1.2386E-20 0.0000E+00 2.7085E+04 0.0000E+003546 8454    9
 5.8671E-23 0.0000E+00 2.8080E+04 0.0000E+00 2.4038E-09 0.0000E+003546 8454   10
 2.8081E+04 0.0000E+00 1.4414E-10 0.0000E+00 2.8082E+04 0.0000E+003546 8454   11
 6.0162E-12 0.0000E+00 2.8083E+04 0.0000E+00 1.7276E-13 0.0000E+003546 8454   12
 2.8084E+04 0.0000E+00 3.3981E-15 0.0000E+00 2.8085E+04 0.0000E+003546 8454   13
 4.6060E-17 0.0000E+00 2.8086E+04 0.0000E+00 4.3205E-19 0.0000E+003546 8454   14
 2.8087E+04 0.0000E+00 2.7466E-21 0.0000E+00 2.8088E+04 0.0000E+003546 8454   15
 7.9194E-24 0.0000E+00 2.9080E+04 0.0000E+00 1.6139E-06 0.0000E+003546 8454   16
 2.9081E+04 0.0000E+00 2.3922E-07 0.0000E+00 2.9082E+04 0.0000E+003546 8454   17
 2.4666E-08 0.0000E+00 2.9083E+04 0.0000E+00 1.7569E-09 0.0000E+003546 8454   18
 2.9084E+04 0.0000E+00 8.6020E-11 0.0000E+00 2.9085E+04 0.0000E+003546 8454   19
 2.9016E-12 0.0000E+00 2.9086E+04 0.0000E+00 6.7839E-14 0.0000E+003546 8454   20
 2.9087E+04 0.0000E+00 1.0852E-15 0.0000E+00 2.9088E+04 0.0000E+003546 8454   21
 1.1834E-17 0.0000E+00 2.9089E+04 0.0000E+00 8.9390E-20 0.0000E+003546 8454   22
 2.9090E+04 0.0000E+00 4.1720E-22 0.0000E+00 3.0080E+04 0.0000E+003546 8454   23
 1.0931E-04 0.0000E+00 3.0081E+04 0.0000E+00 3.9322E-05 0.0000E+003546 8454   24
 3.0082E+04 0.0000E+00 9.8696E-06 0.0000E+00 3.0083E+04 0.0000E+003546 8454   25
 1.7198E-06 0.0000E+00 3.0084E+04 0.0000E+00 2.0694E-07 0.0000E+003546 8454   26
 3.0085E+04 0.0000E+00 1.7192E-08 0.0000E+00 3.0086E+04 0.0000E+003546 8454   27
 9.9219E-10 0.0000E+00 3.0087E+04 0.0000E+00 3.9414E-11 0.0000E+003546 8454   28
 3.0088E+04 0.0000E+00 1.0738E-12 0.0000E+00 3.0089E+04 0.0000E+003546 8454   29
 2.0284E-14 0.0000E+00 3.0090E+04 0.0000E+00 2.6554E-16 0.0000E+003546 8454   30
```

```
3.0091E+04 0.0000E+00 2.3945E-18 0.0000E+00 3.0092E+04 0.0000E+003546 8454   31
1.4863E-20 0.0000E+00 3.0093E+04 0.0000E+00 4.4954E-23 0.0000E+003546 8454   32
3.1080E+04 0.0000E+00 7.8660E-04 0.0000E+00 3.1081E+04 0.0000E+003546 8454   33
6.7472E-04 0.0000E+00 3.1082E+04 0.0000E+00 4.0536E-04 0.0000E+003546 8454   34
3.1083E+04 0.0000E+00 1.6979E-04 0.0000E+00 3.1084E+04 0.0000E+003546 8454   35
4.9345E-05 0.0000E+00 3.1085E+04 0.0000E+00 9.9439E-06 0.0000E+003546 8454   36
3.1086E+04 0.0000E+00 1.3971E-06 0.0000E+00 3.1087E+04 0.0000E+003546 8454   37
1.3606E-07 0.0000E+00 3.1088E+04 0.0000E+00 9.1654E-09 0.0000E+003546 8454   38
3.1089E+04 0.0000E+00 4.2949E-10 0.0000E+00 3.1090E+04 0.0000E+003546 8454   39
1.3978E-11 0.0000E+00 3.1091E+04 0.0000E+00 3.1389E-13 0.0000E+003546 8454   40
3.1092E+04 0.0000E+00 4.8635E-15 0.0000E+00 3.1093E+04 0.0000E+003546 8454   41
5.2143E-17 0.0000E+00 3.1094E+04 0.0000E+00 3.8838E-19 0.0000E+003546 8454   42
3.1095E+04 0.0000E+00 1.9513E-21 0.0000E+00 3.1096E+04 0.0000E+003546 8454   43
2.0019E-24 0.0000E+00 3.2080E+04 0.0000E+00 6.1424E-04 0.0000E+003546 8454   44
3.2081E+04 0.0000E+00 1.2569E-03 0.0000E+00 3.2082E+04 0.0000E+003546 8454   45
1.7982E-03 0.0000E+00 3.2083E+04 0.0000E+00 1.7895E-03 0.0000E+003546 8454   46
3.2084E+04 0.0000E+00 1.2354E-03 0.0000E+00 3.2085E+04 0.0000E+003546 8454   47
5.9295E-04 0.0000E+00 3.2086E+04 0.0000E+00 1.9901E-04 0.0000E+003546 8454   48
3.2087E+04 0.0000E+00 4.6617E-05 0.0000E+00 3.2088E+04 0.0000E+003546 8454   49
7.6319E-06 0.0000E+00 3.2089E+04 0.0000E+00 8.7543E-07 0.0000E+003546 8454   50
3.2090E+04 0.0000E+00 7.0128E-08 0.0000E+00 3.2091E+04 0.0000E+003546 8454   51
3.8894E-09 0.0000E+00 3.2092E+04 0.0000E+00 1.4883E-10 0.0000E+003546 8454   52
3.2093E+04 0.0000E+00 3.9486E-12 0.0000E+00 3.2094E+04 0.0000E+003546 8454   53
7.2944E-14 0.0000E+00 3.2095E+04 0.0000E+00 9.3893E-16 0.0000E+003546 8454   54
3.2096E+04 0.0000E+00 8.4248E-18 0.0000E+00 3.2097E+04 0.0000E+003546 8454   55
5.2637E-20 0.0000E+00 3.2098E+04 0.0000E+00 2.0407E-22 0.0000E+003546 8454   56
3.3080E+04 0.0000E+00 5.0276E-05 0.0000E+00 3.3081E+04 0.0000E+003546 8454   57
2.5099E-04 0.0000E+00 3.3082E+04 0.0000E+00 8.7070E-04 0.0000E+003546 8454   58
3.3083E+04 0.0000E+00 2.0797E-03 0.0000E+00 3.3084E+04 0.0000E+003546 8454   59
3.4115E-03 0.0000E+00 3.3085E+04 0.0000E+00 3.8681E-03 0.0000E+003546 8454   60
3.3086E+04 0.0000E+00 3.0564E-03 0.0000E+00 3.3087E+04 0.0000E+003546 8454   61
1.6868E-03 0.0000E+00 3.3088E+04 0.0000E+00 6.5480E-04 0.0000E+003546 8454   62
3.3089E+04 0.0000E+00 1.7970E-04 0.0000E+00 3.3090E+04 0.0000E+003546 8454   63
3.4800E-05 0.0000E+00 3.3091E+04 0.0000E+00 4.7029E-06 0.0000E+003546 8454   64
3.3092E+04 0.0000E+00 4.3995E-07 0.0000E+00 3.3093E+04 0.0000E+003546 8454   65
2.8624E-08 0.0000E+00 3.3094E+04 0.0000E+00 1.3000E-09 0.0000E+003546 8454   66
3.3095E+04 0.0000E+00 4.1193E-11 0.0000E+00 3.3096E+04 0.0000E+003546 8454   67
9.1138E-13 0.0000E+00 3.3097E+04 0.0000E+00 1.4071E-14 0.0000E+003546 8454   68
3.3098E+04 0.0000E+00 1.5186E-16 0.0000E+00 3.3099E+04 0.0000E+003546 8454   69
1.1540E-18 0.0000E+00 3.3100E+04 0.0000E+00 6.1730E-21 0.0000E+003546 8454   70
3.3101E+04 0.0000E+00 1.3863E-23 0.0000E+00 3.4080E+04 0.0000E+003546 8454   71
4.0486E-07 0.0000E+00 3.4081E+04 0.0000E+00 5.0734E-06 0.0000E+003546 8454   72
3.4082E+04 0.0000E+00 4.3993E-05 0.0000E+00 3.4083E+04 0.0000E+003546 8454   73
2.5978E-04 0.0000E+00 3.4084E+04 0.0000E+00 1.0369E-03 0.0000E+003546 8454   74
3.4085E+04 0.0000E+00 2.8204E-03 0.0000E+00 3.4086E+04 0.0000E+003546 8454   75
5.2837E-03 0.0000E+00 3.4087E+04 0.0000E+00 6.8437E-03 0.0000E+003546 8454   76
3.4088E+04 0.0000E+00 6.1906E-03 0.0000E+00 3.4089E+04 0.0000E+003546 8454   77
3.9618E-03 0.0000E+00 3.4090E+04 0.0000E+00 1.8047E-03 0.0000E+003546 8454   78
3.4091E+04 0.0000E+00 5.8041E-04 0.0000E+00 3.4092E+04 0.0000E+003546 8454   79
1.3045E-04 0.0000E+00 3.4093E+04 0.0000E+00 2.0533E-05 0.0000E+003546 8454   80
3.4094E+04 0.0000E+00 2.2673E-06 0.0000E+00 3.4095E+04 0.0000E+003546 8454   81
1.7532E-07 0.0000E+00 3.4096E+04 0.0000E+00 9.4861E-09 0.0000E+003546 8454   82
3.4097E+04 0.0000E+00 3.5823E-10 0.0000E+00 3.4098E+04 0.0000E+003546 8454   83
9.4662E-12 0.0000E+00 3.4099E+04 0.0000E+00 1.7645E-13 0.0000E+003546 8454   84
3.4100E+04 0.0000E+00 2.3262E-15 0.0000E+00 3.4101E+04 0.0000E+003546 8454   85
```

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2.1760E-17 0.0000E+00 3.4102E+04 0.0000E+00 1.4480E-19 0.0000E+003546 8454   86
3.4103E+04 0.0000E+00 6.3495E-22 0.0000E+00 3.5080E+04 0.0000E+003546 8454   87
3.0431E-10 0.0000E+00 3.5081E+04 0.0000E+00 9.7736E-09 0.0000E+003546 8454   88
3.5082E+04 0.0000E+00 2.1736E-07 0.0000E+00 3.5083E+04 0.0000E+003546 8454   89
3.2707E-06 0.0000E+00 3.5084E+04 0.0000E+00 3.2789E-05 0.0000E+003546 8454   90
3.5085E+04 0.0000E+00 2.2041E-04 0.0000E+00 3.5086E+04 0.0000E+003546 8454   91
1.0065E-03 0.0000E+00 3.5087E+04 0.0000E+00 3.1308E-03 0.0000E+003546 8454   92
3.5088E+04 0.0000E+00 6.6783E-03 0.0000E+00 3.5089E+04 0.0000E+003546 8454   93
9.9337E-03 0.0000E+00 3.5090E+04 0.0000E+00 1.0455E-02 0.0000E+003546 8454   94
3.5091E+04 0.0000E+00 7.7981E-03 0.0000E+00 3.5092E+04 0.0000E+003546 8454   95
4.1049E-03 0.0000E+00 3.5093E+04 0.0000E+00 1.5282E-03 0.0000E+003546 8454   96
3.5094E+04 0.0000E+00 4.0254E-04 0.0000E+00 3.5095E+04 0.0000E+003546 8454   97
7.4872E-05 0.0000E+00 3.5096E+04 0.0000E+00 9.8013E-06 0.0000E+003546 8454   98
3.5097E+04 0.0000E+00 8.9769E-07 0.0000E+00 3.5098E+04 0.0000E+003546 8454   99
5.7611E-08 0.0000E+00 3.5099E+04 0.0000E+00 2.6082E-09 0.0000E+003546 8454  100
3.5100E+04 0.0000E+00 8.3527E-11 0.0000E+00 3.5101E+04 0.0000E+003546 8454  101
1.9032E-12 0.0000E+00 3.5102E+04 0.0000E+00 3.1006E-14 0.0000E+003546 8454  102
3.5103E+04 0.0000E+00 3.6064E-16 0.0000E+00 3.5104E+04 0.0000E+003546 8454  103
2.9992E-18 0.0000E+00 3.5105E+04 0.0000E+00 1.7773E-20 0.0000E+003546 8454  104
3.5106E+04 0.0000E+00 6.6418E-23 0.0000E+00 3.6080E+04 0.0000E+003546 8454  105
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4.1153E-19 0.0000E+00 3.6108E+04 0.0000E+00 2.0263E-21 0.0000E+003546 8454  124
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3.7085E+04 0.0000E+00 1.2600E-09 0.0000E+00 3.7086E+04 0.0000E+003546 8454  129
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4.0096E+04 0.0000E+00 5.0090E-05 0.0000E+00 4.0097E+04 0.0000E+003546 8454  195
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4.1090E+04 0.0000E+00 1.5344E-19 0.0000E+00 4.1091E+04 0.0000E+003546 8454  211
1.4630E-16 0.0000E+00 4.1092E+04 0.0000E+00 2.1849E-14 0.0000E+003546 8454  212
4.1093E+04 0.0000E+00 1.7622E-12 0.0000E+00 4.1094E+04 0.0000E+003546 8454  213
9.5912E-11 0.0000E+00 4.1095E+04 0.0000E+00 3.5308E-09 0.0000E+003546 8454  214
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1.9085E-02 0.0000E+00 4.3110E+04 0.0000E+00 2.0167E-02 0.0000E+003546 8454  264
4.3111E+04 0.0000E+00 1.5770E-02 0.0000E+00 4.3112E+04 0.0000E+003546 8454  265
9.1094E-03 0.0000E+00 4.3113E+04 0.0000E+00 3.8601E-03 0.0000E+003546 8454  266
4.3114E+04 0.0000E+00 1.1926E-03 0.0000E+00 4.3115E+04 0.0000E+003546 8454  267
2.6648E-04 0.0000E+00 4.3116E+04 0.0000E+00 4.2928E-05 0.0000E+003546 8454  268
4.3117E+04 0.0000E+00 4.9845E-06 0.0000E+00 4.3118E+04 0.0000E+003546 8454  269
4.1660E-07 0.0000E+00 4.3119E+04 0.0000E+00 2.5066E-08 0.0000E+003546 8454  270
4.3120E+04 0.0000E+00 1.0844E-09 0.0000E+00 4.3121E+04 0.0000E+003546 8454  271
3.3546E-11 0.0000E+00 4.3122E+04 0.0000E+00 7.3818E-13 0.0000E+003546 8454  272
4.3123E+04 0.0000E+00 1.1506E-14 0.0000E+00 4.3124E+04 0.0000E+003546 8454  273
1.2601E-16 0.0000E+00 4.3125E+04 0.0000E+00 9.6819E-19 0.0000E+003546 8454  274
4.3126E+04 0.0000E+00 5.0759E-21 0.0000E+00 4.3127E+04 0.0000E+003546 8454  275
1.6367E-23 0.0000E+00 4.4098E+04 0.0000E+00 1.0458E-17 0.0000E+003546 8454  276
4.4099E+04 0.0000E+00 3.0243E-15 0.0000E+00 4.4100E+04 0.0000E+003546 8454  277
2.6276E-13 0.0000E+00 4.4101E+04 0.0000E+00 1.5426E-11 0.0000E+003546 8454  278
4.4102E+04 0.0000E+00 6.2689E-10 0.0000E+00 4.4103E+04 0.0000E+003546 8454  279
1.7633E-08 0.0000E+00 4.4104E+04 0.0000E+00 3.4411E-07 0.0000E+003546 8454  280
4.4105E+04 0.0000E+00 4.6655E-06 0.0000E+00 4.4106E+04 0.0000E+003546 8454  281
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4.4123E+04 0.0000E+00 2.5372E-10 0.0000E+00 4.4124E+04 0.0000E+003546 8454  293
6.8057E-12 0.0000E+00 4.4125E+04 0.0000E+00 1.2988E-13 0.0000E+003546 8454  294
4.4126E+04 0.0000E+00 1.7529E-15 0.0000E+00 4.4127E+04 0.0000E+003546 8454  295
1.6629E-17 0.0000E+00 4.4128E+04 0.0000E+00 1.1095E-19 0.0000E+003546 8454  296
4.4129E+04 0.0000E+00 5.0631E-22 0.0000E+00 4.5100E+04 0.0000E+003546 8454  297
1.0642E-18 0.0000E+00 4.5101E+04 0.0000E+00 2.9824E-16 0.0000E+003546 8454  298
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1.2028E-04 0.0000E+00 4.7115E+04 0.0000E+00 6.5761E-04 0.0000E+003546 8454  348
4.7116E+04 0.0000E+00 2.5239E-03 0.0000E+00 4.7117E+04 0.0000E+003546 8454  349
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4.7122E+04 0.0000E+00 1.0349E-02 0.0000E+00 4.7123E+04 0.0000E+003546 8454  353
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4.7125E+04 0.0000E+00 3.6668E-04 0.0000E+00 4.7126E+04 0.0000E+003546 8454  355
6.4234E-05 0.0000E+00 4.7127E+04 0.0000E+00 8.2088E-06 0.0000E+003546 8454  356
4.7128E+04 0.0000E+00 7.6525E-07 0.0000E+00 4.7129E+04 0.0000E+003546 8454  357
5.1946E-08 0.0000E+00 4.7130E+04 0.0000E+00 2.5589E-09 0.0000E+003546 8454  358
4.7131E+04 0.0000E+00 9.0891E-11 0.0000E+00 4.7132E+04 0.0000E+003546 8454  359
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4.7137E+04 0.0000E+00 1.1618E-22 0.0000E+00 4.8108E+04 0.0000E+003546 8454  363
3.3044E-17 0.0000E+00 4.8109E+04 0.0000E+00 4.6474E-15 0.0000E+003546 8454  364
4.8110E+04 0.0000E+00 3.4648E-13 0.0000E+00 4.8111E+04 0.0000E+003546 8454  365
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5.6191E-19 0.0000E+00 4.8139E+04 0.0000E+00 2.9061E-21 0.0000E+003546 8454  384
4.8140E+04 0.0000E+00 7.9694E-24 0.0000E+00 4.9110E+04 0.0000E+003546 8454  385
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8.0841E-08 0.0000E+00 4.9117E+04 0.0000E+00 1.2682E-06 0.0000E+003546 8454  390
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1.0717E-04 0.0000E+00 4.9120E+04 0.0000E+00 5.7738E-04 0.0000E+003546 8454  392
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9.5197E-19 0.0000E+00 5.0144E+04 0.0000E+00 4.9063E-21 0.0000E+003546 8454  428
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5.1117E+04 0.0000E+00 4.4836E-14 0.0000E+00 5.1118E+04 0.0000E+003546 8454  431
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5.1120E+04 0.0000E+00 3.0646E-09 0.0000E+00 5.1121E+04 0.0000E+003546 8454  433
6.5802E-08 0.0000E+00 5.1122E+04 0.0000E+00 1.0121E-06 0.0000E+003546 8454  434
5.1123E+04 0.0000E+00 1.1009E-05 0.0000E+00 5.1124E+04 0.0000E+003546 8454  435
8.4290E-05 0.0000E+00 5.1125E+04 0.0000E+00 4.5600E-04 0.0000E+003546 8454  436
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2.1158E-05 0.0000E+00 5.9145E+04 0.0000E+00 1.1333E-04 0.0000E+003546 8454  612
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1.0695E-03 0.0000E+00 5.9148E+04 0.0000E+00 1.9639E-03 0.0000E+003546 8454  614
5.9149E+04 0.0000E+00 2.6831E-03 0.0000E+00 5.9150E+04 0.0000E+003546 8454  615
2.7680E-03 0.0000E+00 5.9151E+04 0.0000E+00 2.1731E-03 0.0000E+003546 8454  616
5.9152E+04 0.0000E+00 1.3022E-03 0.0000E+00 5.9153E+04 0.0000E+003546 8454  617
5.9353E-04 0.0000E+00 5.9154E+04 0.0000E+00 2.0016E-04 0.0000E+003546 8454  618
5.9155E+04 0.0000E+00 4.8699E-05 0.0000E+00 5.9156E+04 0.0000E+003546 8454  619
8.4907E-06 0.0000E+00 5.9157E+04 0.0000E+00 1.0773E-06 0.0000E+003546 8454  620
5.9158E+04 0.0000E+00 1.0108E-07 0.0000E+00 5.9159E+04 0.0000E+003546 8454  621
7.0408E-09 0.0000E+00 5.9160E+04 0.0000E+00 3.8351E-10 0.0000E+003546 8454  622
6.0137E+04 0.0000E+00 6.3428E-20 0.0000E+00 6.0138E+04 0.0000E+003546 8454  623
6.9927E-18 0.0000E+00 6.0139E+04 0.0000E+00 6.8310E-16 0.0000E+003546 8454  624
6.0140E+04 0.0000E+00 4.3613E-14 0.0000E+00 6.0141E+04 0.0000E+003546 8454  625
2.1301E-12 0.0000E+00 6.0142E+04 0.0000E+00 7.9581E-11 0.0000E+003546 8454  626
6.0143E+04 0.0000E+00 2.1604E-09 0.0000E+00 6.0144E+04 0.0000E+003546 8454  627
4.1144E-08 0.0000E+00 6.0145E+04 0.0000E+00 5.4104E-07 0.0000E+003546 8454  628
6.0146E+04 0.0000E+00 4.8408E-06 0.0000E+00 6.0147E+04 0.0000E+003546 8454  629
2.9349E-05 0.0000E+00 6.0148E+04 0.0000E+00 1.2188E-04 0.0000E+003546 8454  630
6.0149E+04 0.0000E+00 3.5699E-04 0.0000E+00 6.0150E+04 0.0000E+003546 8454  631
7.5518E-04 0.0000E+00 6.0151E+04 0.0000E+00 1.1720E-03 0.0000E+003546 8454  632
6.0152E+04 0.0000E+00 1.3549E-03 0.0000E+00 6.0153E+04 0.0000E+003546 8454  633
1.1977E-03 0.0000E+00 6.0154E+04 0.0000E+00 8.1536E-04 0.0000E+003546 8454  634
6.0155E+04 0.0000E+00 4.2084E-04 0.0000E+00 6.0156E+04 0.0000E+003546 8454  635
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1.6076E-04 0.0000E+00 6.0157E+04 0.0000E+00 4.4931E-05 0.0000E+003546 8454  636
6.0158E+04 0.0000E+00 9.2826E-06 0.0000E+00 6.0159E+04 0.0000E+003546 8454  637
1.4276E-06 0.0000E+00 6.0160E+04 0.0000E+00 1.7232E-07 0.0000E+003546 8454  638
6.1140E+04 0.0000E+00 3.8611E-19 0.0000E+00 6.1141E+04 0.0000E+003546 8454  639
3.4067E-17 0.0000E+00 6.1142E+04 0.0000E+00 3.5784E-15 0.0000E+003546 8454  640
6.1143E+04 0.0000E+00 2.0357E-13 0.0000E+00 6.1144E+04 0.0000E+003546 8454  641
8.6878E-12 0.0000E+00 6.1145E+04 0.0000E+00 2.7051E-10 0.0000E+003546 8454  642
6.1146E+04 0.0000E+00 5.9177E-09 0.0000E+00 6.1147E+04 0.0000E+003546 8454  643
8.8776E-08 0.0000E+00 6.1148E+04 0.0000E+00 9.0423E-07 0.0000E+003546 8454  644
6.1149E+04 0.0000E+00 6.3181E-06 0.0000E+00 6.1150E+04 0.0000E+003546 8454  645
3.0666E-05 0.0000E+00 6.1151E+04 0.0000E+00 1.0388E-04 0.0000E+003546 8454  646
6.1152E+04 0.0000E+00 2.4764E-04 0.0000E+00 6.1153E+04 0.0000E+003546 8454  647
4.2911E-04 0.0000E+00 6.1154E+04 0.0000E+00 5.6036E-04 0.0000E+003546 8454  648
6.1155E+04 0.0000E+00 5.5883E-04 0.0000E+00 6.1156E+04 0.0000E+003546 8454  649
4.2553E-04 0.0000E+00 6.1157E+04 0.0000E+00 2.4661E-04 0.0000E+003546 8454  650
6.1158E+04 0.0000E+00 1.0978E-04 0.0000E+00 6.1159E+04 0.0000E+003546 8454  651
3.7340E-05 0.0000E+00 6.1160E+04 0.0000E+00 9.9275E-06 0.0000E+003546 8454  652
6.2142E+04 0.0000E+00 2.2469E-20 0.0000E+00 6.2143E+04 0.0000E+003546 8454  653
2.4998E-18 0.0000E+00 6.2144E+04 0.0000E+00 2.6511E-16 0.0000E+003546 8454  654
6.2145E+04 0.0000E+00 1.7356E-14 0.0000E+00 6.2146E+04 0.0000E+003546 8454  655
8.2384E-13 0.0000E+00 6.2147E+04 0.0000E+00 2.8668E-11 0.0000E+003546 8454  656
6.2148E+04 0.0000E+00 7.0762E-10 0.0000E+00 6.2149E+04 0.0000E+003546 8454  657
1.2169E-08 0.0000E+00 6.2150E+04 0.0000E+00 1.4454E-07 0.0000E+003546 8454  658
6.2151E+04 0.0000E+00 1.1687E-06 0.0000E+00 6.2152E+04 0.0000E+003546 8454  659
6.3865E-06 0.0000E+00 6.2153E+04 0.0000E+00 2.4149E-05 0.0000E+003546 8454  660
6.2154E+04 0.0000E+00 6.6176E-05 0.0000E+00 6.2155E+04 0.0000E+003546 8454  661
1.3394E-04 0.0000E+00 6.2156E+04 0.0000E+00 1.9937E-04 0.0000E+003546 8454  662
6.2157E+04 0.0000E+00 2.1958E-04 0.0000E+00 6.2158E+04 0.0000E+003546 8454  663
1.9015E-04 0.0000E+00 6.2159E+04 0.0000E+00 1.3578E-04 0.0000E+003546 8454  664
6.2160E+04 0.0000E+00 7.9426E-05 0.0000E+00 6.3145E+04 0.0000E+003546 8454  665
1.5048E-19 0.0000E+00 6.3146E+04 0.0000E+00 1.3529E-17 0.0000E+003546 8454  666
6.3147E+04 0.0000E+00 1.3188E-15 0.0000E+00 6.3148E+04 0.0000E+003546 8454  667
6.8150E-14 0.0000E+00 6.3149E+04 0.0000E+00 2.6054E-12 0.0000E+003546 8454  668
6.3150E+04 0.0000E+00 7.2543E-11 0.0000E+00 6.3151E+04 0.0000E+003546 8454  669
1.4148E-09 0.0000E+00 6.3152E+04 0.0000E+00 1.8644E-08 0.0000E+003546 8454  670
6.3153E+04 0.0000E+00 1.6601E-07 0.0000E+00 6.3154E+04 0.0000E+003546 8454  671
1.0475E-06 0.0000E+00 6.3155E+04 0.0000E+00 4.8194E-06 0.0000E+003546 8454  672
6.3156E+04 0.0000E+00 1.5919E-05 0.0000E+00 6.3157E+04 0.0000E+003546 8454  673
3.6690E-05 0.0000E+00 6.3158E+04 0.0000E+00 6.2548E-05 0.0000E+003546 8454  674
6.3159E+04 0.0000E+00 8.9113E-05 0.0000E+00 6.3160E+04 0.0000E+003546 8454  675
1.1043E-04 0.0000E+00 6.4147E+04 0.0000E+00 9.1342E-21 0.0000E+003546 8454  676
6.4148E+04 0.0000E+00 9.5701E-19 0.0000E+00 6.4149E+04 0.0000E+003546 8454  677
8.7843E-17 0.0000E+00 6.4150E+04 0.0000E+00 4.9464E-15 0.0000E+003546 8454  678
6.4151E+04 0.0000E+00 2.0370E-13 0.0000E+00 6.4152E+04 0.0000E+003546 8454  679
6.0676E-12 0.0000E+00 6.4153E+04 0.0000E+00 1.2628E-10 0.0000E+003546 8454  680
6.4154E+04 0.0000E+00 1.8785E-09 0.0000E+00 6.4155E+04 0.0000E+003546 8454  681
2.0587E-08 0.0000E+00 6.4156E+04 0.0000E+00 1.6358E-07 0.0000E+003546 8454  682
6.4157E+04 0.0000E+00 8.9456E-07 0.0000E+00 6.4158E+04 0.0000E+003546 8454  683
3.5176E-06 0.0000E+00 6.4159E+04 0.0000E+00 1.1364E-05 0.0000E+003546 8454  684
6.4160E+04 0.0000E+00 3.1327E-05 0.0000E+00 6.5150E+04 0.0000E+003546 8454  685
5.1266E-20 0.0000E+00 6.5151E+04 0.0000E+00 4.0270E-18 0.0000E+003546 8454  686
6.5152E+04 0.0000E+00 3.1275E-16 0.0000E+00 6.5153E+04 0.0000E+003546 8454  687
1.3558E-14 0.0000E+00 6.5154E+04 0.0000E+00 4.3160E-13 0.0000E+003546 8454  688
6.5155E+04 0.0000E+00 1.0446E-11 0.0000E+00 6.5156E+04 0.0000E+003546 8454  689
1.9324E-10 0.0000E+00 6.5157E+04 0.0000E+00 2.5611E-09 0.0000E+003546 8454  690
```

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6.5158E+04 0.0000E+00 2.4899E-08 0.0000E+00 6.5159E+04 0.0000E+003546 8454  691
2.0205E-07 0.0000E+00 6.5160E+04 0.0000E+00 1.3601E-06 0.0000E+003546 8454  692
6.6152E+04 0.0000E+00 2.5571E-21 0.0000E+00 6.6153E+04 0.0000E+003546 8454  693
2.5287E-19 0.0000E+00 6.6154E+04 0.0000E+00 1.9154E-17 0.0000E+003546 8454  694
6.6155E+04 0.0000E+00 9.3699E-16 0.0000E+00 6.6156E+04 0.0000E+003546 8454  695
3.4733E-14 0.0000E+00 6.6157E+04 0.0000E+00 1.0038E-12 0.0000E+003546 8454  696
6.6158E+04 0.0000E+00 2.2515E-11 0.0000E+00 6.6159E+04 0.0000E+003546 8454  697
4.2981E-10 0.0000E+00 6.6160E+04 0.0000E+00 6.8866E-09 0.0000E+003546 8454  698
6.7155E+04 0.0000E+00 1.3880E-20 0.0000E+00 6.7156E+04 0.0000E+003546 8454  699
1.1690E-18 0.0000E+00 6.7157E+04 0.0000E+00 8.1622E-17 0.0000E+003546 8454  700
6.7158E+04 0.0000E+00 4.0503E-15 0.0000E+00 6.7159E+04 0.0000E+003546 8454  701
1.5383E-13 0.0000E+00 6.7160E+04 0.0000E+00 4.6473E-12 0.0000E+003546 8454  702
6.8157E+04 0.0000E+00 9.5666E-22 0.0000E+00 6.8158E+04 0.0000E+003546 8454  703
1.2360E-19 0.0000E+00 6.8159E+04 0.0000E+00 1.1141E-17 0.0000E+003546 8454  704
0.0000E+00 0.0000E+00          0          0          0          0 3546    8 99999
```

Attachment 6. Fission barrier library.

Ядро	**Pt**		**Au**		**Hg**		**Tl**	
A	*B, МэВ*	$\hbar\omega$, *МэВ*	*B, МэВ*	$\hbar\omega$, *МэВ*	*B, МэВ*	$\hbar\omega$, *МэВ*	*B, МэВ*	$\hbar\omega$, *МэВ*
179	16,50	1,30						
180	16,60	0,64	15,65	1,34				
181	16,81	0,71	16,23	0,57	13,99	0,63		
182	17,34	0,74	16,22	0,66	14,82	0,70	13,50	0,64
183	17,57	0,74	17,03	0,69	14,77	0,77	14,28	0,61
184	18,18	0,64	17,20	0,61	15,63	0,66	14,02	0,66
185	18,77	0,52	17,78	0,44	15,65	0,58	14,57	0,50
186	18,76	0,35	17,90	0,24	16,14	0,39	14,62	0,43
187	18,87	0,24	18,29	0,32	16,21	0,13	15,13	0,21
188	19,36	0,06	18,43	0,54	16,76	0,26	15,13	0,47
189	19,65	0,24	18,95	0,48	16,97	0,51	15,72	0,54
190	20,11	0,08	19,29	0,57	17,62	0,51	15,79	0,66
191	20,53	0,22	19,89	0,52	18,02	0,60	16,51	0,73
192	21,07	0,17	20,40	0,67	18,67	0,65	16,65	0,84
193	21,58	0,21	20,95	0,61	19,16	0,80	17,22	0,92
194	22,09	0,30	21,52	0,71	19,61	0,77	17,46	1,05
195	22,72	0,25	22,00	0,60	20,06	0,74	18,19	0,52
196	23,09	0,37	22,57	0,58	20,72	0,78	18,78	0,33
197	23,81	0,40	23,14	0,53	21,35	0,70	19,61	0,40
198	24,22	1,16	23,84	1,11	22,13	0,84	20,36	0,42
199	25,32	1,15	24,52	1,14	22,89	0,85	21,25	0,65
200	25,74	1,19	25,47	1,16	23,61	0,93	22,08	0,82
201	26,84	1,19	25,80	1,20	24,61	0,95	22,92	0,86
202	27,45	0,59	26,92	1,22	25,13	0,99	23,98	0,93
203	28,79	0,68	27,50	0,32	26,30	1,03	24,72	1,00
204	29,33	0,71	28,69	0,47	26,92	1,18	25,82	1,08
205	28,48	0,76	29,14	0,49	28,17	1,29	26,69	1,21
206	27,01	0,71	28,24	0,57	28,33	1,38	28,17	1,32
207	26,03	0,77	26,80	0,59	27,34	0,51	28,27	1,39
208	24,81	0,73	25,78	0,68	25,88	0,53	26,93	0,28
209	23,83	0,77	24,61	0,64	24,85	0,76	25,53	0,38
210	22,80	0,74	23,60	0,76	23,71	0,71	24,46	0,39
211	21,84	0,80	22,62	0,75	22,81	0,44	23,32	0,61
212	20,99	0,78	21,65	0,71	21,75	0,74	22,36	0,51
213	20,10	0,84	20,95	0,83	20,76	0,86	21,37	0,77
214	19,44	0,79	20,09	0,93	20,05	0,88	20,38	0,91
215	18,63	0,87	19,51	0,89	19,24	0,96	19,68	0,89
216	18,11	0,85	18,60	0,95	18,69	0,93	18,82	0,98
217	17,17	0,93	18,19	0,95	17,59	1,01	18,28	0,54
218	16,83	0,89	16,68	0,94	17,19	0,98	17,30	0,55
219	15,85	0,90	16,57	0,95	15,98	0,71	17,07	0,44
220			15,23	0,93	15,55	0,97	16,18	0,40
221					14,69	0,67	16,00	0,33
222							15,08	0,21

Ядро	**Pb**		**Bi**		**Po**		**At**	
A	*B*, *МэВ*	$\hbar\omega$, *МэВ*	*B*, *МэВ*	$\hbar\omega$, *МэВ*	*B*, *МэВ*	$\hbar\omega$, *МэВ*	*B*, *МэВ*	$\hbar\omega$, *МэВ*
183	11,51	0,66						
184	12,36	0,66	8,98	0,40				
185	12,13	0,64	9,60	0,17	7,16	0,45		
186	12,69	0,57	9,78	0,28	7,23	0,68	6,66	0,66
187	12,54	0,50	10,06	0,77	7,80	0,81	6,77	0,65
188	13,17	0,18	9,96	0,81	7,93	0,86	7,29	0,67
189	13,12	0,40	10,67	0,50	8,33	0,89	7,11	0,77
190	13,82	0,51	10,93	0,54	8,67	0,82	7,38	0,80
191	13,89	0,65	11,39	0,72	8,92	0,69	7,49	0,69
192	14,71	0,67	11,46	0,83	9,18	0,61	7,82	0,74
193	14,91	0,79	11,99	0,94	9,33	0,50	7,94	0,74
194	15,59	0,87	12,14	1,02	9,77	1,06	8,39	1,10
195	15,80	1,00	13,02	0,89	10,27	1,04	8,94	0,97
196	16,58	0,99	13,54	0,79	10,76	0,91	9,16	0,91
197	17,17	0,38	14,41	0,67	11,12	0,76	9,66	0,75
198	18,12	0,47	15,03	0,61	12,12	0,60	9,94	0,47
199	18,84	0,37	15,90	0,55	12,55	0,39	10,35	0,37
200	19,80	0,57	16,58	0,41	13,42	0,31	10,67	0,09
201	20,64	0,59	17,47	0,26	13,93	0,15	11,52	0,04
202	21,59	0,69	18,51	0,26	14,97	0,13	12,04	0,82
203	22,61	0,72	19,31	0,11	15,89	0,70	13,06	0,73
204	23,46	0,86	20,45	0,36	16,99	0,62	14,07	0,64
205	24,44	0,95	21,00	0,24	18,31	0,45	14,99	0,53
206	25,37	1,11	22,70	0,20	19,21	0,38	16,53	0,32
207	26,85	1,21	23,20	0,19	20,62	0,26	17,28	0,19
208	27,09	1,31	24,64	0,47	21,49	0,21	18,80	0,36
209	25,73	0,66	24,88	0,20	23,10	0,49	19,46	0,34
210	24,30	0,04	23,82	0,24	23,40	0,41	20,96	0,52
211	23,40	0,19	22,57	0,61	22,32	0,51	21,39	0,45
212	22,25	0,29	21,78	0,53	20,79	0,28	20,31	0,48
213	21,33	0,34	20,97	0,51	19,57	0,24	18,89	0,25
214	20,50	0,55	20,20	0,50	18,65	0,63	17,67	0,25
215	19,69	0,56	19,52	0,46	17,84	0,62	16,68	0,78
216	19,09	0,57	17,95	0,14	17,14	0,62	15,82	0,71
217	18,30	0,60	17,42	0,14	16,30	0,59	15,10	0,69
218	17,78	0,55	16,07	0,36	15,73	0,60	14,16	0,64
219	16,87	0,55	15,67	0,32	14,94	0,57	13,70	0,63
220	16,60	0,53	14,25	0,50	14,49	0,61	13,08	0,57
221	15,79	0,52	13,95	0,50	13,59	0,58	12,59	0,62
222	15,55	0,50	12,91	0,78	13,29	0,57	12,12	0,52
223	14,77	0,45	12,75	0,76	12,45	0,51	11,66	0,48
224			12,12	0,73	11,98	0,49	11,28	0,79
225					11,45	0,42	10,98	0,75
226							10,88	0,78

Ядро	**Rn**		**Fr**		**Ra**		**Ac**	
A	*B, МэВ*	$\hbar\omega$, *МэВ*	*B, МэВ*	$\hbar\omega$, *МэВ*	*B, МэВ*	$\hbar\omega$, *МэВ*	*B, МэВ*	$\hbar\omega$, *МэВ*
187	9,04	0,64						
188	8,73	0,64	8,23	0,61				
189	8,96	0,69	8,04	0,69	7,25	0,58		
190	8,75	0,79	8,15	0,70	7,23	0,67	6,66	0,64
191	9,36	0,83	8,03	0,70	7,55	0,60	6,77	0,72
192	8,91	0,76	8,20	0,66	7,36	0,63	7,29	0,70
193	9,27	0,64	7,87	0,75	7,69	0,75	7,11	0,71
194	8,97	0,64	8,05	0,78	7,38	0,63	7,38	0,75
195	9,35	1,09	8,14	0,90	7,47	0,65	7,49	0,68
196	9,72	0,96	8,57	0,95	7,21	0,62	7,82	0,67
197	10,08	0,89	8,77	0,77	7,47	0,54	7,94	0,68
198	10,44	0,69	8,81	0,73	7,45	0,85	8,39	0,57
199	10,69	0,53	8,94	0,59	7,57	0,77	8,94	0,69
200	11,00	0,41	9,02	0,41	7,74	0,59	9,16	0,75
201	11,22	0,07	9,42	0,23	7,99	0,48	9,66	0,69
202	11,79	0,28	9,78	0,33	8,30	0,25	9,94	0,74
203	12,47	0,80	10,36	0,78	8,58	0,34	10,35	0,78
204	13,30	0,71	11,12	0,72	9,07	0,47	10,67	0,76
205	14,18	0,62	11,82	0,60	9,83	0,77	11,52	0,74
206	14,95	0,53	12,68	0,46	10,50	0,64	12,04	0,69
207	15,93	0,37	13,28	0,34	11,44	0,54	13,06	0,54
208	16,65	0,25	14,30	0,12	11,92	0,45	14,07	0,38
209	17,83	0,36	14,68	0,32	12,75	0,26	14,99	0,19
210	18,57	0,34	15,72	0,51	13,08	0,22	16,53	0,32
211	19,90	0,55	16,53	0,54	14,22	0,49	17,28	0,42
212	20,10	0,49	17,79	0,67	14,63	0,51	18,80	0,55
213	18,87	0,59	18,03	0,70	15,98	0,79	19,46	0,73
214	17,37	0,47	16,77	0,69	16,12	0,79	20,96	0,84
215	16,03	0,44	15,48	0,57	14,73	0,69	21,39	0,71
216	14,89	0,77	14,30	0,55	13,54	0,58	20,31	0,72
217	14,03	0,74	12,98	0,81	12,32	0,64	18,89	0,52
218	13,18	0,74	12,93	0,73	11,49	0,64	17,67	0,60
219	12,85	0,66	12,09	0,74	11,51	0,65	16,68	0,58
220	12,01	0,66	12,24	0,59	10,62	0,66	15,82	0,46
221	11,98	0,58	11,61	0,57	10,97	0,58	15,10	0,47
222	11,28	0,66	11,36	0,40	10,39	0,56	14,16	0,41
223	10,67	0,55	10,51	0,56	10,18	0,41	13,70	0,47
224	10,06	0,56	10,29	0,59	9,49	0,41	13,08	0,30
225	9,74	0,44	9,72	0,61	9,33	0,26	12,59	0,51
226	9,02	0,54	9,64	0,63	8,73	0,45	12,12	0,45
227	8,71	0,73	8,86	0,55	8,44	0,59	11,66	0,52
228			8,31	0,55	7,65	0,47	11,28	0,48
229					7,36	0,41	10,98	0,51
226							10,88	0,46

Ядро	**Th**				**Pa**			
A	B_1, *МэВ*	$\hbar\omega_1$, *МэВ*	B_2, *МэВ*	$\hbar\omega_2$, *МэВ*	B_1, *МэВ*	$\hbar\omega_1$, *МэВ*	B_2, *МэВ*	$\hbar\omega_2$, *МэВ*
210	10,04	1,16	7,50	0,84	8,10	1,15	5,44	0,91
211	11,32	1,16	8,43	0,81	9,19	1,16	6,44	0,80
212	12,47	1,14	9,62	0,69	10,28	1,18	7,19	0,73
213	13,75	1,15	10,70	0,46	8,32	0,53	11,20	0,84
214	14,57	1,10	11,84	0,47	9,78	0,58	12,38	0,83
215	16,18	1,14	13,41	0,56	10,86	0,56	13,36	0,80
216	16,51	1,05	14,16	0,42	12,68	0,57	14,99	0,86
217	15,07	1,01	12,81	0,42	13,02	0,56	15,35	0,40
218	13,71	0,81	11,95	0,39	11,81	0,47	14,09	0,49
219	12,25	0,83	10,67	0,29	12,70	0,88	10,54	0,22
220	10,98	0,76	10,08	0,22	11,25	0,89	9,28	0,11
221	9,52	0,77	8,97	0,43	9,98	0,82	8,70	0,27
222	8,51	0,71	8,40	0,37	8,73	0,85	7,80	0,56
223	8,85	0,60	8,85	0,31	8,12	0,79	7,30	0,45
224	8,19	0,53	8,19	0,26	8,10	0,80	7,34	0,51
225	8,21	0,52	8,21	0,20	7,62	0,71	7,00	0,38
226	7,99	0,48	7,99	0,58	7,65	0,71	7,22	0,36
227	8,13	0,43	8,13	0,63	7,29	0,67	6,79	0,34
228	7,72	0,51	7,72	0,60	7,42	0,68	7,03	0,38
229	7,56	0,51	7,56	0,57	7,10	0,68	6,61	0,42
230	7,12	0,62	7,12	0,48	7,05	0,69	6,62	0,46
231	6,87	0,78	6,87	0,55	6,78	0,92	6,16	0,31
232	6,55	0,34	6,55	0,44	6,52	0,93	6,02	0,34
233	6,59	0,39	6,59	0,34	6,29	0,98	5,64	0,18
234	6,26	0,66	6,26	0,18	6,29	1,01	5,75	0,25
235	6,51	0,93	5,74	0,63	6,15	0,88	5,46	0,54
236	6,42	1,03	5,33	0,73	6,29	0,85	5,54	0,67
237	6,65	1,10	5,19	0,87	6,22	0,93	5,15	0,77
238	6,47	1,08	5,21	0,82	5,53	1,20	6,45	0,57
239	6,97	1,09	5,85	0,08	5,11	1,13	6,26	0,59
240	6,81	1,10	5,36	0,54	5,59	1,09	6,62	0,47
241	5,38	1,03	7,28	0,65	5,19	1,05	6,46	0,58
242	4,64	0,92	6,75	0,66	5,63	1,07	6,97	0,63
243	4,85	0,96	7,00	0,74	4,94	0,98	6,45	0,69
244	6,69	1,15	4,39	0,63	4,99	1,00	6,53	0,76
245	4,30	0,74	6,91	0,78	4,42	0,93	6,19	0,77
246	3,96	0,26	6,60	0,76	4,36	0,82	6,40	0,81
247	4,22	0,44	6,74	0,77	3,88	0,18	6,17	0,22
248	3,99	0,48	6,26	0,71	4,08	0,43	6,48	0,14
249	4,51	0,26	6,42	0,67	3,97	0,50	6,04	0,15
250	4,47	0,38	6,04	0,59	4,22	0,25	6,01	0,18

Ядро	**U**				**Np**			
A	B_1, *МэВ*	$\hbar\omega_1$, *МэВ*	B_2, *МэВ*	$\hbar\omega_2$, *МэВ*	B_1, *МэВ*	$\hbar\omega_1$, *МэВ*	B_2, *МэВ*	$\hbar\omega_2$, *МэВ*
210	3,65	0,33	6,35	0,91	3,59	0,322	7,51	1,00
211	4,71	0,95	7,69	0,90	4,29	0,425	8,13	0,99
212	5,07	0,24	8,14	0,91	4,80	0,094	8,96	0,97
213	6,16	0,99	9,27	0,92	5,59	0,271	9,64	1,00
214	7,44	0,34	10,56	0,98	6,49	0,396	10,68	1,02
215	8,71	0,51	11,86	1,01	7,56	0,553	11,56	1,07
216	9,67	0,46	12,61	0,95	8,78	0,65	12,79	1,10
217	11,35	0,50	14,28	0,51	9,77	0,583	13,51	1,01
218	11,78	0,46	14,64	0,54	11,32	0,612	15,00	0,63
219	10,51	0,47	13,30	0,60	11,72	0,51	15,15	0,61
220	9,31	0,40	11,82	0,58	10,48	0,487	13,76	0,68
221	8,02	0,33	10,37	0,66	9,22	0,449	12,19	0,64
222	6,84	0,26	9,11	0,58	7,88	0,417	10,73	0,69
223	5,69	0,13	7,79	0,64	6,65	0,362	9,36	0,62
224	5,13	0,08	7,19	0,57	6,06	0,251	8,56	0,67
225	5,24	0,18	7,18	0,60	5,35	0,217	7,76	0,60
226	4,74	0,10	6,70	0,49	5,55	0,096	7,78	0,63
227	4,97	0,31	6,66	0,51	5,07	0,159	7,28	0,51
228	4,32	0,33	6,37	0,28	5,13	0,268	7,15	0,28
229	4,56	0,47	6,59	0,35	4,61	0,342	6,83	0,34
230	4,06	0,38	6,29	0,31	4,88	0,455	7,02	0,38
231	4,18	0,34	6,25	0,46	4,40	0,432	6,65	0,20
232	3,87	0,49	5,91	0,67	4,54	0,339	6,49	0,38
233	4,56	0,89	6,08	0,66	4,23	0,472	6,09	0,48
234	4,45	0,93	5,86	0,59	4,83	0,956	6,07	0,55
235	5,21	1,07	6,01	0,48	4,78	0,984	5,80	0,63
236	5,09	1,04	5,87	0,81	5,44	1,063	5,80	0,55
237	5,62	1,08	6,13	0,74	5,25	1,03	5,51	0,37
238	5,39	1,07	6,08	0,66	5,69	1,115	5,45	0,73
239	5,79	1,23	6,32	0,55	5,41	1,106	5,25	0,65
240	5,41	1,15	6,17	0,56	5,70	1,228	5,29	0,63
241	5,98	1,09	6,64	0,41	5,35	1,182	4,98	0,60
242	5,61	1,05	6,52	0,53	5,68	1,128	5,14	0,45
243	6,06	1,09	7,05	0,60	5,37	1,087	4,85	0,55
244	5,45	1,02	6,52	0,65	5,62	1,051	5,21	0,58
245	5,29	0,99	6,63	0,73	5,12	1,044	4,50	0,70
246	5,03	0,96	6,35	0,75	4,61	0,968	4,47	0,80
247	4,87	0,80	6,51	0,81	4,66	0,99	4,34	0,15
248	4,42	0,72	6,23	0,11	4,57	0,926	4,43	0,28
249	4,61	0,71	6,38	0,18	4,36	0,919	3,96	0,35
250	4,25	0,60	5,92	0,24	4,07	0,79	3,70	0,40

Ядро	**Pu**				**Am**			
A	B_1, *МэВ*	$\hbar\omega_1$, *МэВ*	B_2, *МэВ*	$\hbar\omega_2$, *МэВ*	B_1, *МэВ*	$\hbar\omega_1$, *МэВ*	B_2, *МэВ*	$\hbar\omega_2$, *МэВ*
210	3,32	0,168	5,88	0,913	3,01	0,082	4,78	0,632
211	3,54	0,301	6,82	1,015	3,26	0,25	5,25	0,65
212	4,21	0,395	7,40	1,005	3,24	0,406	5,94	1,098
213	4,82	0,076	8,59	1,012	3,74	0,409	6,37	0,619
214	5,47	0,119	8,98	1,015	4,40	0,24	7,59	1,11
215	6,43	0,349	10,30	1,055	4,80	0,192	7,76	0,615
216	7,61	0,496	11,21	1,103	5,83	0,342	9,11	1,146
217	8,71	0,62	12,48	1,166	6,70	0,538	9,77	0,689
218	9,67	0,592	13,14	0,605	7,98	0,614	11,22	0,762
219	11,30	0,598	14,66	0,653	8,80	0,551	11,86	0,704
220	11,62	0,536	14,71	0,651	10,39	0,545	13,31	0,742
221	10,36	0,537	13,30	0,716	10,70	0,474	13,28	0,709
222	9,00	0,504	11,71	0,669	9,47	0,446	11,86	0,463
223	7,62	0,462	10,15	0,426	8,03	0,476	10,34	0,402
224	6,39	0,392	8,82	0,627	6,70	0,435	8,91	0,494
225	5,62	0,292	7,81	0,464	5,58	0,352	7,61	0,427
226	4,99	0,262	7,14	0,38	5,26	0,275	7,24	0,533
227	5,03	0,139	7,02	0,513	4,65	0,224	6,49	0,46
228	4,56	0,18	6,65	0,522	4,75	0,068	6,52	0,572
229	4,63	0,266	6,60	0,435	4,31	0,106	6,04	0,37
230	4,08	0,346	6,21	0,379	4,39	0,298	5,95	0,465
231	4,28	0,45	6,36	0,456	4,12	0,293	5,91	0,401
232	3,99	0,111	5,93	0,092	4,22	0,214	6,01	0,467
233	4,21	0,967	5,75	0,323	4,14	0,169	5,76	0,215
234	4,06	0,974	5,41	0,445	4,38	1,032	5,53	0,21
235	4,75	1,116	5,50	0,682	4,66	1,065	5,55	0,381
236	4,94	1,136	5,52	0,632	5,36	1,079	5,65	0,703
237	5,58	1,063	5,53	0,566	5,56	1,043	5,69	0,665
238	5,41	0,989	5,23	0,774	6,21	1,049	5,71	0,591
239	5,92	1,043	5,38	0,707	6,04	1,04	5,39	0,811
240	5,65	1,022	5,17	0,657	6,27	1,119	5,58	0,644
241	5,86	1,148	5,23	0,635	6,00	1,089	5,38	0,669
242	5,66	1,092	5,07	0,601	6,29	1,159	5,48	0,662
243	6,14	1,131	5,38	0,456	6,07	1,105	5,30	0,651
244	5,86	1,109	5,13	0,564	6,33	1,068	5,62	0,541
245	5,92	1,025	5,50	0,658	6,28	1,089	5,40	0,652
246	5,55	1,054	4,79	0,738	6,10	0,956	5,78	0,731
247	4,98	0,947	4,78	0,827	5,78	1,017	5,08	0,802
248	5,04	0,975	4,49	0,108	5,34	0,88	4,90	0,881
249	4,84	0,905	4,54	0,299	5,13	0,958	4,62	0,201
250	4,65	0,889	4,03	0,399	5,17	0,957	4,65	0,364

Ядро	**Cm**								
A	*B_1*, *МэВ*	$\hbar\omega_1$, *МэВ*	*B_2*, *МэВ*	$\hbar\omega_2$, *МэВ*	A	*B_1*, *МэВ*	$\hbar\omega_1$, *МэВ*	*B_2*, *МэВ*	$\hbar\omega_2$, *МэВ*
210	1,86	0,219	2,13	0,556	251	5,77	1,005	5,15	0,398
211	2,02	0,184	2,56	0,649	252	5,40	0,979	4,67	0,473
212	2,32	0,138	3,08	0,676	253	5,55	0,945	4,54	0,483
213	2,54	0,77	3,80	0,615	254	5,25	0,91	3,92	0,51
214	2,91	0,312	4,42	0,702	255	5,31	0,884	3,64	0,558
215	3,74	0,855	5,11	0,543	256	5,05	0,851	3,07	0,514
216	3,87	0,038	5,79	0,729	257	5,15	0,759	3,29	0,503
217	4,97	0,869	6,70	0,621	258	4,95	0,702	2,96	0,496
218	5,74	0,535	7,87	0,756	259	4,41	0,588	2,49	0,523
219	7,02	0,583	9,32	0,804	260	3,80	0,582	1,66	0,505
220	7,92	0,511	9,84	0,462	261	3,21	0,798	0,85	0,545
221	9,52	0,52	11,50	0,538	262	2,94	0,552	0,38	0,489
222	9,76	0,478	11,51	0,498	263	2,65	0,81	0,00	0,126
223	8,51	0,449	10,28	0,57	264	2,46	0,495	0,00	0,27
224	7,08	0,461	8,77	0,522	265	2,67	0,673	0,17	0,46
225	5,74	0,401	7,41	0,567	266	2,60	0,631	0,46	0,47
226	4,65	0,436	6,22	0,507	267	3,02	0,616	1,00	0,599
227	4,30	0,334	5,78	0,556	268	2,98	0,565	1,19	0,605
228	3,69	0,305	5,09	0,499	269	3,76	0,529	1,98	0,72
229	3,78	0,177	5,09	0,593	270	3,65	0,502	2,00	0,752
230	3,33	0,203	4,60	0,429	271	4,03	0,419	2,56	0,836
231	3,34	0,265	4,58	0,481	272	3,75	0,707	2,49	0,814
232	3,03	0,295	4,26	0,434	273	4,49	0,75	3,09	0,845
233	3,33	0,231	4,41	0,464	274	4,82	0,734	3,46	0,843
234	3,58	0,913	4,35	0,175	275	5,73	0,749	4,32	0,869
235	4,08	1,013	4,27	0,288	276	6,14	0,725	4,85	0,809
236	4,48	1,09	4,40	0,456	277	7,08	0,653	5,94	0,753
237	5,17	1,11	4,62	0,671	278	7,31	0,626	6,15	0,676
238	5,44	1,085	4,79	0,666	279	8,40	0,643	7,36	0,645
239	6,11	1,077	4,84	0,592	280	8,56	0,586	7,61	0,582
240	5,99	1,079	4,65	0,724	281	7,42	0,572	6,65	0,49
241	6,62	1,239	4,85	0,781	282	5,86	0,533	5,18	0,467
242	6,43	1,258	4,74	0,758	283	5,38	0,56	4,76	0,225
243	6,56	1,141	5,21	0,622	284	4,46	0,56	3,66	0,334
244	6,53	1,122	5,24	0,634	285	4,22	0,665	3,18	0,246
245	6,62	1,08	5,71	0,535	286	3,29	0,594	2,25	0,299
246	6,59	1,099	5,55	0,643	287	3,27	0,674	2,02	0,278
247	6,59	1,036	6,04	0,722	288	2,27	0,559	1,12	0,343
248	6,09	1,023	5,42	0,796	289	2,27	0,586	0,97	0,345
249	5,80	0,949	5,29	0,876	290	1,57	0,505	0,50	0,391
250	5,56	0,994	5,02	0,286					

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