Calculations of GeV-Nucleon Data with MCFx Code

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ABSTRACT

Nuclear data for GeV projectile energies are needed to design an Accelerator Driven System (target, material activation, heating, shielding etc.), for radiation therapy etc. The KRIT library of evaluated neutron and proton nuclear data were created in ENDF-6 format for the projectile energies from 20 MeV to 3 GeV. The evaluated data of the files are based mainly on the modern theoretical model calculations with MCFx code system [1, 2]. The developed code system is based on a detailed description of all stages of nucleon-induced reactions on heavy nuclei for E > 20 MeV including: description of entrance channel in the framework of coupled channel method; simulation of direct processes with the intranuclear cascade model; simulation of preequilibrium particle emission; description of fission/evaporation competitions on the base of detailed statistical model. The benchmarking of the data evaluated was performed by the comparison of the results of the transport calculations against the measured neutron leakage from the thin and thick Pb and U targets irradiated by the protons of 100 MeV – 3 GeV.

INTRODUCTION

The development of modern nuclear technologies requires a large amount of nuclear data to supply needs for the conceptual design of different fields of applications: the technology of radioactive waste transmutation and power production, radiotherapy, shielding problems and so on.

There are two ways of nuclear data supply for practical goals – to include the nuclear data generator into the transport codes or to produce nuclear data files outside. We guess the second way is more reliable due to the possibility of modern and sufficiently complicated code applications. The development of the nuclear data libraries as well as corresponding computer codes has to be done for nuclear reactions induced by proton and neutron beams in projectile energy region 20 MeV – 3 GeV.

MCFx CODE

Further development of the MCFx system [1, 2] was recently realized: relativistic corrections was introduced to optical model calculations, the sharp cutting off energy for intranuclear cascade processes was replaced by smooth barrier penetration, Monte Carlo multi-particle preequilibrium model (MCP) was developed and tested [3], the new sets of the statistical model parameters was generated and verified. The approach developed is adopted for evaluation of nuclear data for energies up to 3 GeV as follows: yields of evaporation residuals; yields of fission products; spectra of secondary gammas, protons and neutrons, including emission from fission fragments; total, elastic and fission.

Entrance channel

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 the nucleon probability of penetration into a target nucleus, i.e. the optical model reaction (absorption) cross section.

The optical potentials are key quantities in any optical model calculations and therefore their reliable definition is very important.

Simulation of the entrance channel within the framework of a coupled channel method [4] in a relativistic approximation and development of a global optical potential for heavy nuclei in wide energy region were performed. The comparisons of the available experimental and theoretical data on total and reaction cross-sections are presented.

An extension of a beam energy range up to a few GeV needed some modification of the KRI2000 [5] parameterization. Namely, potentials have been simplified slightly; energy dependence 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 dependences; some additional fit has been carried out to the available experimental data for the projectile energy up to 3 GeV. Note that these modifications practically have no influence on the reaction cross sections calculated for the energy region below 200 MeV.

The comparison of the experimental and calculated results is shown in Fig. 1. The optical model parameter set KRI2004 [4] was created by the fitting to the experimental cross sections of wide target mass region. The optical model itself guarantees good description of the nucleon elastic scattering (Fig. 1). Indeed, the changing of the differential cross sections is 8-10 orders of magnitude. The calculated data differ from the measured ones considerably for the negligible values only (Fig. 1, 200 MeV).

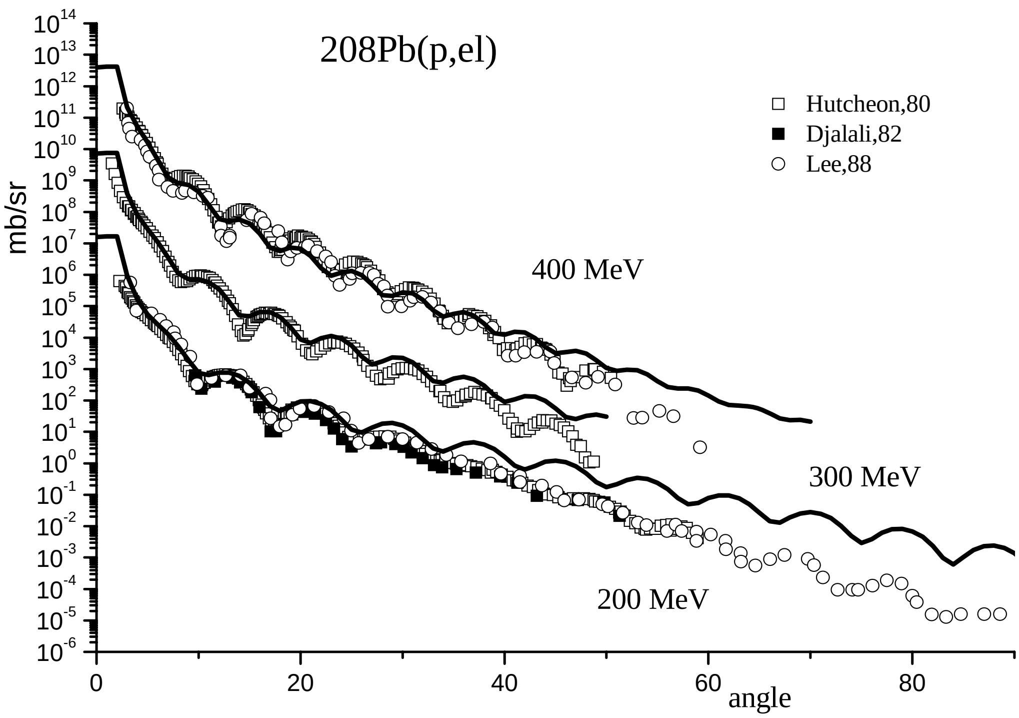

Fig. 1. Angular distributions of elastic scattering for ^{208}Pb+p at different projectile energies: 200, 300, and 400 MeV.

Reaction fast stage

The fast direct stage of nucleon-nucleus interaction in the MCFx code is described with the modified Dubna version of intranuclear cascade model [6]. All calculations of intranuclear cascades are performed in the three dimension geometry. The function of nuclear density distribution is described by Fermi distribution with parameters taken from the experimental data on electron-nucleus scattering. 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 interacting 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 50 MeV. Such a limitation is a significant point of the model. Practically the lowest limit of intranuclear cascade applicability can be established by the analysis of calculation results. We replaced the cut off threshold by the parabolic barrier with fixed height of 10 MeV and a width of 50 MeV. So it leads to a smooth slowing down of an INC contribution to the reaction cross sections as a projectile energy decreases, and to smooth neutron spectrum shape at the low ejectile energies.

Preequilibrium multiparticle emission

The idea of multiparticle preequilibrium emission in the frameworks exciton statistical model is simple - to repeat the calculation of equilibration for new composite system after the first nucleon emission. The proposed scheme of calculation (model MCP) of the reaction cross sections for nucleons of the intermediate and high energies: at the preequilibrium stage (which begins with various initial excitations and configurations) residual nucleus should pass to the equilibrium emitting out the nucleons [3]. To choose the time of equilibration we used the comparison of the calculated neutron spectrum shape with the evaporation one. It is appeared that the configurations higher then 30^{th} emit neutrons of evaporational spectra, so they are the states of compound nucleus. The results of neutron multiplicity calculations with the new method of equilibration time choosing are in the coincidence with the experimental data for 208Pb+p reaction [7].

RESULTS

The fission cross sections of the two different types of fissile nuclei are shown in Fig. 2 and 3. The ^{238}U has high fission probability. On the other hand, the fission cross sections of ^{208}Pb are small in comparison with the reaction cross section for the projectile energies up to 3 GeV.

It is known the description of small cross sections, which are very sensitive for the competition of more strong reaction channels, is enough complicated. On another hand, the fitting can be done easily by the fission barrier changing.

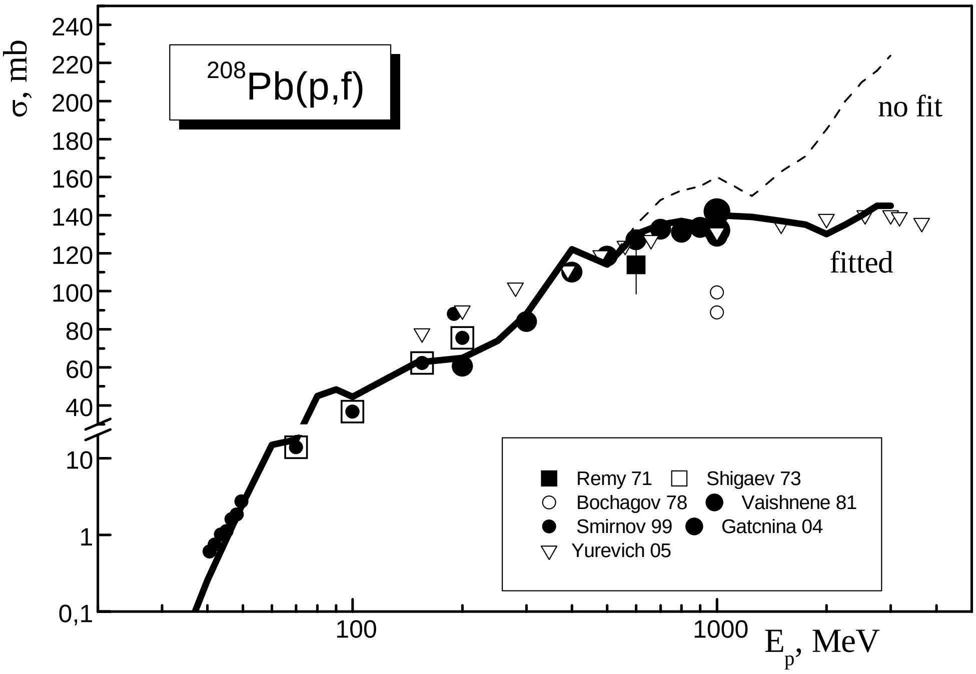

Fig. 2. Fission cross section of ^{208}Pb+p reaction.

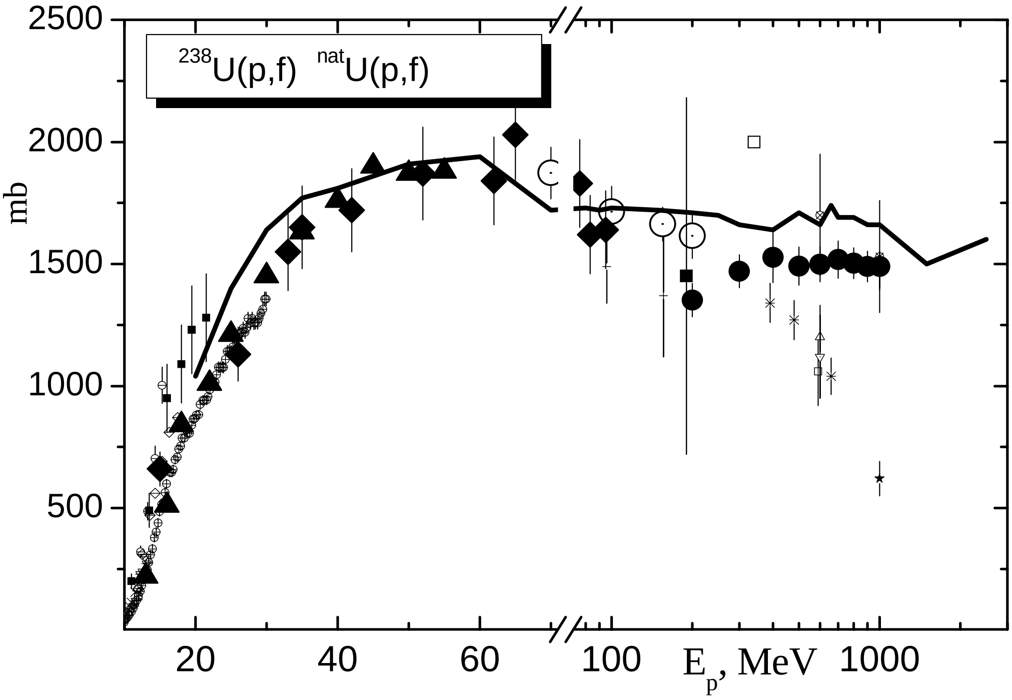

Fig. 3. Fission cross section of ^{238}U+p reaction.

In calculations of fission cross sections the shell corrections and fission barriers (shown in Fig. 4) were used. The values were computed by the methods proposed in [8]. It can be seen from fig. 4 that: i) the shell corrections for the barriers are smaller then the values for the ground states and ii) the mass dependence of the barriers reproduced reasonably good for long isotopic chains.

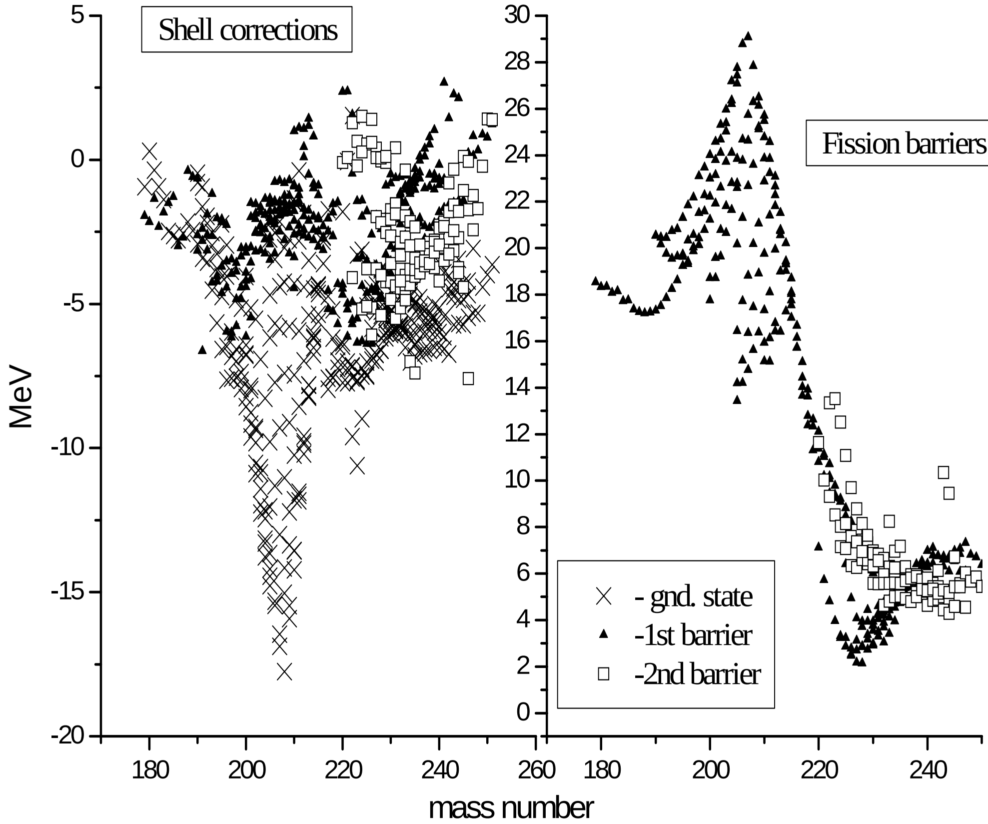

Fig. 4. Shell corrections (left side) and fission barriers used in calculations. Circles are corrections for ground states, triangles are corrections and barrier heights for 1st barrier, squares are values for 2nd barrier.

The results presented in Figs. 1 and 2 were calculated without the parameter fitting. In fact, the data comparison shows the real predictability of MCFx code. It can be seen that for ^{238}U target the experimental fission cross sections, in spite of some deviation, are described by the theoretical calculations reasonably good for proton energies from 20 MeV to 1000 MeV. On the contrary, the measured fission cross sections of ^{208}Pb target are worse described by the calculations especially for proton energies from 700 MeV to 3000 MeV. The main reason of this bad description is small values of cross sections.

For the information representation we used three files of complete file according to ENDF-6 manual recommendations. File 1 contains general information where in very brief style the methods of data evaluation are described. File 2 was not prepared because neutron projectile energies of our evaluations start from 20 MeV. We believe it is better to insert different complete files into transport calculation separately instead of compilation one data file for the energy from 10^{-5} eV to 3 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 of the data presentation to save the file volume. So for each energy of the nucleon spectra the probability of emission and non-equilibrium part of reaction are presented.

CONCLUSION

The results of nucleon emission characteristics and fission cross sections calculations are presented and discussed.

The work was performed under ISTC Project # 3751.

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