Simulation using CASCADE.04 code

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Abstract. The Intra-nuclear, Pre-equilibrium, Evaporation/Fission model CASCADE.04 has been successfully used to reproduce nuclear reactions at intermediate energies with reasonable accuracy. In this paper, we present the results obtained from the present version of the code, with option of particle emission upto ^{4}He. Some of the mandatory data decided for the International Benchmark of the Model codes are presented. The results are in good agreement with the experimental data for isotope production, excitation function, and double differential neutron, proton, and pion production cross-section but the code needs further development for the complex particle production cross-sections.

1. Introduction

The particle transport in CASCADE.04 is realized in three stages:

1) sampling of particle (ion) mean free path in the medium taking into account the energy loss of a charged particle and a possible decay of non-stable particles (π^0, $\pi^\pm$). All π^0-mesons are considered to decay into γ-quanta at the point of their creation. The ionization losses of π^- mesons, protons and light ions are calculated by Sternheimer's method [1] using Bathe formula for the average ionization loss calculations with proper density effects. Here, it is important to mention that the density effect shows reduction in ionization loss for fast charged particles due to dielectric polarization of the medium. In the lower energy region (< 2.0MeV) Lindhard's approach [2] is used and a semi-phenomenological procedure [3] is applied for the heavy ions. The algorithm has recently been modified [4] so that the code can be used for thin targets too.
2) In case of inelastic interaction the CASCADE.04 code considers three stages of reaction for calculation:
    a) Intra-nuclear cascade: The present version of the Intra-Nuclear Cascade (INC) is a time dependent version developed at Dubna [5]. At this stage, primary particles can be re-scattered and they may produce secondary particles several times prior to absorption or escape from the target. Cross-sections of the hadron-nucleus collisions are calculated based on the compilations of the experimental data [6, 7]. To calculate the nucleus-nucleus cross-sections we have used analytical approximations with parameters defined in ref. [8]. Criteria of transition from intra-nuclear cascade to pre-equilibrium stage are the cut-off energy (binding energy above the Fermi energy), below which the particles are considered to be absorbed by the nucleus. Particles are tracked down to this cut-off energy and then the second stage, pre-equilibrium starts,
    b) Pre-equilibrium stage: In this part of the reaction, relaxation of the nuclear excitation is treated according to the exciton model of the pre-equilibrium decay. The relaxation is calculated by the method based on the Blann's model [9, 10]. Proton, neutron, deuterium, tritium, ^{3}He, and ^{4}He are considered as emitted particles in the pre-equilibrium and in the subsequent equilibrium stage. All nuclear transitions changing the number of excitons n with Δn=+2, -2, 0 are considered with multiple particle emissions. Transition from pre-equilibrium to equilibrium state of the reaction occurs when the probability of nuclear transitions changing the number of excitons n with

$\Delta n=+2$ becomes equal to the probability of transitions in the opposite direction, with $\Delta n=-2$,

c) Equilibrium stage: This part considers the particle evaporation/fission of the thermally equilibrated nucleus as described in [11]. The higher fragment emission up to ^{28}Mg is included but not used for the present calculations due to higher CPU time. The fission model is based on Fong's statistical fission model [12]. It was assumed that cascade particle is stopped if its energy is less than the boundary energy E_b which equals to 2 MeV for $\pi^{\pm}$, 4 MeV for proton and deuteron, 15 MeV for tritium, and 10 MeV/nucleon for all heavier nuclei. However, it is important to have a careful consideration of these low energy particles for bio-physical problems, investigation of radiation damage to micro-electronic devices and some other applications where large radiation damage produced by low-energy particles are important. Low energy π^- mesons are captured in a nucleus creating new intranuclear cascades.

3) The third stage considers the transport of neutrons. The code uses 26-group constants [13] for neutron transport below 10.5MeV. The neutrons can moderate by numerous elastic/inelastic collisions; can make fission in case of fissile/fertile materials and finally get captured in (n, γ) reaction. Neutrons are traced down to thermalization. The algorithm is cyclic in nature and is reduced to several repetitions of all these possible operations.

General scheme of the code for thin and thick target simulation is given in the Fig.1.

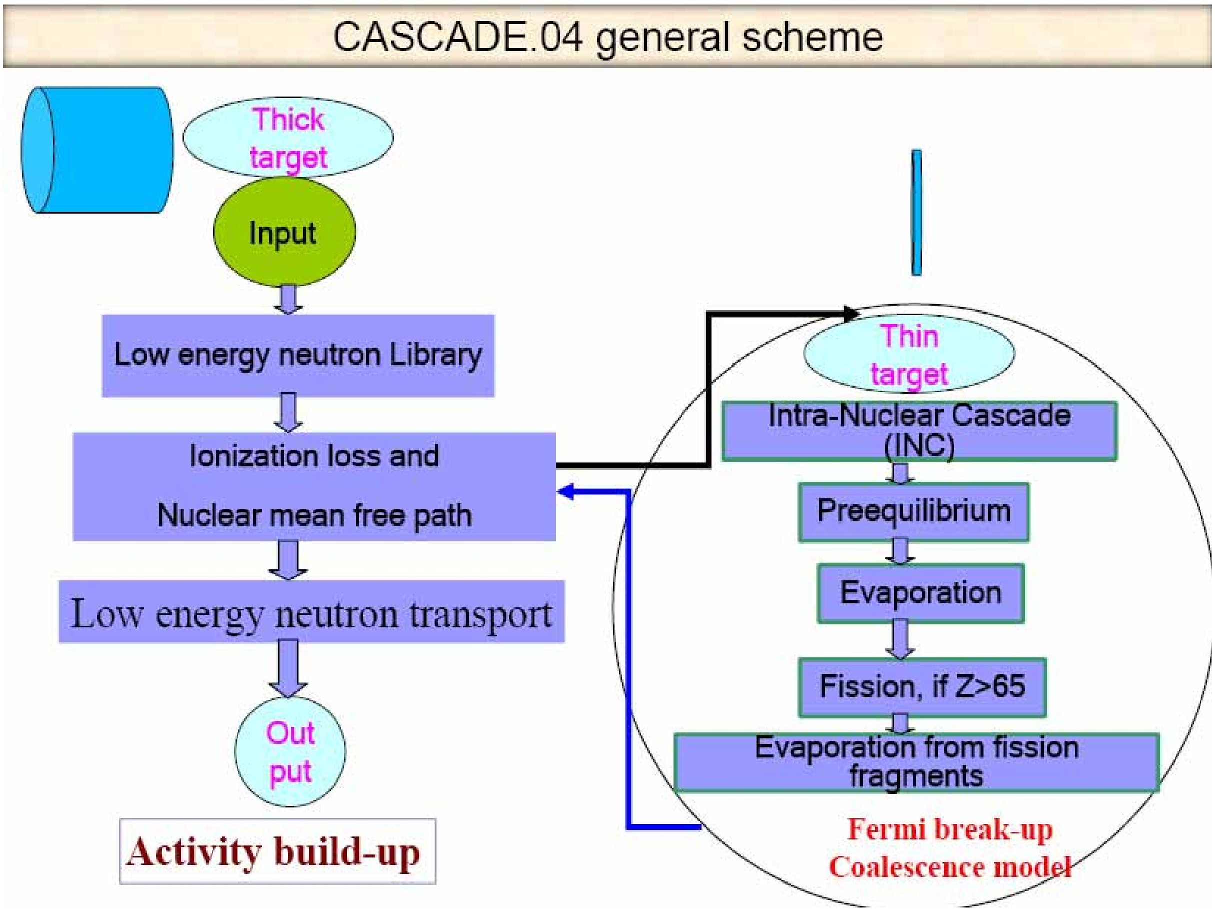

FIG.1. General scheme of the CASCADE.04 code.

2. Results and discussions

The CASCADE.04 code has been applied to calculate the residue production cross-sections, excitation functions, double differential cross-section for neutron, Light Charge Particles (LCP), and pions. We don't present the LCP and pion production cross-sections at present. The residue production cross-sections for p(1.0GeV)+^{208}Pb are given in fig.2. The calculated values are in good agreement with the experimental data [14] close to the target charge number. The deviation starts far from the target charge number (deep spallation region). The deep spallation region might be populated if heavy fragment emission is made possible at the pre-equilibrium stage. Some even odd-effect is also visible in the calculations which needs to be investigated.

The calculated excitation functions for various isotopes have also been compared with the experimental data from [15]. The discrepancy in deep spallation region and for light residues is visible from fig.3. We have also calculated the residues for middle mass target like Sn. The results have been presented only at 8.1GeV proton energy and for ^{112}Sn isotope (see fig.4) that are in good agreement except for few isotopes which are far from the target mass number. We have also compared these results with that obtained from the other code like Statistical Multi-fragmentation Model (SMM) and the calculated values are taken from [16]. Our results are even better, compared with results from SMM, near target mass number. It is seen that SMM gives better predictions for light residues. We have also performed calculations for ^{112,118,120,124}Sn at 1.0, 3.65, and 8.1GeV which show that CASCADE.04 code predictions are very similar for all isotopes and all energies that mean the isotopic/energy dependence has been taken care in the code around GeV range. The deviation starts to increase below 0.2-0.3GeV and above 10GeV of proton energy.

Double differential neutron production cross-sections for various energies of proton on Pb target are presented in fig.5. The agreement of calculated values with experimental data [17-19] is good at all the energies.

3. Summary

CASCADE.04 code describes the residue, neutron, and light charge particles production cross-sections better than the previous versions. The light charge particle production cross-sections need to be improved in the future versions. The predictions of pion production cross-sections are similar to that from the previous version and are in good agreement with the experimental data. The code has been extended for the neutron shielding calculations, and activity calculation due to spallation decay products in the recent past. The work is in progress for the inclusion of ENDF point data in place of the 26-group cross-sections for low energy neutron transport.

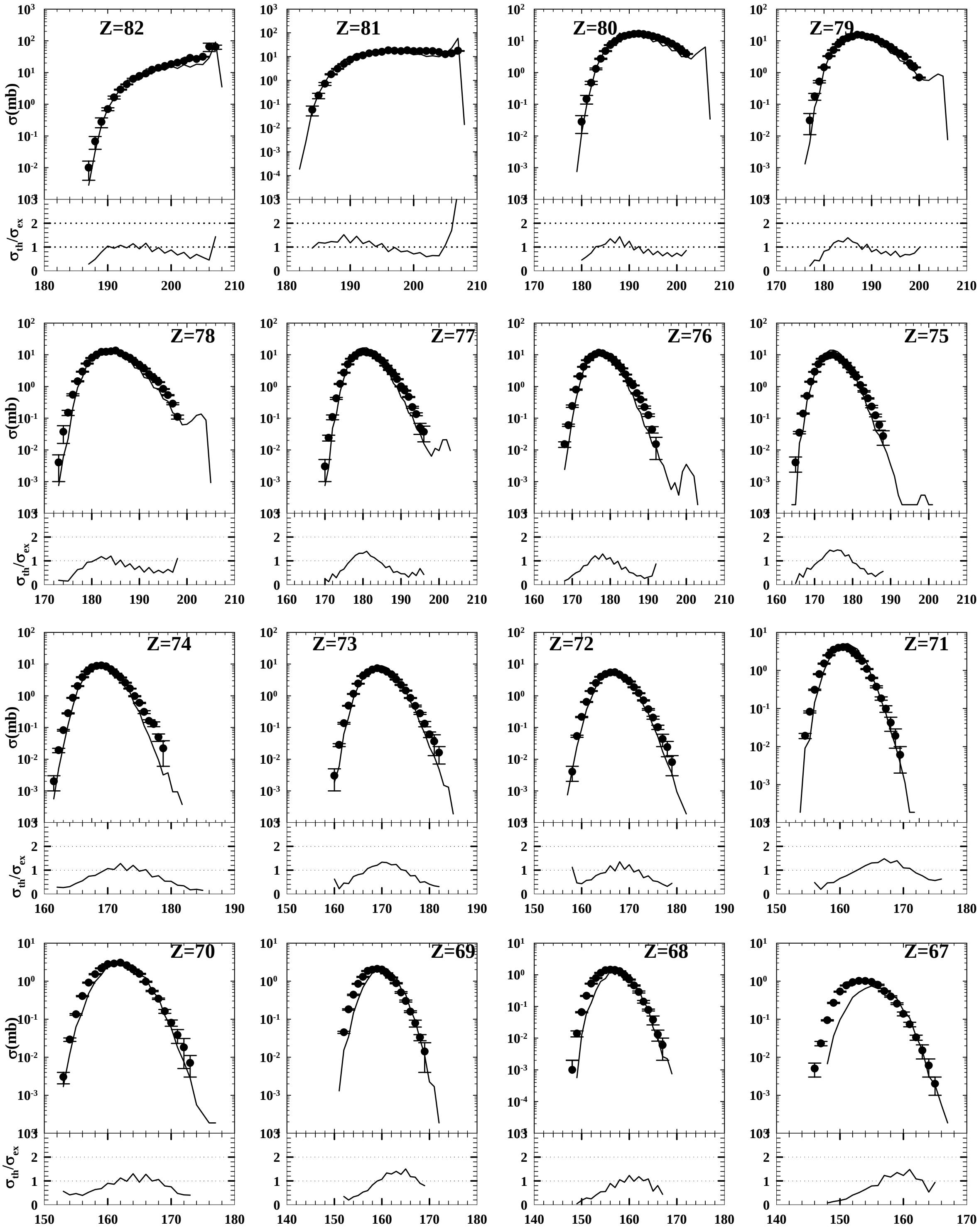

FIG.2. Comparison of calculated and experimental cross-sections for various spallation products for p(1.0GeV)+^{208}Pb reaction. The experimental data are taken from ref. [14].

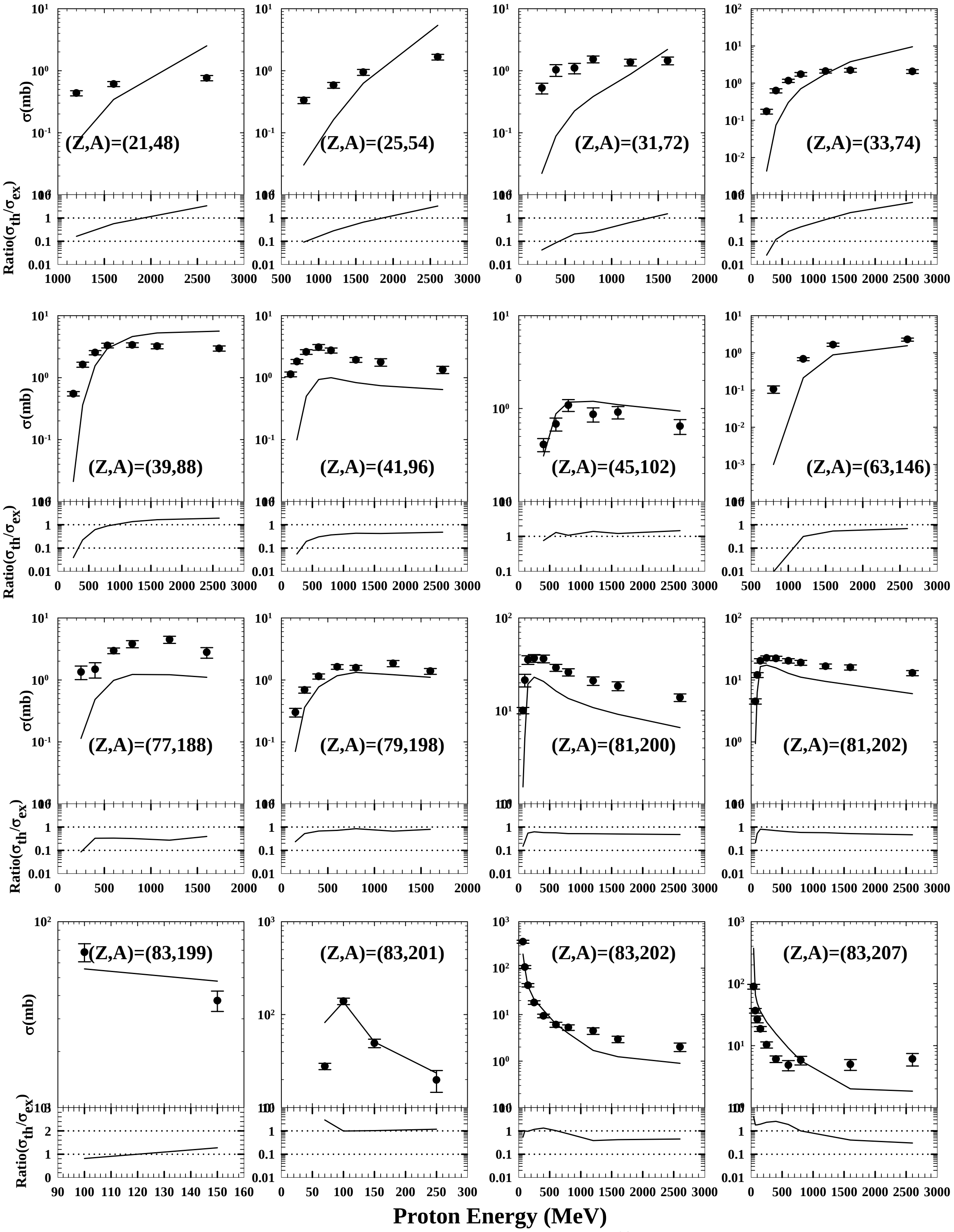

FIG.3. Comparison of the calculated excitation functions for p+^{208}Pb reaction with experimental data and ratio of the theoretical and experimental cross-sections. The experimental data are taken from Ref. [15].

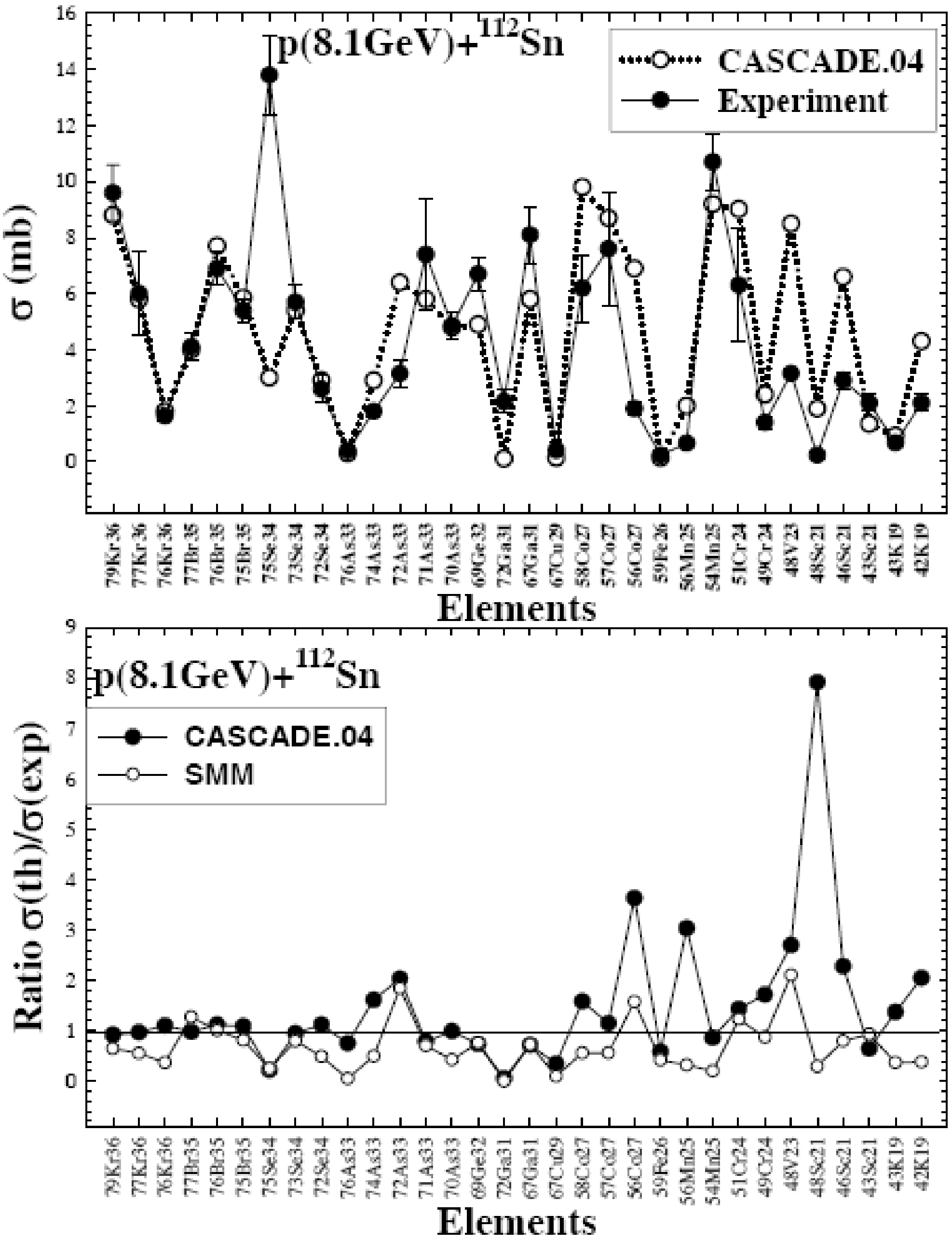

FIG.4. Comparison of calculated and experimental cross-sections for various spallation products for p(8.1GeV)+^{112}Sn reaction. The experimental data and SMM calculations are taken from ref. [16].

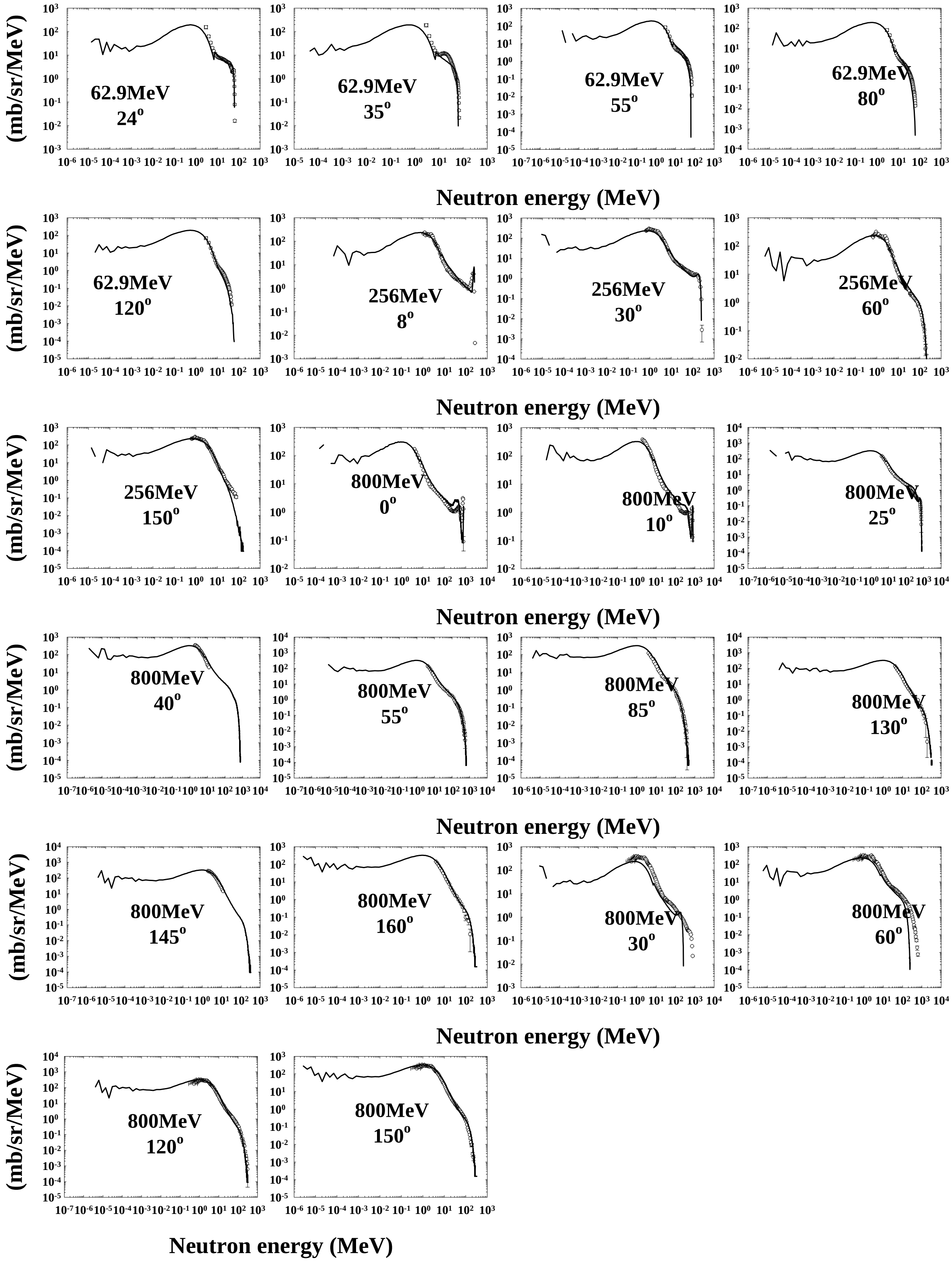

FIG.5. Comparison of the calculated double differential neutron production cross-sections, for p+^{208}Pb reaction at various energies (62.9, 256 and 800MeV), with experimental data. The experimental data are taken from Ref. [17-19].

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