Evaluations of Cross Sections on Zr, Nb, and W up to 200 MeV for JENDL High Energy File

Satoshi KUNIEDA*, Nobuhiro SHIGYO, and Kenji ISHIBASHI

Department of Applied Quantum Physics and Nuclear Engeneering, Kyushu University

Nuclear data were evaluated on Zr isotopes, ^{93}Nb and W isotopes for neutron- and proton-induced reactions up to 200 MeV. Optical model potential parameters were determined to give good agreements with experimental values of elastic-scattering, total, and total-reaction cross sections by the traditional phenomenological approach. The GNASH nuclear model code was used for evaluations of particle-production cross sections. Since the direct inelastic-scatterings induced by the excitations of giant resonances are not negligible for medium/heavy nuclei, the calculation was performed to take them into consideration. For composite-particle emission cross sections from pre-equilibrium states, semi-empirical models were utilized to give good agreements with experimental data. Evaluated cross sections were compared with experimental values and the LA150 evaluations.

I. Introduction

The evaluated nuclear reaction data are required in the intermediate energy range for the designs of various accelerator-based application facilities. The program for completion of the JENDL High Energy File[1)] is now ongoing under the Japanese Nuclear Data Committee to meet these needs.

In the design of accelerator-driven system, zirconium will be an useful material as a constituent of the nuclear fuel pellet or blanket tube. Niobium is one of the major elements as superconducting materials. Such compounds as NbTi or Nb_3Sn are applied for the superconducting magnet of accelerators. For the sake of the design of spallation neutron source, tungsten is one of the candidate materials both for the beam window and the spallation target. Evaluating nuclear reaction data on these elements is essential for the recent and the future nuclear technologies.

Optical model potential parameters were searched to evaluate elastic-scattering, total and total-reaction cross sections, and to obtain the transmission coefficients for outgoing nucleons. The GNASH nuclear model code[2)] was used for the evaluations of particle-production cross sections. Reasonable parameters were used for the Hauser-Feshbach, the exciton model, and DWBA calculations. In addition to the model calculations, the contribution of giant resonance excitation was considered by a simple way. The original GNASH code utilizes semi-empirical methods for computations of composite-particle (deuteron, triton, ^{3}He and α-particle) production cross sections from pre-equilibrium states. In spite of its frequent use for nuclear data evaluations in the intermediate energy range, a problem remained at least for α-particle emissions from medium and heavy nuclei. The original functional forms for α-knockout process were modified to give good agreements with experimental data in this work.

We made evaluations for such values of total, total-reaction, angular-differential elastic-scattering, energy-differential particle-production, and double-differential particle-production cross sections. Present results were compared with available experimental data and the LA150 evaluations.[3)]

II. Optical Model Analysis

The optical model is an efficient method to calculate angular-differential elastic-scattering, total and total-reaction cross sections. It also provides transmission coefficients for outgoing particles required in the statistical model. The phenomenological optical model potential (OMP) parameters were determined

* Corresponding author, Tel. +81-92-642-3765, E-mail: kuni@meteor.nucl.kyushu-u.ac.jp

in order that the model calculations could reproduce measured values for neutron and proton. The optical model calculations were performed with the ECIS-96 code.[4] To describe OMP parameters varying continuously on the incident energy, we assumed functional forms similar to that of Koning and Delaroche.[5] And local OMP parameters were obtained by an empirical way on the nuclei $A \sim 90$ and ~ 184, respectively. The experimental data for total-reaction cross sections were scant above ~ 100 MeV. Values by the systematics derived from the TOTELA code[6] were employed as substitutional values for them. Evaluated cross sections are shown in **Figs. 1 - 4** with experimental data. [7–25]

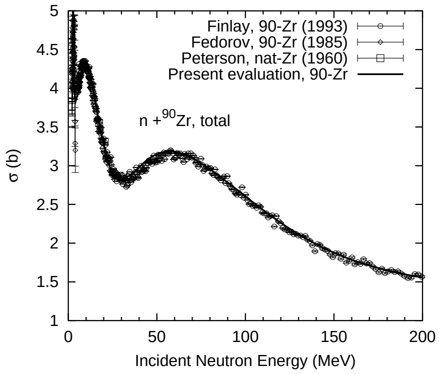

Fig. 1 Present evaluations and experimental data[7–9] for neutron-induced total cross sections on ^{90}Zr

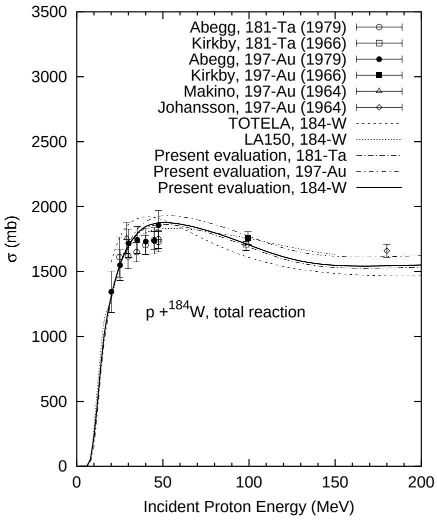

Fig. 2 Present evaluations and experimental data[10–13] for proton-induced total-reaction cross sections on ^{181}Ta, ^{184}W, ^{197}Au. The LA150[3] and TOTELA[6] prediction are also presented.

III. Particle Production Cross Sections

The GNASH nuclear model code[2] was basically utilized for the evaluations of particle-production cross sections. In the code, the Hauser-Feshbach(H-F) statistical model is employed for the equilibrium decay, and the exciton model for the pre-equilibrium reaction. The inelastic scattering cross sections are also calculated by DWBA/CC. Productions of light particles such as neutron(n), proton(p), deuteron(d), triton(t), helium-3(^3He), and alpha-particle(α) were considerd in this work. Because the exciton model could not calculate any emission-angle information by itself, double-differential cross sections were calculated by the Kalbach angular-distribution systematics.[26]

1. Nucleon production

In the H-F model, transmission coefficients of the emitted particles are derived from the optical model calculations. The local OMP parameters obtained in this study were used for neutron and proton. The global OMP of Daehnick *et al.*[27] was employed for deuteron, that of Becchetti-Greenlees[28] for triton and ^{3}He, and that of Avrigeanu *et al.*[29] for alpha-particle. The level density parameter of Ignatyuk *et al.*[30] was adopted for almost all residual nuclei.

The exciton model has some adjustable parameters such as the single-particle state density parameter g, the average squared matrix element $|M|^2$, and the average effective potential well depth value $\overline{V}_{\text{eff}}$. The standard value $A/13$ was used for g, and $|M|^2$ was determined on the basis of the original functional form.[2] The surface localization effect[31] of the pre-equilibrium reaction is commonly introduced in the exciton model, and also in the GNASH code. The the average effevtive well depth value $\overline{V}_{\text{eff}}$ is the

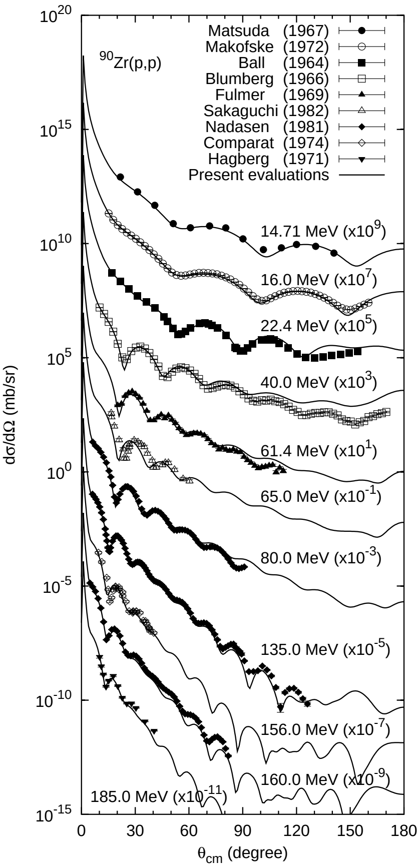

Fig. 3 Present evaluations and experimental data[14–22] for proton-induced elastic-scattering differential cross sections on ^{90}Zr

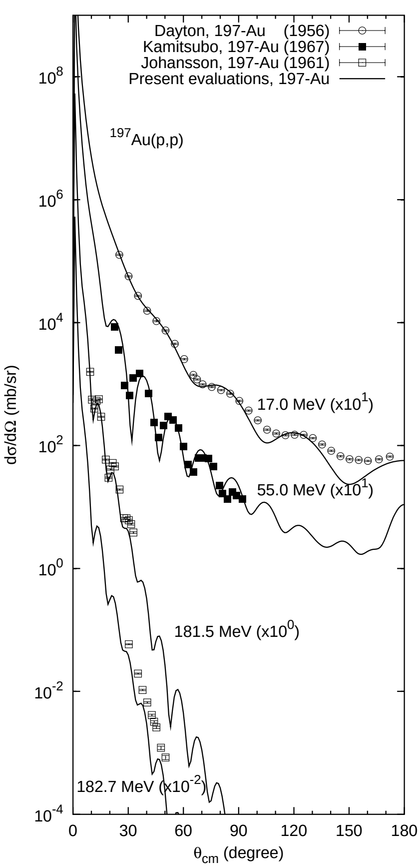

Fig. 4 Present evaluations and experimental data[23–25] for proton-induced elastic-scattering differential cross sections on ^{197}Au

only parameter for the effect, and the choice brings large influence on the slope of energy spectrum at around incident energy. Therefore, reasonable value was determined phenomenologically. Because neutron-induced experimental data have not been obtained above 26 MeV, the original effevtive well depth parameter[31] was used for our neutron-induced evaluations.

Inelastic scattering cross sections were calculated by DWBA. Required low-lying discrete level informations such as excitation energy, spin, parity, and deformation parameters were taken from RIPL[32] (They were the values used for JENDL-3.3). We also considered the excitations of the giant resonance, following the method of Demetriou *et al.*[33]

Evaluated double-differential cross sections are shown for ^{90}Zr(p, xn) in **Fig. 5**. Present evaluations agree with experimental data[34,35] in wide emission energies and angles. The LA150 evaluations are not shown, because they have no data for Zr isotopes. **Figure 6** stands for the results of ^{93}Nb(p, xp) double-differential cross sections. Both present and LA150 evaluations reproduce measurements[36–38] with enough accuracy. As presented in **Fig. 7** for ^{nat}W(p, xn) at 113 MeV, LA150 evaluations tend to overestimate experimental values[39] at around 100 MeV, while our evaluations give good agreements. It is ascribable to the difference of the average well depth value. The original $\overline{V}_{\text{eff}}$ value[31] was employed in LA150, while $\overline{V}_{\text{eff}} \sim 35$ MeV was used in this evaluation. The excitation of low-energy octupole giant resonance (LEOR) is not negligible especially on the heavy nuclei such as W isotopes. The result of ^{184}W(n, xn) energy-differential cross section is shown in **Fig. 8** at 26 MeV. The original GNASH can not reproduce experimental data,[40] since it dose not consider the giant resonance excitation. Present

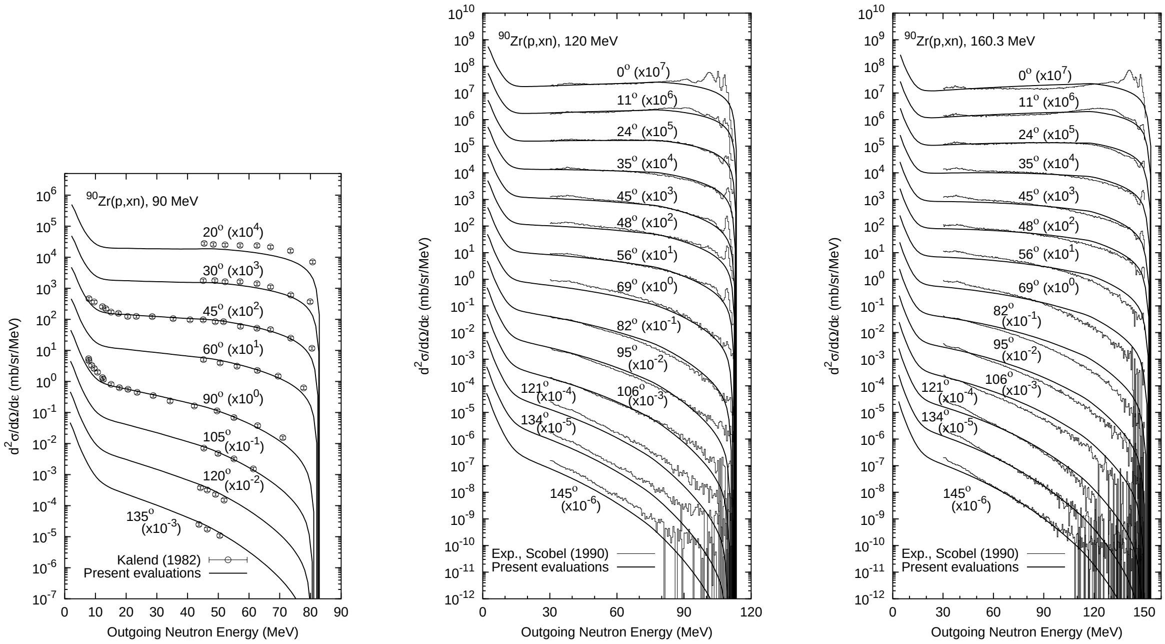

Fig. 5 Present evaluations and experimental data[34,35] of double-differential cross sections for (*p*,*xn*) reactions on ^{90}Zr at 90, 120 and 160.3 MeV.

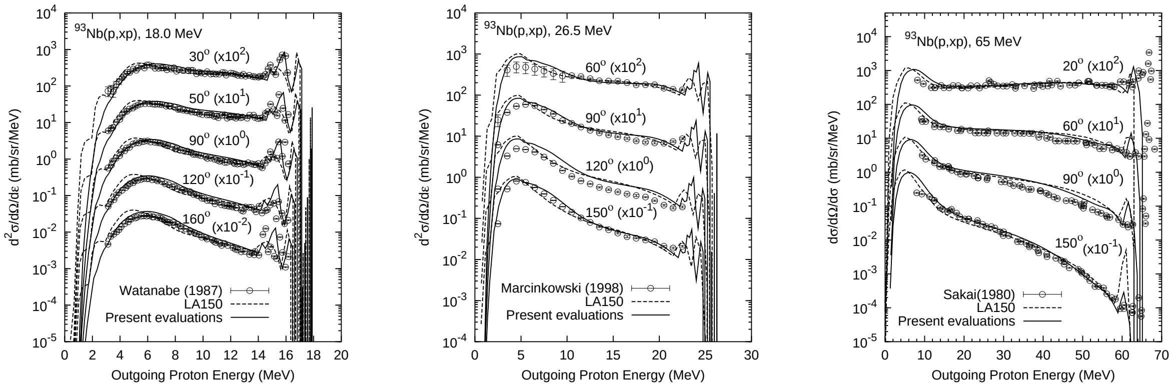

Fig. 6 Present evaluations and experimental data[36–38] of double-differential cross sections for (*p*,*xp*) reactions on ^{93}Nb at 18, 26.5 and 65 MeV. The LA150 evaluations[3] are also shown for the comparisons.

evaluation as well as LA150 agree with experimental data, because both evaluations made correction for LEOR excitaion.

2. Composite-particle production

We made cross section evaluations not only for the nucleon productions but also for the composite-particle (d, t, ^{3}He, and α) productions. The evaporation components were calculated by the H-F model. The GNASH employs the semi-empirical exciton model[41] for the pre-equilibrium emissions. The pickup and the α-knockout model are considered in the semi-empirical model. **Figure 9** shows the evaluated results for ^{93}Nb(p, xd) double-differential cross sections at 65 MeV compared with experimental data[38] and the LA150 values. Our results give reasonable agreements with measurements in the overall emission energy and angle, while the LA150 results take relatively lower values at evaporation region. The difference of OMP produces such a tendency (The global OMP of Perey[42] was utilized in the LA150

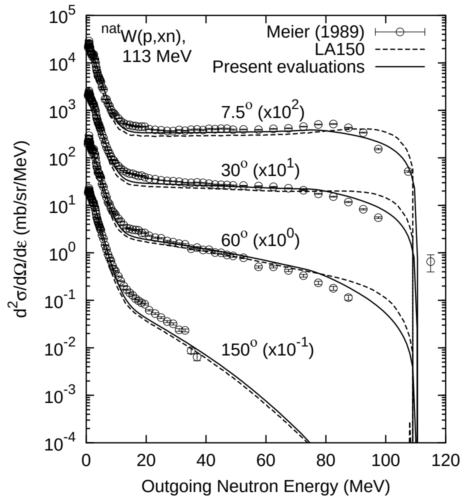

Fig. 7 Present evaluations and experimental data[39] of double-differential cross sections for (*p,xn*) reaction on ^{nat}W at 113 MeV. The LA150 evaluations[3] are also shown for the comparisons.

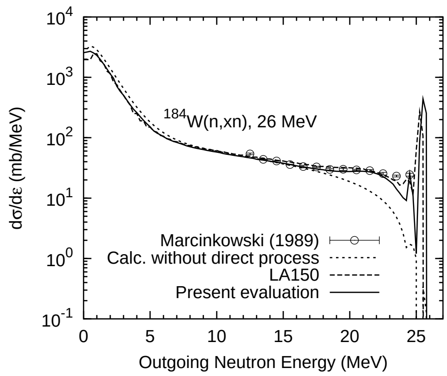

Fig. 8 Present evaluation and experimental data[40] of energy-differential cross sections for (*n,xn*) reaction on ^{184}W at 26 MeV. The GNASH calculation without direct reactions and the LA150 evaluation[3] are also shown for the comparison.

evaluations). We could easily confirm the validity of the pickup model. On the other hand, the original GNASH can not reproduce experimental data of ^{90}Zr$(p, x\alpha)$ energy-differential cross sections at least on the medium and heavy nuclei as presented in **Fig. 10**. The problem arises from insufficient expression of the functional form for α-knockout. In order to improve the calculation of α-particle emission, the original α-knockout functional form was modified to depend on the ratio of state densities $\omega(U)/\omega(U_{\rm max})$ rather than $\omega(U)/E^3$, where E, U, and $\omega(U)$ are the incident energy, excitation energy, and state density. And $\omega(U)$ was determined using a tentative functional form in order to get reasonable evaluated cross sections. As presented in Fig. 10, good results were obtained in this evaluation.

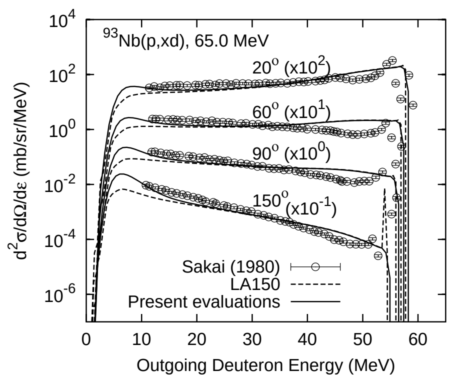

Fig. 9 Present evaluations and experimental data[38] of double-differential cross sections for (*p,xd*) reaction on ^{93}Nb at 65 MeV. The LA150 evaluations[3] are also presented for the comparisons.

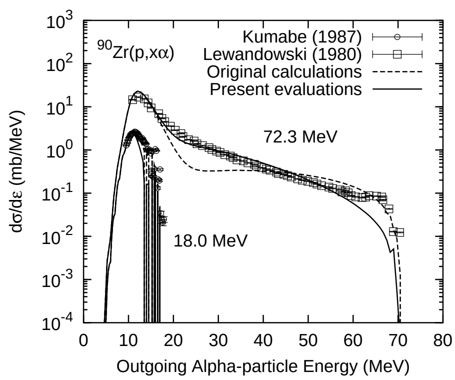

Fig. 10 Present evaluations and experimental data[43, 44] of energy-differential cross sections for (*p,x*α) reactions on ^{90}Zr at 18 and 72.3 MeV. The original GNASH calculations are also shown.

IV. Summary

Various cross sections were evaluated on Zr isotopes, ^{93}Nb, and W isotopes for neutron- and proton-incidence. OMP parameters were determined by the phenomenological way. The GNASH nuclear model code was employed for the evaluations of particle-production cross sections. Reasonable parameters were utilized for the H-F, the exciton model, and DWBA calculations. Composite-particle emission cross sections were also evaluated using the H-F and the semi-empirical exciton model. The evaluated cross section data were obtained with enough accuracy.

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