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Evaluation of Be and Li cross section data up to 200 MeV

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Abstract. Nuclear cross section data on lithium and beryllium isotopes are evaluated in the incident energy up to 200 MeV for proton and neutron incidence. For the first step for overall evaluation, parameters for phenomenological optical potential are obtained. Evaluated cross sections include neutron total cross section, total reaction cross section, angular differential elastic scattering cross section, nonelastic cross section.

1 Introduction

Both lithium and beryllium play an important role as a neutron converter for the boron neutron capture therapy (BNCT) using a proton accelerator. Beryllium is also one of essential materials as a target window and a reflector for a spallation neutron source. Evaluated nuclear data for these nuclei are contained in the energy region below 20 MeV in the JENDL [1] at the moment and those in higher energy region are desired for such kinds of application. In this study, nuclear cross section data on Li and Be isotopes are evaluated in the incident energy up to 200 MeV for proton and neutron incidence as the first step of overall evaluation.

The evaluated cross section data include neutron total cross section, total reaction cross section, angular differential elastic scattering cross section, nonelastic cross section and double differential secondary particle production cross section. The phenomenological optical model parameters are found to give good agreement with experimental data of total, elastic- and nonelastic-scattering cross sections. These evaluated cross sections are compared with available experimental values. The evaluated nuclear data will be merged into the JENDL High Energy File (JENDL-HE) [2] in the near future after evaluation of particle emission cross sections by the GNASH code [3].

2 Optical potentials

The optical potential is described as follows:

$$U = \frac{2(E+m_pc^2)}{E+2m_pc^2} \times \left[-V_Rf_R + i\left\{4W_Da_D\frac{d}{dr}f_D - W_Vf_V\right\} + V_C\right] + \left(\frac{\hbar}{m_\pi c}\right)^2 (V_{SO}+iW_{SO})\frac{1}{r}\frac{d}{dr}f_{SO}l\dot{\sigma}, \quad (1)$$

where, V_R, W_D, W_V, V_{SO}, W_{SO}, V_C stand for real volume, imaginary surface, imaginary volume, real and imaginary spin-orbit and Coulomb terms, respectively. These terms were originally suggested by Delaroche et al. [4] and modified by Kunieda et al. [5] for the intermediate mass range. In this study, the forms by Kunieda as following are used for Be and Li isotopes:

$$V_R = \left\{V_{R0} + V_{R1}E^\dagger + V_{R2}E^{\dagger 2} + V_{R3}E^{\dagger 3} + V_{R4}e^{-\lambda_R E^\dagger}\right\} \times \left[1 + \frac{1}{V_{R0}+V_{R4}}(-1)^{Z_p+1}C_V\frac{N-Z}{A}\right] + C_C\frac{ZZ_p}{A^{1/3}}\phi_C(E^\dagger), \quad (2)$$

$$W_D = \left\{W_{D0} + (-1)^{Z_p+1}C_W\frac{N-Z}{A}\right\} \times e^{-\lambda_D E^\dagger}\frac{E^{\dagger 2}}{E^{\dagger 2}+W_{D1}^2}, \quad (3)$$

$$W_V = W_{V0}\frac{E^{\dagger 2}}{E^{\dagger 2}+W_{V1}^2}, \quad (4)$$

$$V_{SO} = V_{SO0}e^{-\lambda_{SO}E^\dagger}, \quad (5)$$

$$W_{SO} = W_{SO0}\frac{E^{\dagger 2}}{E^{\dagger 2}+W_{SO1}^2}, \quad (6)$$

$$\phi_C = \left(\lambda_R V_{R4}e^{-\lambda_R E^\dagger} - V_{R1} - 2V_{R2}E^\dagger - 3V_{R3}E^{\dagger 2}\right) \times \left[1 + \frac{1}{V_{R0}+V_{R4}}(-1)^{Z_p+1}C_V\frac{N-Z}{A}\right], \quad (7)$$

where, V_{R0}, V_{R1}, V_{R2}, V_{R3}, V_{R4}, W_{D0}, W_{V0}, V_{SO0} and W_{SO0} are potential depths. The parameters λ_R, λ_D, W_{D1}, W_{V1}, λ_{SO} express the energy variations of the potential depths. The variables N, Z and A correspond to nucleon, proton and neutron numbers in the target nucleus, respectively. The energy $E^\dagger$ is defined as $E - E_f$. The E_f is the Fermi energy. The values C_V, C_C, C_W denote coefficients and are fixed. The Woods-Saxon form is used for the nuclear radius and diffuseness, respectively.

$$f_i(r) = \frac{1}{1+\exp\{(r-R_i)/a_i\}}, \qquad i = R, D, V, SO, \quad (8)$$

where, R_i and a_i are the geometry parameters. In this study, all R_i and a_i values are fixed.

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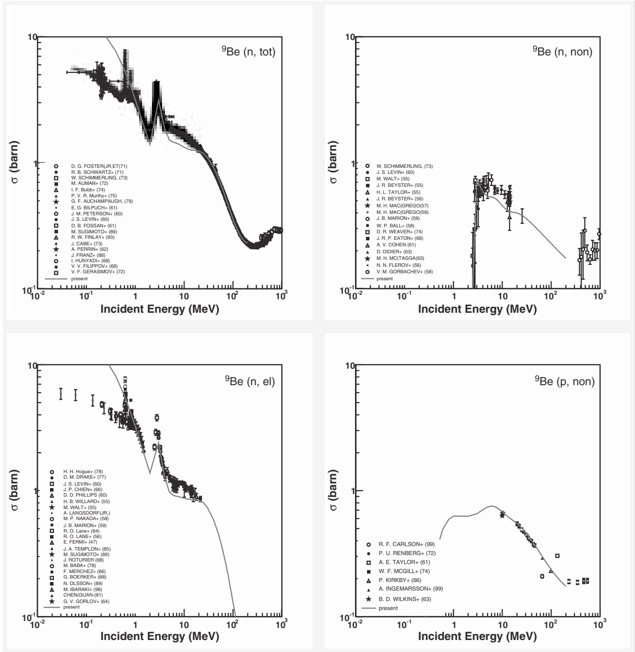

Fig. 1. The neutron incident total (upper left), nonelastic (upper right), elastic (bottom left) and proton incident nonelastic (bottom right) cross sections on ^{9}Be.

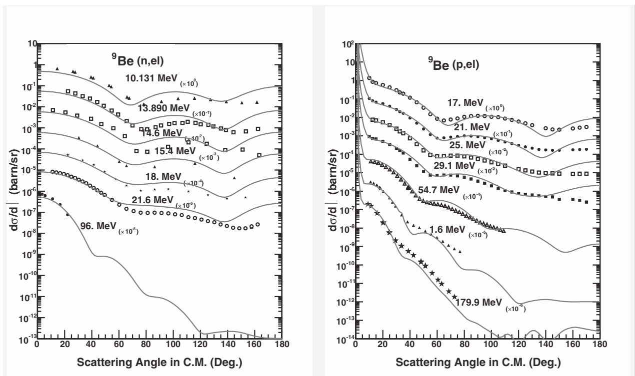

Fig. 2. The angular distributions of neutron (left pane) and proton (right pane) incident elastic scattering on ^{9}Be.

Experimental data of cross sections are retrieved from the EXFOR data base [8]. The optimum parameters of the optical potential are searched for the V_{R0}, V_{R1}, V_{R2}, V_{R3}, V_{R4}, W_{D0}, W_{V0}, V_{SO0}, W_{SO0}, λ_R, λ_D, W_{D1}, W_{V1}, λ_{SO} by the ECIS-97 code[6] and the ROOT object-oriented data analysis framework [7]. At first, the parameters for ^{9}Be are searched because the number of experimental data for Be is larger than that for Li isotopes.

3 Results

Figure 1 shows neutron incident total [9–26] (upper left), nonelastic [11, 17, 27–41] (upper right), elastic cross sections [17, 19, 27, 33, 42–60] (bottom left) and for proton incident nonelastic one [61–66] (bottom right) on ^{9}Be. Lines and marks stand for the calculated values and experimental data,

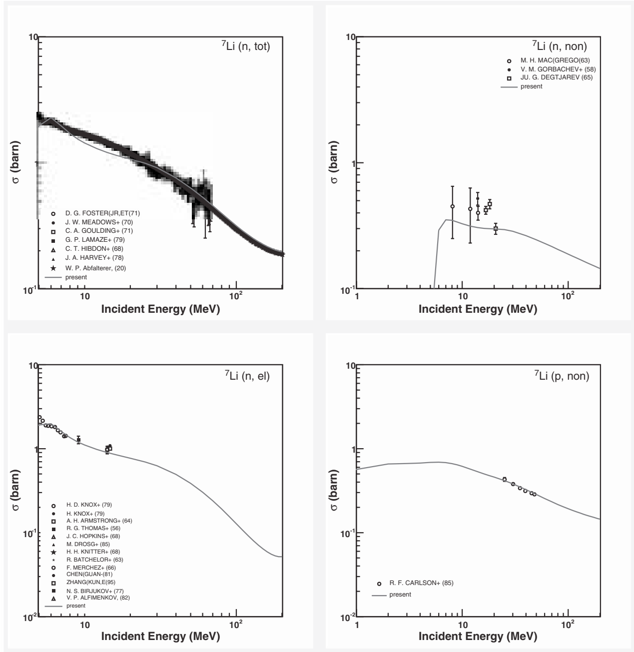

Fig. 3. The neutron incident total [9, 73–78] (upper left), nonelastic [41, 79, 80] (upper right), elastic [55, 59, 81–90] (bottom left) and proton incident nonelastic [91] (bottom right) cross sections on ^{7}Li.

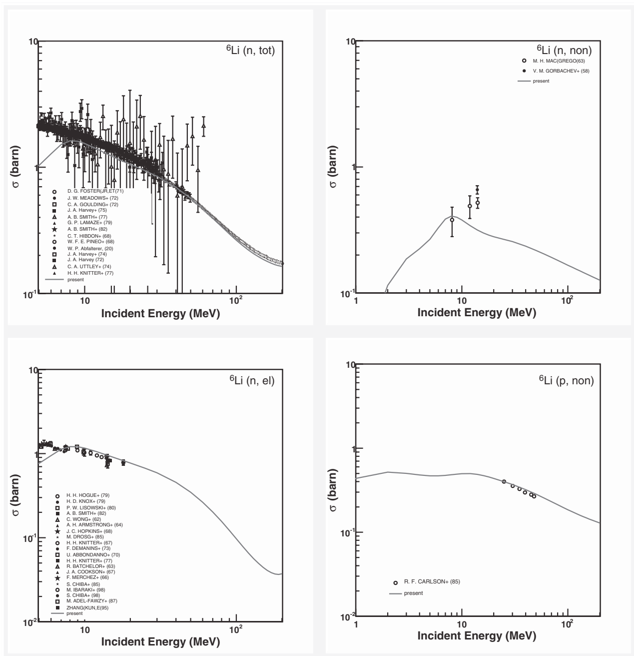

Fig. 4. The neutron incident total [9, 75, 76, 78, 92–101] (upper left), nonelastic [41, 79] (upper right), elastic [55, 58, 81, 82, 84, 85, 87, 88, 96, 101–111] (bottom left) and proton incident nonelastic [91] (bottom right) cross sections on ^{6}Li.

respectively. One can see that the optical potentials obtained by the search reproduce experimental data above 20 MeV for all type of cross sections. The calculated values particularly gives good agreement with the proton incident nonelastic scattering cross sections.

The angular distributions of elastic scattering on ^{9}Be are presented in figure 2. The left side is neutron incident data

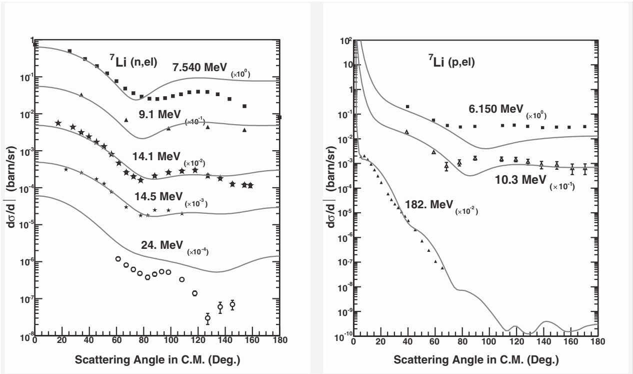

Fig. 5. The angular distributions of neutron [55, 87, 89, 112, 113] (left pane) and proton [114, 115] (right pane) incident elastic scattering on ^{7}Li.

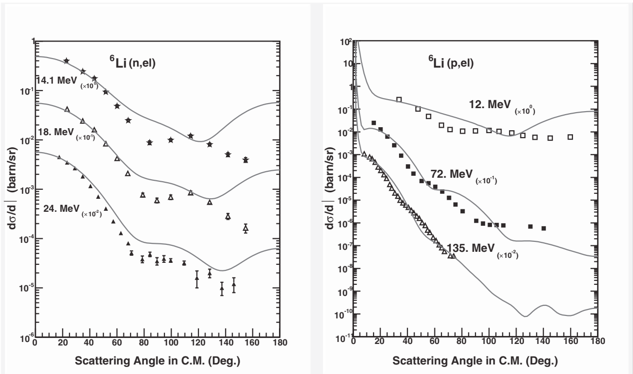

Fig. 6. The angular distributions of neutron [58, 110, 113] (left pane) and proton [116–118] (right pane) incident elastic scattering on ^{6}Li.

[52, 54, 56–58, 67, 68] and the right side is proton ones [69–72], respectively. The calculations also reproduce the experimental data. Especially, the calculated values agree with the experimental ones for 96 MeV neutron incident and 179.9 MeV proton incident elastic scattering.

Figures 3 and 4 stand for the neutron incident total, nonelastic, elastic cross sections and the proton incident nonelastic cross section for ^{7}Li and ^{6}Li, respectively. In these figures, the calculated data give agreement with the experimental values. The calculation reproduce the neutron incident elastic scattering cross sections for ^{7}Li and proton incident nonelastic scattering ones for both Li isotopes.

The angular distributions of elastic scattering for ^{7}Li and ^{6}Li are presented in figures 5 and 6. The left side is neutron incident data and the right side proton incident ones on each figure, respectively. The use of the obtained optical potential parameters are suitable for calculation of the angular distribution of elastic scattering cross section. In particular, the calculated values agree with the experimental ones of proton incident elastic scattering cross sections 182 MeV incidence on ^{7}Li and 135 MeV incidence on ^{6}Li.

4 Summary

The parameters of optical potential for Be and Li were obtained in the energy region from 20 to 200 MeV. The neutron incident total, nonelastic, elastic, and the proton incident nonelastic cross sections by the calculation reproduce the experimental data above 20 MeV. These results will be introduced into JENDL-HE after the overall evaluation including particle emission cross sections.

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