Evaluation of cross sections for nucleons up to 3 GeV on ^{12}C

Y. Watanabe, O. Iwamoto[†], T. Fukahori[†], S. Chiba[‡], and E.Sh. Sukhovitskiĩ[¶]
Department of Advanced Energy Engineering Science, Kyushu University,
Kasuga, Fukuoka 816-8580, Japan
[†]*Nuclear Data Center, JAERI, Japan*
[‡]*Advanced Science Research Center, JAERI, Japan*
[¶]*Radiation Physics and Chemistry Problems Institute, 220109, Minsk-Sosny, Belarus*
Corresponding e-mail: watanabe@aees.kyushu-u.ac.jp

We have performed an evaluation of cross sections on ^{12}C for both neutron and proton with energies between 20 MeV and 3 GeV. The evaluation is based on measured data as well as predictions from nuclear model calculations and some systematics. The results are compared with available experimental data and the LA150 evaluation. Thick target neutron production spectra for proton incident on carbon are analyzed using the evaluated double-differential (p,xn) cross sections.

1. Introduction

High-energy neutron and proton nuclear data for ^{12}C are requested with high priority in various applications, such as shielding design of accelerator facilities, dose evaluation in cancer therapy with neutron and proton beams, efficiency calculation of neutron detectors, and nucleosynthesis prediction of light elements, Li, Be, and B. The LA150 library developed in LANL[1,2] as a high-energy nuclear database is currently used for computer code simulations of accelerator-driven systems[3], which treats the nuclear interaction of neutrons and protons with energies up to 150 MeV with materials. In such the simulations, the Monte Carlo codes based on microscopic simulation approach such as the intranuclear cascade model are built-in to deal with the nuclear processes at energies above 150 MeV, instead of the nuclear data library. Because of saving the computation time, however, the nuclear data above 150 MeV is also required for calculations of the transport of high-energy nucleons in medium and estimations of isotope production. In the present work, the cross sections of ^{12}C have been evaluated for both neutrons and protons with energies between 20 MeV and 3 GeV, in order to meet the requirement and contribute to a development project of the JENDL High-Energy File in the Japanese Nuclear Data Committee (JNDC) [4].

In Sec.2, an outline of evaluation method is described, and several results are shown with experimental data and the LA150 evaluation in Sec. 3. A summary is given in Sec. 4.

2. Evaluation method

The evaluation of cross sections on ^{12}C has been performed using experimental data as well as predictions from nuclear model calculations and systematics. The cross sections evaluated for both neutrons and protons with energies between 20 MeV and 3 GeV are as follows: total cross sections, elastic scattering cross sections and their angular distributions, light-particle and gamma-ray production cross sections and double-differential cross sections, and isotope production cross sections.

A theoretical model calculation system developed in the present work is illustrated in **Fig.1**. The calculation codes are divided into two groups, depending upon the incident energy.

A major code used for intermediate energies up to 150 MeV was the GNASH code[5] based on statistical Hauser-Feshbach plus preequilibrium models. Optical model calculations were carried out using the OPTMAN code[6] based on the coupled-channels method with the nuclear Hamiltonian parameters determined by the soft-rotator model[7]. Transmission coefficients obtained by the CC calculation were used in GNASH calculations of particle and gamma ray emission cross sections and isotope production cross sections up to 150 MeV. We have partially revised the GNASH code so as to take into account the surface effect in two nucleons emission in the preequilibrium process and level widths in the statistical decay between discrete levels in residual nuclei. The DDXs in c.m. system were finally converted into the DDXs in laboratory system in an empirical way that the moving source model[8] and the Kalbach systematics[9] are applied to the evaporation and preequilibrium components, respectively. The DWUCK4 code[10] was used for calculations of the following two direct transitions to discrete states: the ^{12}C(p,d) and (n,d) pick-up processes for the ground state transition and the ^{12}C(p,n) charge-exchange reaction for the ground and first excited states. Note that the latter calculation is based on the microscopic DWBA with a Yukuka-type effective interaction of range 1 fm whose depth was determined by normalizing some experimental data.

In the energy range above 150 MeV, the code JQMD[11] based on Quantum Molecular Dynamics (QMD) plus statistical decay model (GEM[12]) was employed. Also, the code TOTELA[4] based on systematics was employed as a tool for evaluation of total, elastic, and proton reaction cross-sections. The Niita systematics[13] was used in TOTELA with partial modification for the empirical formula of elastic angular distributions in which a fitting with experimental data is improved around the first minimum of the angular distributions.

Several isotope production cross sections were evaluated by fitting their available experimental data: ^{7}Be, ^{10}Be, and ^{11}C in the p+^{12}C reaction. In addition, the JQMD/GEM calculations were applied for energies below 150 MeV for some isotope production reactions in order to obtain rather smooth connection between GNASH and JQMD results as mentioned below.

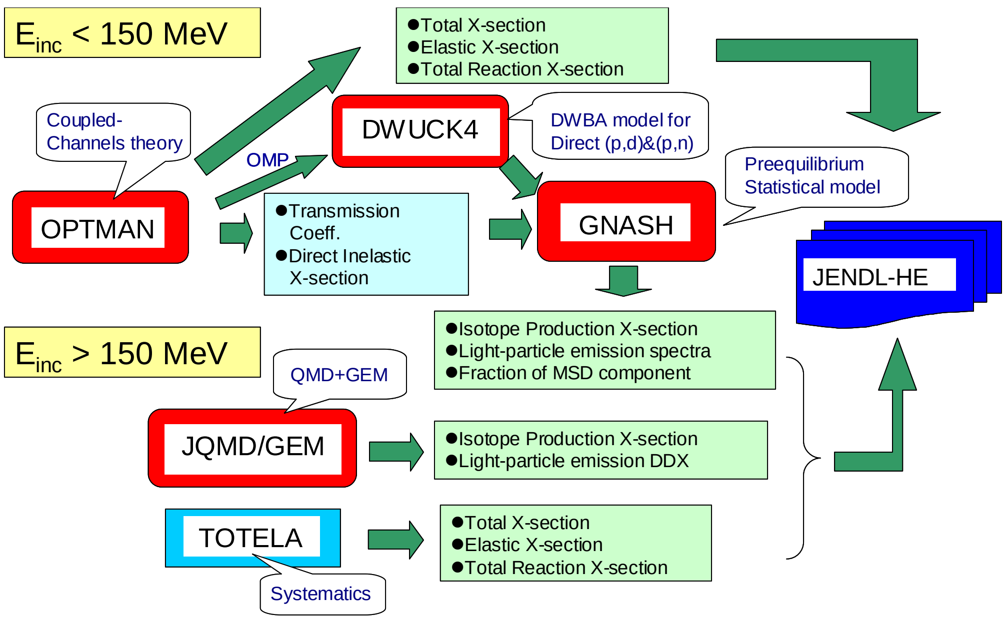


Fig.1 Model calculation code system used in the present evaluation.

3. Results and discussions

The evaluated neutron total, elastic, and reaction cross sections are shown in **Fig. 2**, and compared with available experimental data and the LA150 evaluation[2]. The total cross sections were evaluated by fitting measured data at energies up to 600 MeV with the GMA code[14] and using the Niita systematics at energies above 600 MeV. The neutron elastic cross section was obtained by subtraction of the reaction cross section from the total cross section at each incident energy. The OPTMAN calculation with the parameters determined in ref.[7] was made for evaluation of angular distributions of nucleon elastic scattering from ^{12}C.

Figure 3 shows light particle production cross sections for the n+^{12}C reaction. The evaluated cross sections are compared with the LA150 evaluation and experimental data[15,16,17]. The GNASH prediction for the proton production was multiplied by a factor of 1.3 in order to reproduce the measured data of Slypen et al.[17]. It should be noted that the present evaluation includes the production of triton and ^{3}He, while there is no data in the LA150.

In **Fig. 4**, excitation functions for the A=6 to 11 isobars produced from the p+^{12}C reaction are compared with a compilation of measured data by Read and Viola[18] and the LA150 data. The present evaluation shows better agreement with the measured data than the LA150 at energies below 100 MeV. The QMD/GEM calculation for each isotope was normalized to a few experimental data[18] at energies above 1 GeV. The same normalization factor was used for the QMD/GEM prediction for the neutron-induced reactions. **Fig. 5** shows a comparison of evaluated excitation function of ^{11}C production in n+^{12}C with experimental data and the LA150 evaluation. The evaluated cross sections are larger than the LA150 data over the whole energy range, and are in good agreement with the measured data[19,20], but underestimate the data of Kim et al.[21] at energies above 40 MeV.

Evaluated double-differential cross sections (DDXs) are compared with measured ones and the LA150 evaluation for ^{12}C(p,xp) at 68 MeV[22] and ^{12}C(p,xn) at 3 GeV[23] in **Figs. 6 and 7**, respectively, showing overall good agreement with the measured data. For the ^{12}C(p,xn) reaction, the evaluated DDXs for 113 MeV are compared with experimental ones[24] in **Fig. 8**. Fairly good agreement is obtained except for the high-energy end at 7.5 and 30 degrees. The transformation was made of the equilibrium component of DDXs from the c.m. into the laboratory system based on the moving source model[8]. We emphasize that this led to the agreement seen at low emission energies. Note that the LA150 result reported in ref.[25] overestimates the measurement remarkably at emission energies below 30 MeV.

We have analyzed thick target neutron production spectra for proton incident on carbon using a simple calculation method[26] that involves an integration of the evaluated double differential (p,xn) cross sections with a stopping-power weighting. The result for an incident energy of 68 MeV is compared with measurement[26] in **Fig. 9**. The calculation shows good agreement with the measured data, except for the high-energy end of the spectra. The disagreement may be partly because we neglect a contribution from (p,xn) on ^{13}C and the energy resolution of the detector used.

4. Summary and conclusion

We have evaluated the cross sections for nucleons up to 3 GeV on ^{12}C, using available experimental data, model calculations, and systematics. The present evaluation was compared with the LA150 evaluation and the experimental data. In addition, several thick target neutron production data were analyzed using the present DDX data and the satisfactory agreement was obtained except for the high emission energy region where the contribution from ^{13}C(p,n) is expected. Finally the cross sections evaluated in the present work will be accepted into the JENDL High-Energy File.

Acknowledgements

The authors are grateful to the member of the JNDC high-energy nuclear data evaluation working group for their valuable comments on this work. A part of this work was supported by International Science and Technology Center under Project B-521 (Funding Party is Japan).

References

[1] M.B. Chadwick et al., Nucl. Sci. Eng. **123**, 17 (1996).
[2] M.B. Chadwick et al., Nucl. Sci. Eng. **131**, 293 (1999).
[3] M.B. Chadwick et al., Prog. in Nucl. Energy, **38**, 179 (2001).
[4] T. Fukahori et al., J. Nucl. Sci. and Technol. Suppl. **2**, 25 (2002).
[5] P.G. Young et al., LA-12343-MS, Los Alamos National Laboratory (1992).
[6] E.Sh. Sukhovitskii et al., OPTMAN and SHEMMAN codes, JAERI-Data/Code 98-019 (1988).
[7] S. Chiba et al., J. Nucl. Sci. and Technol. **37**, 498 (2000).
[8] H. Kitsuki et al., J. Nucl. Sci. and Technol. **38**, 1 (2001).
[9] C. Kalbach, Phy. Rev. C **37**, 2350 (1988).
[10] P.D. Kunz and E. Rost, DWUCK4 code, *Computational Nuclear Physics 2: Nuclear Reactions*, (Springer-Verlag, Berlin, 1993, Eds. K. Langanke et al.), p. 88.
[11] K. Niita et al., Phys. Rev. C, **52**, 2620 (1995); JAERI-Data/Code 99-042 (1999).
[12] S. Furihata, Nucl. Inst. Method in Phys. Res. B 171, 251 (2000); S. Furihata and T. Nakamura, J. Nucl. Sci. and Technol. Suppl. **2**, 758 (2002).
[13] K. Niita, Proc. of the 1999 Nuclear Data Symp.; JAERI-Conf 2000-005 (2000), p.98.
[14] S. Chiba et al., Proc. 1993 Nuclear Data Symp., JAERI-M 94-019, p.300 (1994).
[15] T.S. Subramanian et al., Phys. Rev. C **34**, 1580 (1986).
[16] I. Slypen et al., Phys. Rev. C **53**, 1309 (1996).
[17] I. Slypen et al., Nucl. Phys. A **671**, 3 (2000).
[18] S.M. Read and V.E. Viola, Jr., At. Data Nucl. Data Table, **31**, 359 (1984).
[19] O.D. Brill et al., Sov. Phys. Dokl. **6**, 24 (1961).
[20] T.S. Soewarsono et al., JAERI-M-92-027 (1992), p.354.
[21] E. Kim et al., Nucl. Sci. and Eng., **129**, 209 (1998).
[22] M. Harada et al., J. of Nucl. Sci. and Technol., Suppl. **1**, 687 (2000); J. Nucl. Sci. and Technol. Suppl. **2**, 393 (2002).
[23] K. Ishibashi et al., J. Nucl. Sci. Technol. **34**, 529 (1997).
[24] M.M. Meier et al., Nucl. Sci. Eng. **102**, 310 (1989).
[25] M.B. Chadwick et al., Proc. of Int. Conf. on Nuclear Data for Science and Technology, Trieste (1997), p.1683.
[26] S. Meigo et al., Proc. of Int. Conf. on Nuclear Data for Science and Technology, Trieste (1997), p.413.

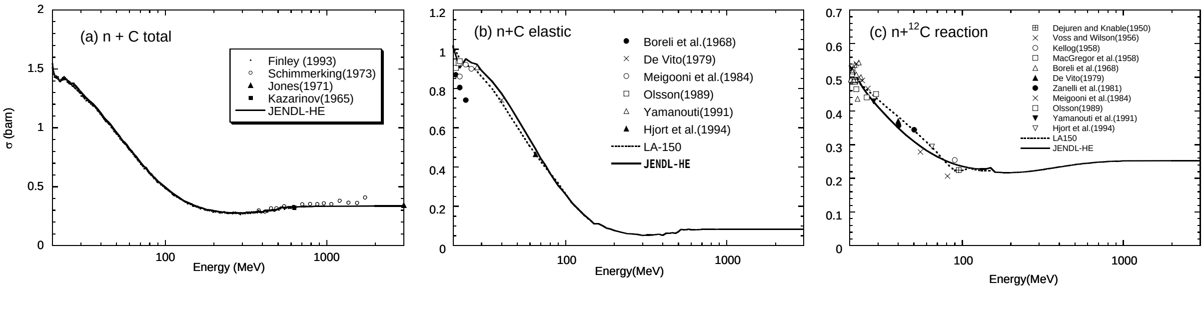


Fig.2 Total, elastic and reaction cross sections for n+^{12}C. The solid curves (JENDL-HE) are the present evaluation and the dotted ones are the LA150 evaluation.

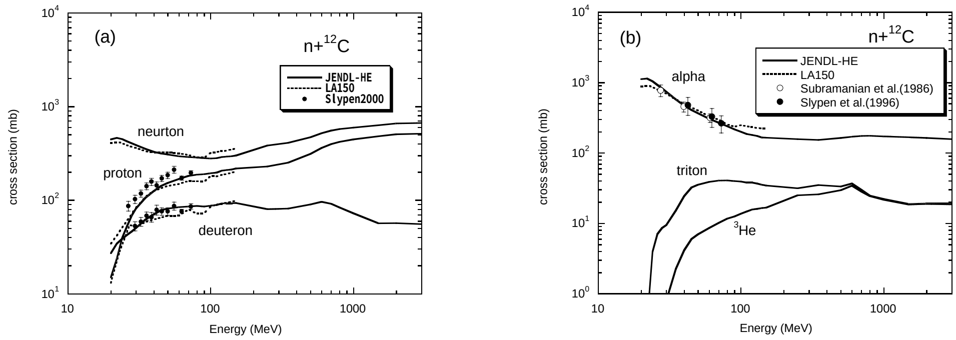


Fig.3 Light particle production cross-sections for n+^{12}C. The solid curves (JENDL-HE) are the present evaluation and the dotted ones are the LA150 evaluation.

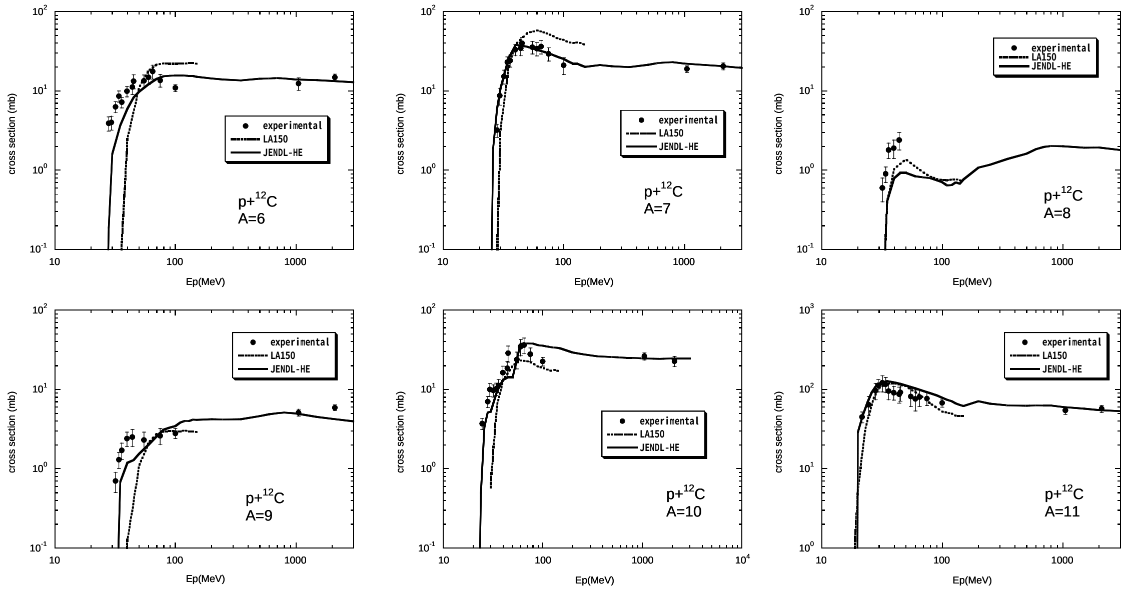


Fig.4 Excitation functions for the A=6 to 11 isobars produced from the p+^{12}C reaction. The solid curves (JENDL-HE) are the present evaluation and the dotted ones are the LA150 evaluation.

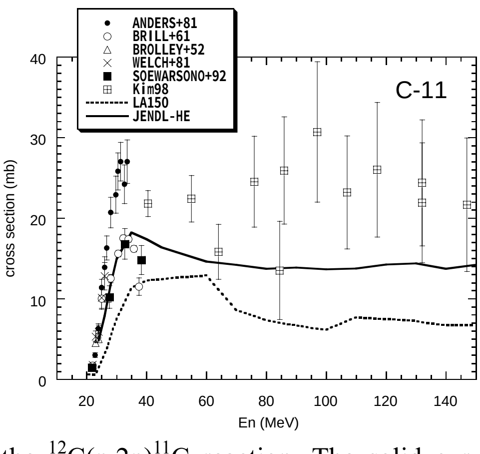
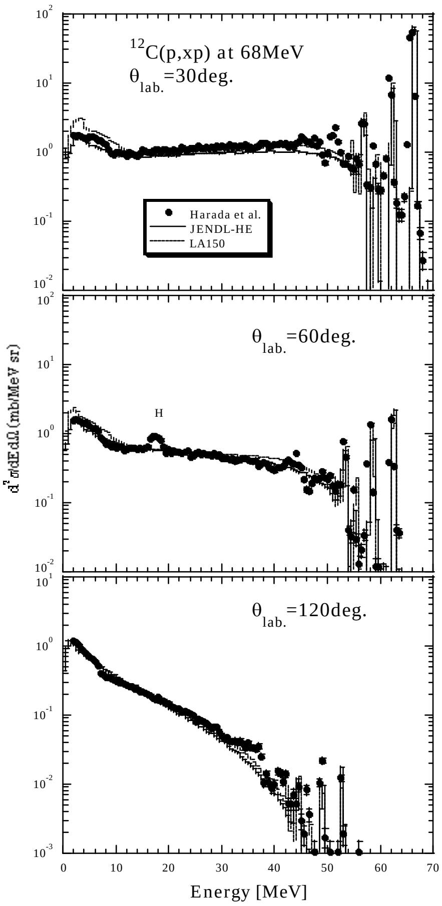


Fig.5 Excitation function of the ^{12}C(n,2n)^{11}C reaction. The solid curves (JENDL-HE) are the present evaluation and the dotted ones are the LA150 evaluation.



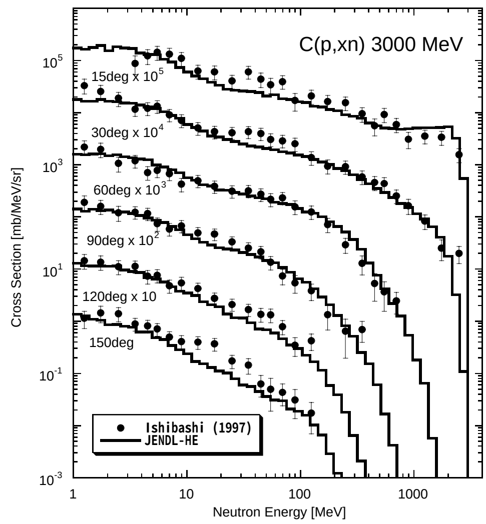
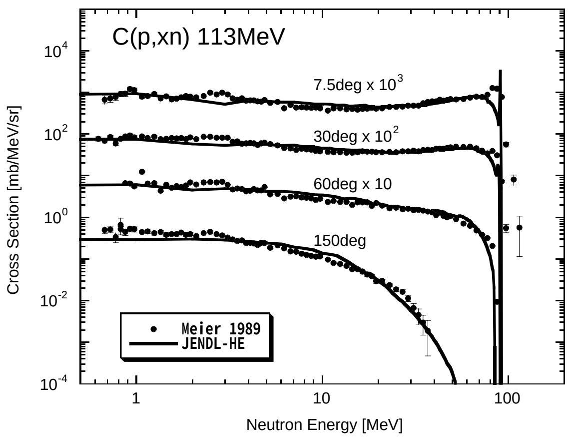


Fig.7 Double-differential (p,xn) cross sections at 3 GeV. The experimental data are taken from [23].

Fig.6 Double-differential (p,xp) cross sections at 68 MeV. The solid histograms are the present evaluation and the dotted ones are the LA150 evaluation. The experimental data are taken from [22].



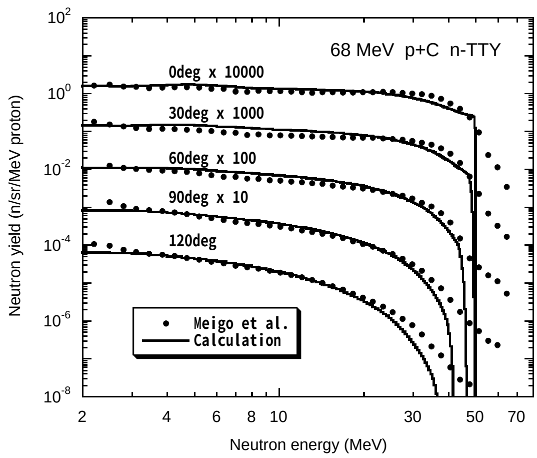


Fig.8 Double-differential (p,xn) cross sections for 113 MeV. The experimental data are taken from [24].

Fig.9 Thick target neutron production spectra for 68-MeV proton incident on carbon. The experimental data are taken from [26].