International Atomic Energy Agency

INDC(CPR)-020
Distr.: L

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

SYSTEMATICS OF INTERMEDIATE ENERGY PROTON NONELASTIC AND NEUTRON TOTAL CROSS SECTION

Qing-biao Shen
Institute of Atomic Energy
P.O. Box 275, Beijing, P.R. of China

July 1991

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

INDC(CPR)-020
Distr.: L

SYSTEMATICS OF INTERMEDIATE ENERGY PROTON NONELASTIC AND NEUTRON TOTAL CROSS SECTION

Qing-biao Shen
Institute of Atomic Energy
P.O. Box 275, Beijing, P.R. of China

July 1991

Reproduced by the IAEA in Austria
August 1991

91-03122

SYSTEMATICS OF INTERMEDIATE ENERGY PROTON NONELASTIC AND NEUTRON TOTAL CROSS SECTION

Qing–biao SHEN
Institute of Atomic Energy, P. O. Box 275, Beijing, P. R. China

With the development of intermediate and high energy accelerator, intermediate energy nuclear experimental data are being accumulated. Moreover, with the development of science and technology, the application fields of intermediate energy nuclear data (IEND) are becoming promising and expanding. For example, the design and utilization of spallation neutron sources, accelerator shielding, space science, nuclear waste disposal, radiation damage, and medical isotope production are all need IEND.

In order to meet the needs of IEND, the evaluation work must be done. The projectiles of IEND are first neutron and proton. Generally speaking, the incident proton energy is from a few MeV to 1000 MeV, the incident neutron energy is 20—1000 MeV. The proton nonelastic or reaction and neutron total cross sections are the most important and basic. Nowadays, a large amounts of experimental data for both of them have been accumulated. The experimental data of intermediate energy proton nonelastic cross sections were collected and published [1,2]. The experimental data of intermediate energy neutron total cross sections can be found in some references[3–7]. These two kinds of intermediate energy cross sections can be calculated by relativistic optical model [8,9]. However, in order to fit the experimental data there are too many adjustable parameters in the relativistic optical model calculation for selecting. Considered that there are many experimental data for these two kinds of cross sections, studying their systematics is obviously valuable in practice.

Based on the analysis of experimental data, Letaw obtained the systematic formula of the proton nonelastic cross section for energies above 20 MeV of the Coulomb barrier [10]. Then, based on Letaw formula, Pearlstein obtained the systematic formula of the neutron total cross section for energies above 20 MeV [11] and the both formulas are used in the calculations of the intermediate energy nuclear data for reactions p+^{56}Fe and n+^{56}Fe [4,11]. In order to examine Letaw intermediate energy proton nonelastic cross section systematic formula, we chose the following 12 nuclei ^{12}C, ^{16}O, ^{27}Al, ^{40}Ca, ^{56}Fe, ^{63}Cu, ^{90}Zr, ^{107}Ag, ^{118}Sn, ^{181}Ta, ^{208}Pb, and ^{238}U, which have more experimental data. Through calculations and comparisons with experimental data, it is found that the calculated results by Letaw intermediate energy proton σ_{ne} formula agree with the

experimental data pretty well for light nuclei, but become worse for $A \geqq 40$ heavier nuclei. Although for heavier nuclei the calculated results by Letaw formula agree with the experimental data still better in $E > 100$ MeV high energy region, it becomes obviously far larger than experimental data in low energy region, and the heavier of nuclei, the larger of deviation. So Letaw proton nonelastic cross section systematic formula is not universal. In order to examine Pearlstein intermediate energy neutron total cross section systematic formula, we chose the following 10 nuclei ^{12}C, ^{16}O, ^{27}Al, ^{56}Fe, ^{63}Cu, ^{107}Ag, ^{181}Ta, ^{208}Pb, ^{209}Bi, and ^{238}U, which have more experimental data.

The aim of this work is to improve Letaw and Pearlstein systematic formulas. First, some changes on their systematic expresions are made. Then we define

$$X^2 = \frac{1}{M} \sum_{i=1}^{M} \frac{1}{N(i)} \sum_{j=1}^{N(i)} \left(\frac{\sigma_C(i,j) - \sigma_E(i,j)}{\Delta\sigma_E(i,j)} \right)^2 \tag{1}$$

where σ_C is the calculated value of cross section, σ_E is the experimental value of cross section, and $\Delta\sigma_E$ expresses the experimental error. The sum over i and j denotes that we do the sum for all chosen nuclei and energies, respectively. The parameters of new systematic formula can be obtained through search of the minimum deviation between the calculated results and experimental data by computer automatically. After careful researching, the new intermidiate energy proton nonelastic cross section systematic formula is obtained as follows:

$$\sigma_{ne}(A,E) = 0.0426A^{0.701} f(A)g(E)h(A,E) \tag{2}$$

$$f(A) = 1 + 0.0144Sin(3.63 - 2.82logA) \tag{3}$$

$$g(E) = 1 - 0.67e^{-E/150} Sin(12E^{-0.289}) \tag{4}$$

$$h(A,E) = [1 + (0.018A^2 - 1.15A)/E^2]^{-1} \tag{5}$$

The unit of the cross section is barn. Figs.1–12 show the comparisons of the proton nonelastic cross sections calculated by our new formula and by Letaw formula with the experimental data for the above 12 elements. In these figures, besides the isotope experimental data have been presented, the corresponding natural element experimental data are also given. It is seen that the calculated results by our new formula for the above 12 nuclei ranging $A = 12$–238 in ener-

gies E_p = few−1000 MeV are all in pretty good agreement with the experiments. The both experimental data and calculated results show that the proton nonelastic cross sections have a broad peak at about several tens MeV and a minimum at about 200−300 MeV. The calculated results by Letaw proton nonelastic cross section formula become very bad for $A \geqq 40$ heavier nuclei in low energy region, but our new formula overcome this drawback. So far, the proton nonelastic cross section experimental data are not sufficient and are scattered, therefore, the recommended systematic formula in this paper should be improved when more and better experimental data are available in the future.

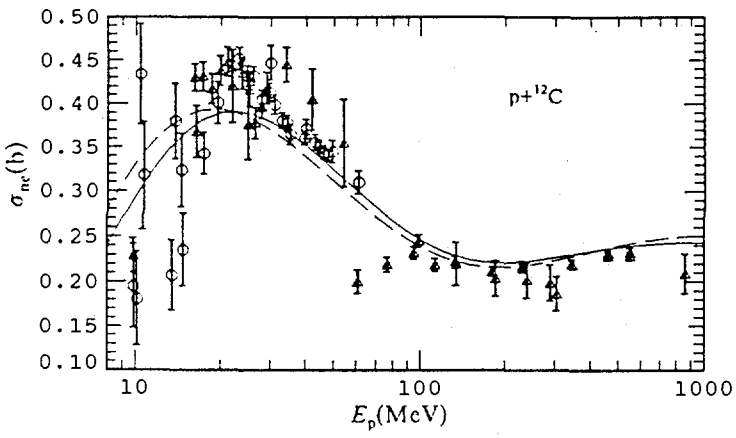

Fig.1 Comparison of the intermediate energy proton nonelastic cross sections calculated by Letaw systematic formula (dashed line) and our systematic formula (solid line) with experimental data for ^{12}C [1]. The symbol circle and triangle present the experimental data for isotope and corresponding natural element, respectively.

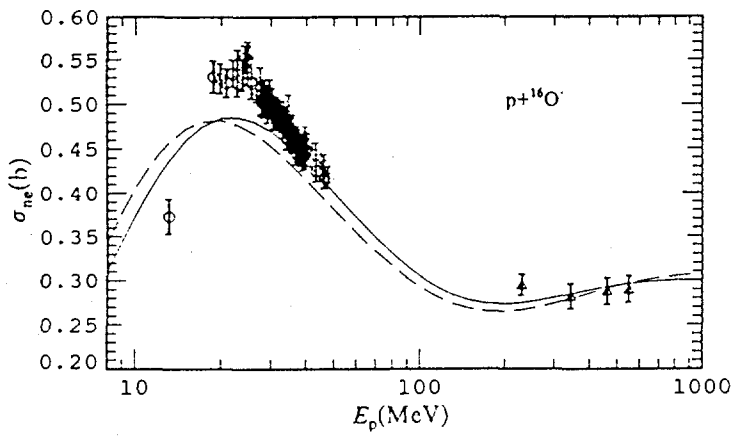

Fig.2 The same as Fig.1 except for ^{16}O.

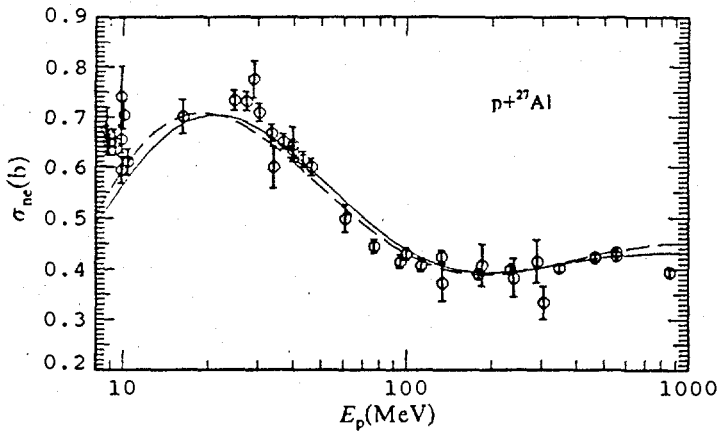

Fig.3 The same as Fig.1 except for ^{27}Al.

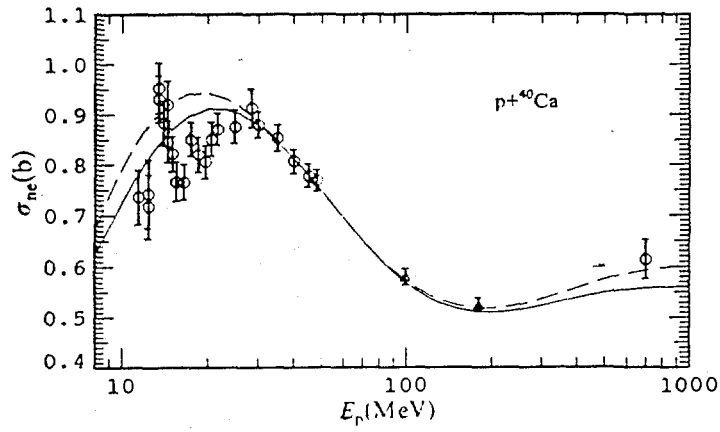

Fig.4 The same as Fig.1 except for ^{40}Ca.

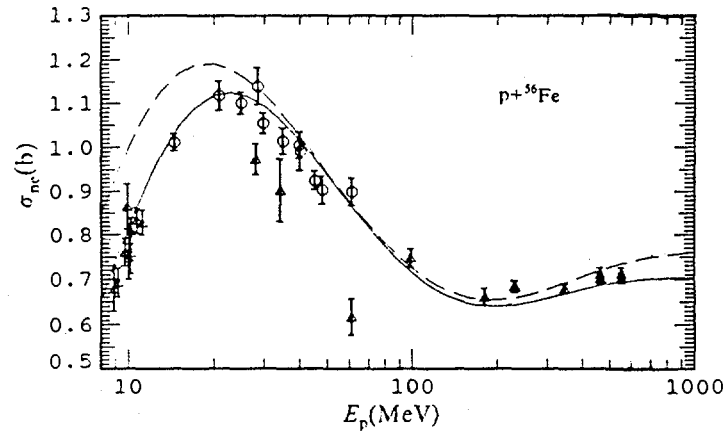

Fig.5 The same as Fig.1 except for ^{56}Fe and the experimental data taken from references [1] and [2].

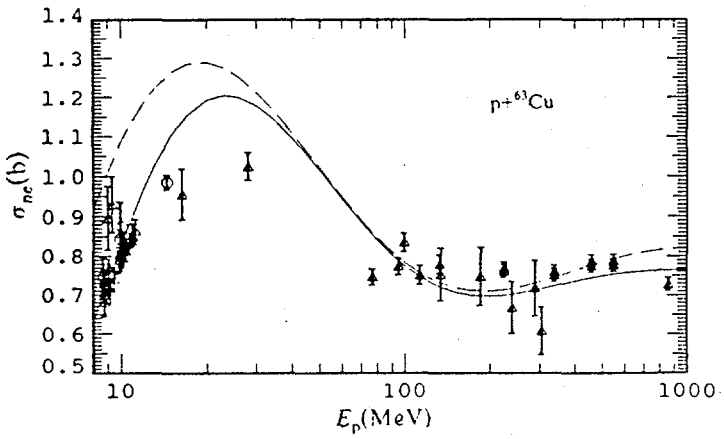

Fig.6 The same as Fig.1 except for ^{63}Cu.

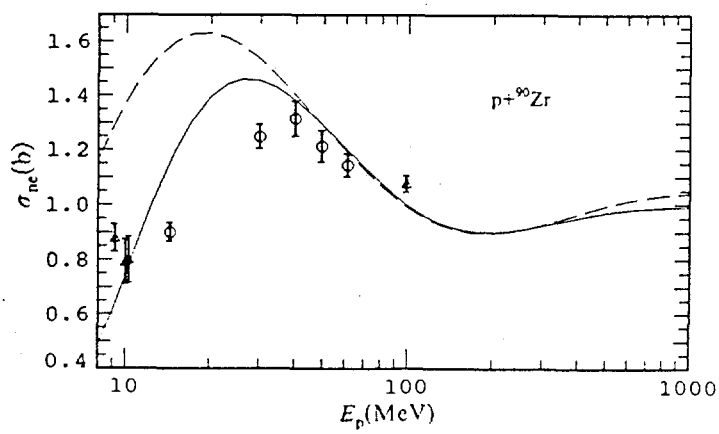

Fig.7 The same as Fig.1 except for ^{90}Zr.

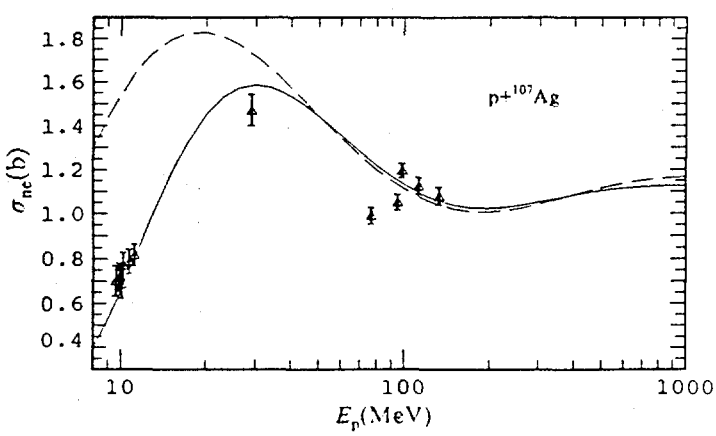

Fig.8 The same as Fig.1 except for ^{107}Ag.

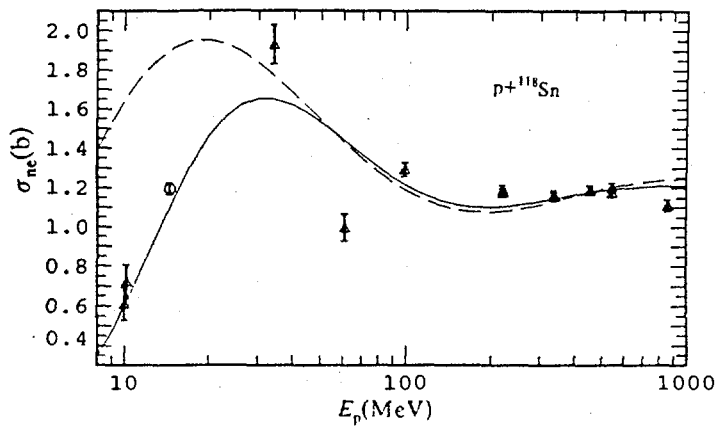

Fig.9 The same as Fig.1 except for ^{118}Sn.

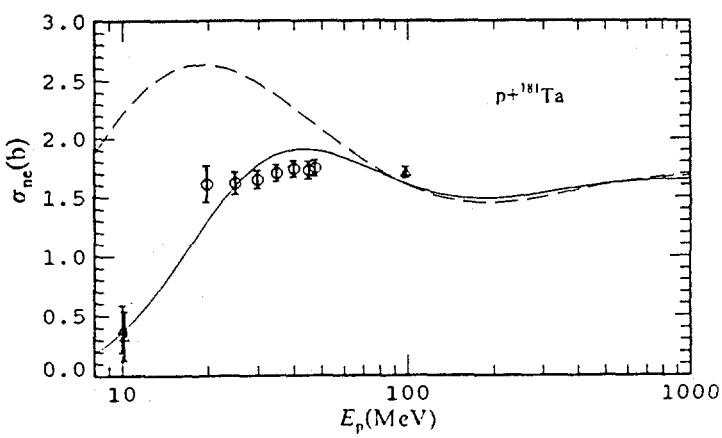

Fig.10 The same as Fig.1 except for ^{181}Ta.

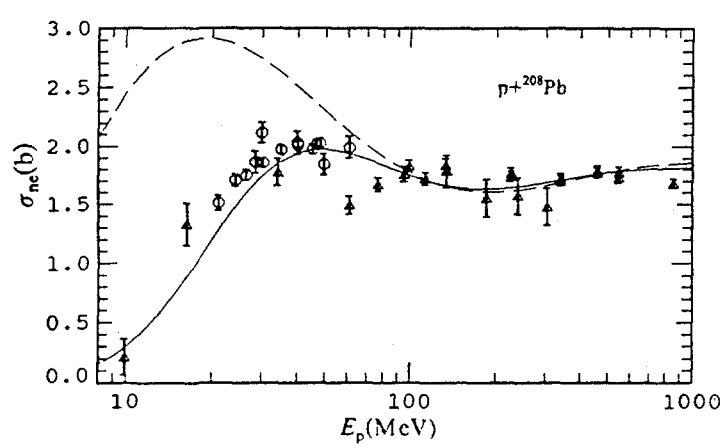

Fig.11 The same as Fig.1 except for ^{208}Pb.

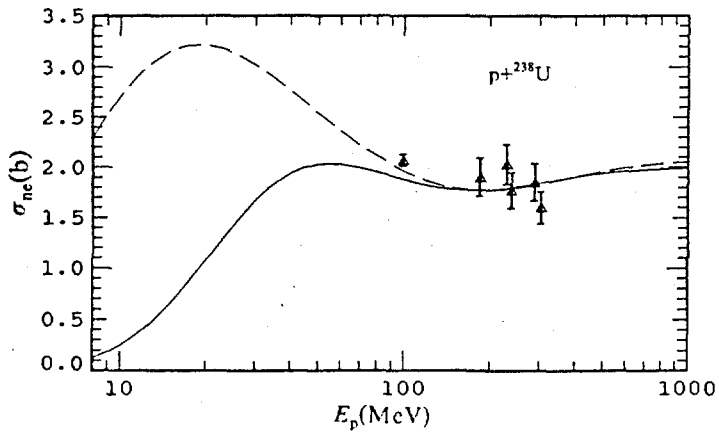

Fig.12 The same as Fig.1 except for ^{238}U.

By use of the same method, our new intermediate energy neutron total cross section systematic formula is as follows:

$$\sigma_t(A,E) = 0.04586A^{0.7}s(A)t(E)(1+k_4) + k_1A^{1/3}\sum_{i=1}^{2} e^{-[k_2 log(E_{pi}/E)]^2} \tag{6}$$

$$s(A) = 1 + 0.02946Sin(3.03 - 1.967logA) \tag{7}$$

$$t(E) = 1 - 0.57e^{-E/298}Sin(10.63E^{-0.2836}) \tag{8}$$

$$E_{p1} = k_3A^{1/3} \tag{9}$$

$$E_{p2} = E_{p1} - 13.78A^{1/3} + 0.275(51-A)\Theta(51-A) \tag{10}$$

$$logk_1 = 0.298 - 0.685logA + 0.075(logA)^2 \tag{11}$$

$$logk_2 = -0.297 - 0.0124logA + 0.0292(logA)^2 \tag{12}$$

$$logk_3 = 0.929 + 0.726logA - 0.0709(logA)^2 \tag{13}$$

$$logk_4 = -2.14 + 0.487logA - 0.0271(logA)^2 \tag{14}$$

$$\Theta(51-A) = \begin{cases} 0 & 51-A \leqq 0 \\ 1 & 51-A > 1 \end{cases} \tag{15}$$

The unit of the cross section is barn, too. Figs.13–22 show the comparison of the neutron total cross section calculated by our new formula and by Pearlstein formula with experimental data for 10 nuclei mentioned above. It is seen that the calculated results by our new formula in $E_n = 20-1000$ MeV for 10 nuclei ranging $A = 12-238$ are all in pretty good agreement with the experiments. Even if for $A \geqq 56$ seven heavier nuclei, for which Pearlstein formula can be used, it is

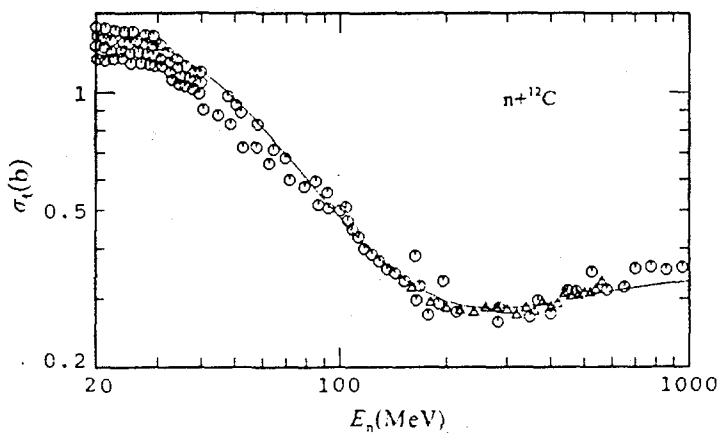

Fig.13 Comparison of the intermediate energy neutron total cross sections calculated by our new systematic formula (solid line) with experimental data for ^{12}C. The symbol circle and triangle present the experimental data taken from references[3–5] and [7], respectively.

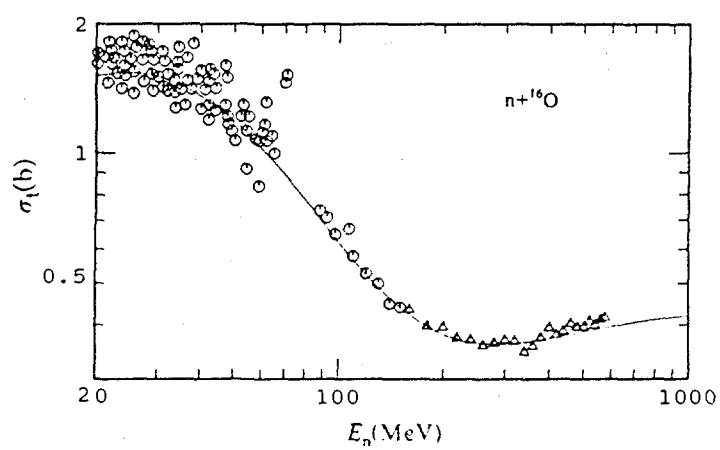

Fig.14 The same as Fig.13 except for ^{16}O.

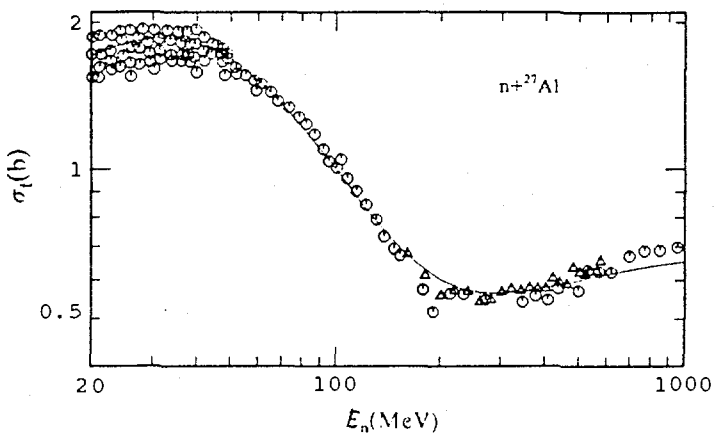

Fig.15 The same as Fig.13 except for ^{27}Al.

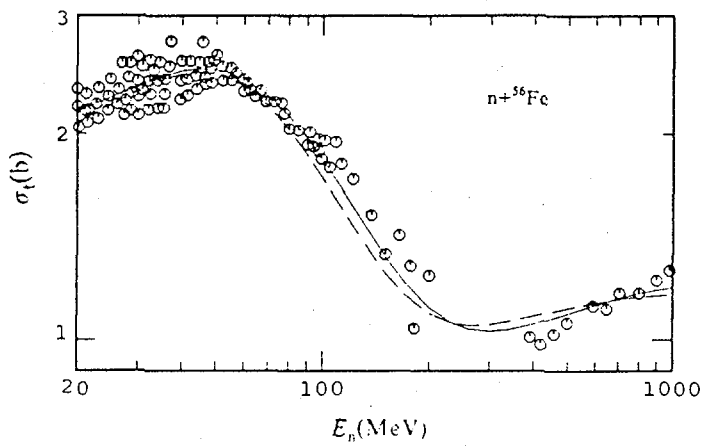

Fig.16 Comparison of the intermediate energy neutron total cross sections calculated by Pearlstein systematic formula (dashed line) and our new systematic formula (solid line) with experimental data for ^{56}Fe. The symbol circle presents the experimental data taken from references[3–5].

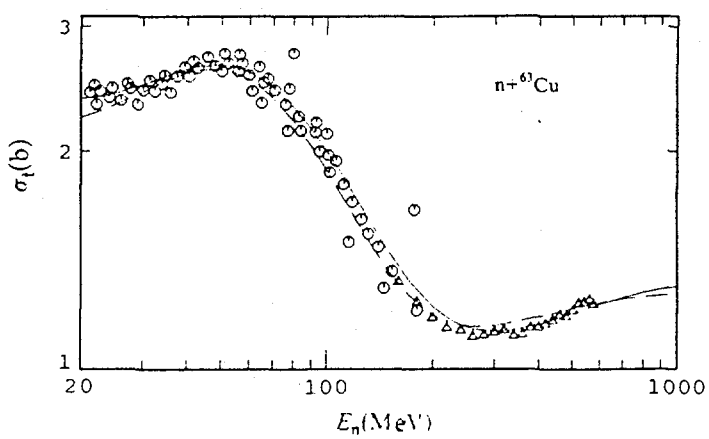

Fig.17 The same as Fig.16 except for ^{63}Cu and the symbol triangle presents the experimental data taken from reference [7].

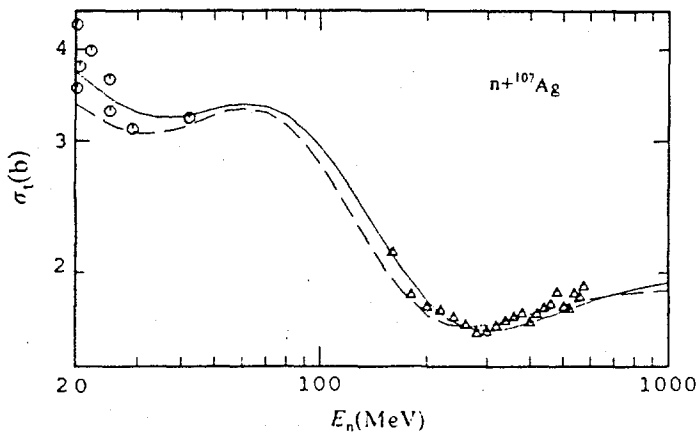

Fig.18 The same as Fig.17 except for ^{107}Ag.

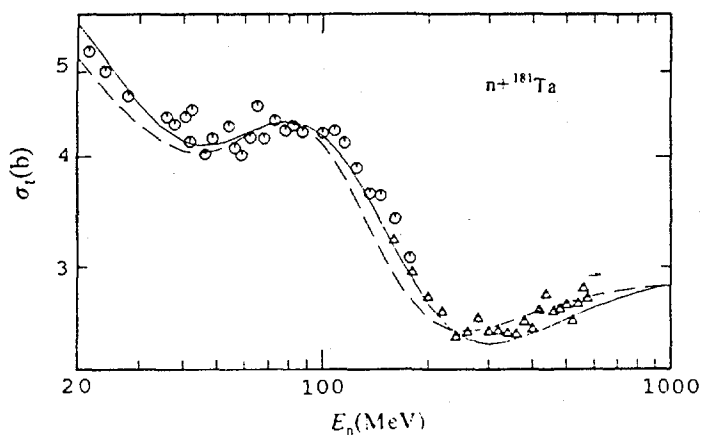

Fig.19 The same as Fig.17 except for ^{181}Ta.

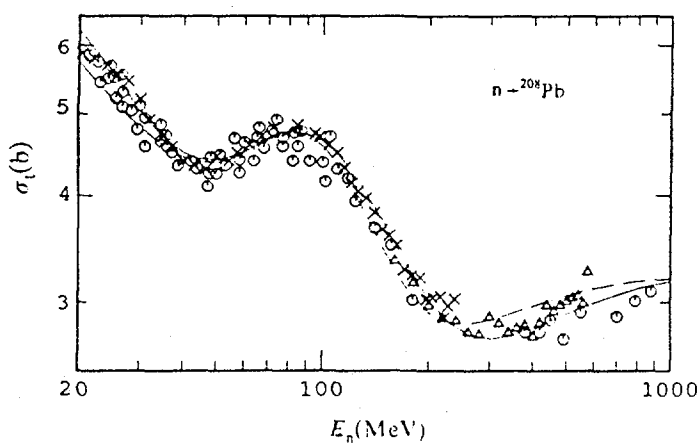

Fig.20 The same as Fig.17 except for ^{208}Pb and the symbol cross presents the experimental data taken from reference [6].

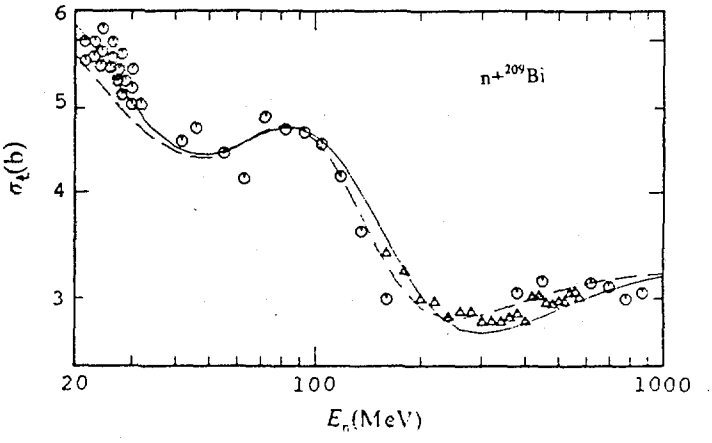

Fig.21 The same as Fig.17 except for ^{209}Bi.

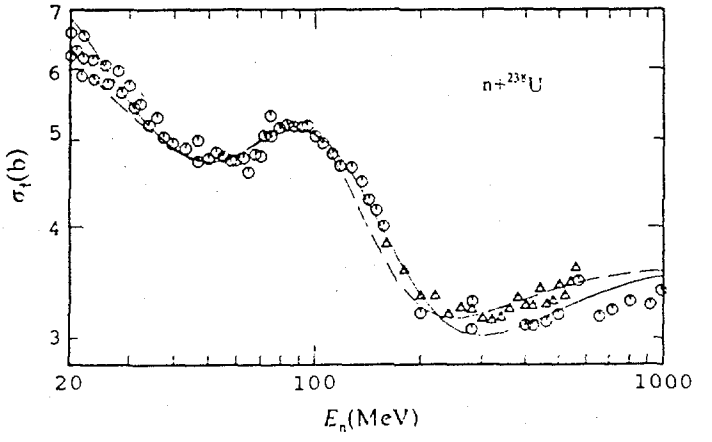

Fig.22 The same as Fig.17 except for ^{238}U.

also shown that the calculated results by our new formula are better than that by Pearlstein one. Of course, the obtained intermediate energy neutron total cross section systematic formula in this paper should be developed with the experimental data increasing.

Based on Letaw and Pearlstein systematic formulas and considered the experimental data as many as possible, the new systematic formulas for intermediate energy proton nonelastic and neutron total cross sections, which are in pretty good agreement with experiments for A = 12–238 nuclei, are obtained. Therefore, they are universal and can be used in intermediate energy nuclear data evaluation.

Finally, the author would like to express gratitude to Prof. Zhuo Yi–zhong for his helpful discussion.

REFERENCES

[1] W. Bauhoff, Atom. Data and Nucl. Data Tables, 35, 429 (1986).

[2] R. H. McCamis, N. E. Davison, W. T. H. van Oers, R. F. Carlson, and A. J. Cox, Can. J. Phys. 64, 685 (1986).

[3] V. McLane, C. L. Dunford, and P. F. Rose, Neutron Cross Sections, BNL–325, Vol.2, Academic Press, 1988.

[4] S. Pearlstein, Nuclear Data for Science and Technology, Proc. Inter. Conf., 1988, Mito, Japan, p.1115.

[5] T. Fukahori and S. Pearlstein, Presented at IAEA Advisory Group Meeting on Intermediate Energy Nuclear Data for Applications, Vienna, Austria, 9–12, October, 1990.

[6] R. L. Schutt, R. E. Shamu, P. W. Lisowski, M. S. Moore, and G. L. Morgan, Phys. Lett. B203, 22 (1988).

[7] J. Franz, H. P. Grotz, L. Lehmann, E. Rossle, H. Schmitt, and L. Schmitt, Nucl. Phys. A490, 667 (1988).

[8] S. Hama, B. C. Clark, E. D. Cooper, H. S. Sherif, and R. L. Mercer, Phys. Rev. C41, 2737 (1990).

[9] Shen Qing–biao, Feng Da–chun, and Zhuo Yi–zhong, Phys. Rev. C, to be published.

[10] J. L. Letaw, R. Silberberg, and C. H. Tsao, Astrophys. J. Suppl. Ser., 51, 271 (1983).

[11] S. Pearlstein, Astrophysical Journal, 346, 1049 (1989).