No. 6
(1991)
CNIC-00596
CNDC-0008
INDC(CPR)-025/L

COMMUNICATION OF NUCLEAR DATA PROGRESS

China Nuclear Information Center
Chinese Nuclear Data Center
Atomic Energy Press

CNIC-00596
CNDC-0008
INDC(CPR)-025 / L

COMMUNICATION OF NUCLEAR DATA PROGRESS

No. 6 (1991)

Chinese Nuclear Data Center

China Nuclear Information Centre

Atomic Energy Press

Beijing, 1991, 12

EDITORIAL NOTE

This is the sixth issue of *Communication of Nuclear Data Progress* (CNDP), in which the first part of CENDL-2 (Chinese Evaluated Nuclear Data Library, Version 2.0) papers is published. It includes the evaluation reports of 38 elements and isotopes with incident neutron energy from 10^{-5} eV to 20 MeV, which are as follows:

^{1}H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B, ^{14}N, ^{16}O, ^{19}F, Mg, Al, Si, S, K, Ti, V, Cr, Fe, Ni, Cu, Zr, Nb, Mo, Ag, ^{107}Ag, ^{109}Ag, Sn, Sb, ^{181}Ta, W, ^{197}Au, Pb, ^{238}U, ^{237}Np.

The other evaluation reports of 16 elements and isotopes will be published in the supplement to CNDP No. 6 soon.

We hope that our readers and colleagues will not spare their comments, in order to improve the publication.

Please write to Drs. Liu Tingjin and Zhuang Youxiang
Mailing Address : Chinese Nuclear Data Center
China Institute of Atomic Energy
P. O. BOX 275 (41), Beijing 102413
People's Republic of China
Telephone : 9357729 or 9357830
Telex : 222373 IAE CN.

CONTENTS

A BRIEF DESCRIPTION OF THE SECOND VERSION OF CHINESE EVALUATED NUCLEAR DATA LIBRARY CENDL–2

Chinese Nuclear Data Center

(CHINA INSTITUTE OF ATOMIC ENERGY)

The Chinese Nuclear Data Center and Nuclear Data Committee of China started evaluation and compilation work for CENDL–2 at the beginning of 1986. The main purpose for making CENDL–2 is to develop and improve the CENDL–1, such as to extend the incident neutron energy to thermal energy region, supplement the data type of evaluations, improve and update the earlier evaluations, and add some newly evaluations to the library. CENDL–2 was finally completed in July 1991, it contains data for main engineering, construction and fuel materials in nuclear reactors, radiation shielding materials and so on.

The CENDL–2 was prepared based on the CENDL–1, 54 nuclides in all are included in this version, as shown in Table 1, among them, 36 nuclides are from CENDL–1, but have been re–evaluated or extensively revised around the years 1989 / 1990, the rest (1 / 3) are newly evaluated. All evaluations were performed by Chinese evaluators of CNDC and Chinese Nuclear Data Coordination Network (CNDCN) except that a few ones were completed by Chinese evaluators at home or abroad for foreign libraries under international cooperation and these evaluations are also included in CENDL–2, and some evaluations are based on existing foreign libraries, such as ENDF / B–6, JENDL–3 and BROND, with partial updating and revisions performed by Chinese evaluators.

Table 1 Nuclides contained in CENDL-2

^{1}H	Mg	Ni	W
^{2}H (DDX,G,COV.)	^{27}Al	Cu	^{197}Au
^{3}H (DDX,COV.)	Si	Zr	Pb
^{3}He (DDX,COV.)	^{31}P	^{93}Nb	^{232}Th
^{4}He	S	Mo	^{235}U
^{6}Li	K	Ag	^{238}U
^{7}Li	Ca	$^{107}Ag^{**}$ (G)	^{237}Np
^{9}Be	Zn	$^{109}Ag^{**}$ (G)	^{239}Pu
^{10}B (G)	Ti	Cd	^{240}Pu
^{11}B	^{51}V	In	$^{241}Am^{*}$ (G,COV.)
^{14}N	Cr	Sn	$^{249}Bk^{*}$
^{16}O	^{55}Mn	Sb	$^{249}Cf^{*}$
$^{19}F^{*}$ (DDX, G, COV.)	Fe	Hf	
^{23}Na	^{59}Co	^{181}Ta	

DDX : double differential cross section data included

G : gamma-ray production data included

COV. : covariance file included

* : accepted by ENDF / B-6

* * : accepted by JENDL-3

Note : The evaluation for Ag-nat contained in CENDL-2 was evaluated by Wang Yansen et al. not that evaluated by Liu Tingjin for JENDL-3 in JAERI, whereas the evaluations for individual isotopes ^{107}Ag, ^{109}Ag were evaluated by Liu Tingjin, so they are probably inconsistent physically, the reason for this selection is that we want to present another new evaluation for Ag-nat to users at home and abroad.

The library contains full sets of neutron data, i. e. resonance parameters in the resonance region and cross sections of all reactions and angular and energy distributions of secondary neutrons, and for some evaluations also double differential cross sections or γ-production data, in the neutron energy range from 10^{-5} eV to 20 MeV, most of evaluations are presented in the ENDF / B-5 format, some in ENDF / B-6 which contains double differential cross section or Reich-Moore resonance parameters in resolved resonance region, which are not permitted in ENDF / B-5 format.

All the evaluations were carefully checked and reviewed by Chinese Nuclear Data Evaluation Working Group and checked with programs CHECKR, PHYCHE, FIZCON and then accepted by CENDL-2.

Generally, most recent measured data in the smooth energy region have been taken into account in the evaluations, and the evaluations have been compared with the newly available evaluations, and for some evaluations every efforts have been made to update them significantly.

So CENDL–2 is much more improved compared with the CENDL–1, and it seems that most of the evaluations included in CENDL–2 are comparable to the corresponding files of the available newest versions of other libraries.

Each evaluation in CENDL–2 contains a short description (MF 1) giving:

— Information about the authors and dates of the evaluation;

—Brief information on the sources of the experimental data, the evaluation method, and the theoretical calculations;

— Contents of the evaluation and related references.

More detailed descriptions of the evaluations contained in CENDL–2 are given in this *Communication of Nuclear Data Progress* (CNDP) with two issues, No. 6 (special issue for CENDL–2) and its supplement (to be published).

In order to manage the library, the ENDF data base system, i. e. the storage and retrieval system, developed at NNDC, U. S. A. has been installed in Micro–VAX–II computer at CNDC. The ENDF utility programs, version 6.6, from NNDC have also been transplanted on Micro–VAX–II computer and used for checking and processing evaluated neutron data for CENDL–2.

A code CRECTJ5 developed at JAERI / NDC has been transplanted to Micro–VAX–II computer and used for evaluation and compilation work of CENDL–2.

THE EVALUATION OF DEUTERON NEUTRON DATA

Zhuang Youxiang   Chu Lianyuan   Wang Cuilan   Cai Dunjiu

(CHINESE NUCLEAR DATA CENTER, IAE)

ABSTRACT

Based on the experimental evaluation[1] and theoretical calculation[2], the neutron cross sections and angular distributions, double–differential cross sections of neutron and spallation proton have been recommended in energy range 10^{-5} eV ~ 20 MeV for CENDL–2. The comparison with other evaluations has been carried out.

INTRODUCTION

Because the interaction of neutron on deuteron is one of the simple three nucleons reactions without Coulomb interaction, it is very significant for research after nuclear force and for test of nuclear theory. Deuterium also is one of important fusion fuels, therefore neutron nuclear data of deuteron are useful to nuclear power development.

When the low–energy neutron acts on deuteron, possible reactions induced are as follows :

$n + {}^2H \rightarrow n + {}^2H$, elastic scattering;

$n + n + p - 2.225$ MeV, spallation reaction;

$\gamma + {}^3H + 6.257$ MeV radiative capture.

Thus $\sigma_t = \sigma_{n,n} + \sigma_{n,2n} + \sigma_{n,\gamma}$.

1 EVALUATION OF EXPERIMENTAL DATA

Total cross sections from thermal to several hundred MeV were measured mostly by means of transmission method, the high pressure gas targets of enriched deuterium were used in some experiments. The wide energy region, dense energy spacing and high precision were obtained from recent experiments, and the errors of some new measurements are less than 1%.

The recommended values of total cross section are based on a least–squares fit to the data of Refs. [3~12], as shown in Fig. 1.

Angular distribution of n–D elastic scattering can be deduced from measured recoil deuteron with the aid of proportional deuteron counter or deuteron scintillator. It has advantages of high efficiency and low affection induced by spectrometer unstability. The shortcoming of this method is poor angular resolution and narrow region of measured angle.

Another method is to measure scattering neutron with fast neutron TOF spectrometer and telescope. Its merit is low background and wide region of measured angle. The experimental data are distributed mainly in 0.1~9 MeV and at 14 MeV, but there were a few data in 15~20 MeV and 9.1~14 MeV.

It is more difficult to measure $^{2}H(n,2n)^{1}H$ reaction cross section. The measured methods used can be divided into two categories:

(1) to measure the two neutrons by means of large–liquid scintillator[13~16] or TOF[17~20];

(2) to measure the proton with the aid of particle identification[8, 21~23].

The accuracies of all the measurements are not very high, because there are many correction factors in both methods. Near the threshold, (n,2n) cross section is small, the uncertainty is about 60%; in the energy region much far from the threshold the errors are about 7~10%. All the experimental data coincide within their errors on the whole and line up one another.

The recommended values of (n,2n) cross sections were obtained on basis of least–squares fit to the experimental data of Refs. [8, 13~23], as shown in Fig. 2.

2 THEORETICAL CALCULATION

All the n–D interaction data have been calculated from the three–body model based on the Faddeev equation[2]. The theoretical angular distributions of elastic scattering are shown in Fig. 3, and the double–differential cross sections of neutron and spallation proton in $^{2}H(n,2n)^{1}H$ reaction are shown in Fig. 4, as seen the coincidence of theoretical data with measured data is generally good.

3 COMPREHENSIVE RECOMMENDATION

3.1 The experimental evaluated data of total cross sections and (n,2n) cross sections were taken as their own recommended values, because the former has high–precission, the latter is complete and small below 200 millibarns.

The radiative capture cross sections are extrapolated from the thermal cross section according to $1/v$ law up to 1 keV. The curve above 1 keV is drawn to include measurements on the inverse reaction by Bosch. They are in microbarns.

Thus, the elastic scattering cross section is essentially equal to the total cross section below the (n,2n) threshold and the total cross section minus the (n,2n) cross section above the threshold, see Fig. 5.

3.2 The elastic angular distribution in the center of mass system is presented as Legendre coefficients which were taken from Ref. [2] based on Faddeev equation, seeing that the experimental data haven't formed a complete set yet.

3.3 The double–differential cross sections of neutron and spallation proton in ^{2}H(n,2n)^{1}H reaction in laboratory frame are expressed as normalized probabilitiy distributions versus outgoing neutron energies of scattering angle. They were taken from Ref. [2] based on Faddeev equation, because of the lack of experimental data.

3.4 The decay information added for tritium production was taken from Ref. [24].

4 COMPARISION WITH OTHER EVALUATION

4.1 MF3, Cross Sections

The total cross sections of CENDL–2, ENDF / B–6 and JENDL–3 are coincident within the error of 1%. as shown in Fig. 1.

The (n,2n) reaction cross sections of CENDL–2 go up from the threshold and come down above about 17 MeV, coincide with all the experimental data. Those of ENDF / B–6 are going up to 20 MeV, and JENDL–3 maintains a constant above 15 MeV and is close to CENDL–2, see Fig. 2.

4.2 MF4, Elastic Scattering Angular Distribution

CENDL–2, ENDF / B–6 and JENDL–3 are taken from theoretical calculations based on same measurements in the main.

4.3 MF6, Double–Differential Cross Sections of ^{2}H(n,2n)^{1}H Reaction

ENDF / B–6 is represented as a poor 3 body phase space distribution.

CENDL–2 and JENDL–3 were calculated from the 3–body model based on the rigorous Faddeev equation.

The double–differential cross sections of spallation proton in ^{2}H(n,2n)^{1}H reaction are given in CENDL–2, up to now they haven't been found in other evaluation yet.

4.4 MF12, and 14, Photon Production Multiplicities and Angular Distributions, MF33, Covariances of Neutron Cross Sections

Photon production data and covariance files are given in CENDL–2. The covariance of neutron cross sections is not included in any other evaluations.

In general, CENDL–2 has not been inferior to any evaluation so far.

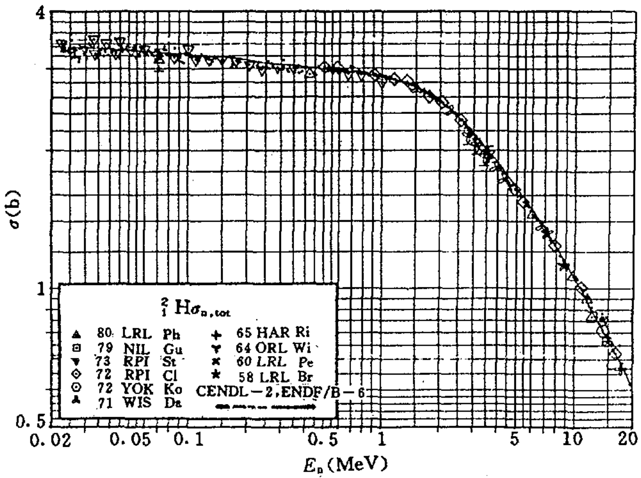

Fig. 1 The total cross sections

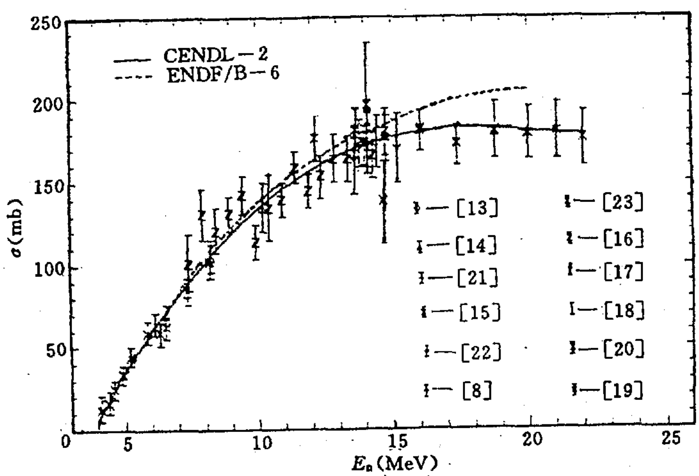

Fig. 2 ^{2}H(n,2n)^{1}H reaction cross sections

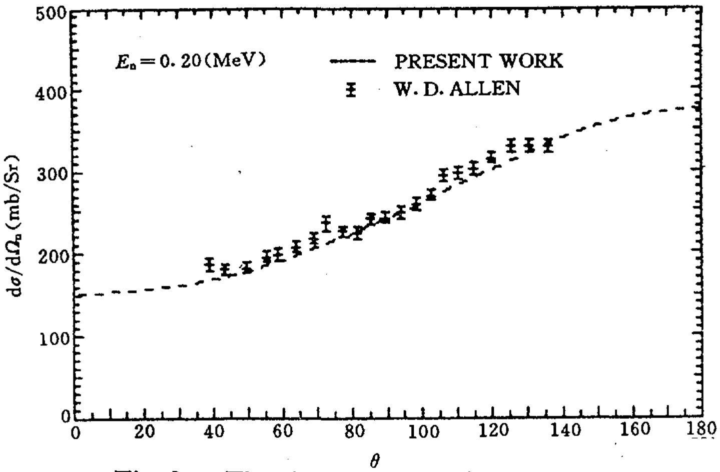

Fig. 3a The elastic angular distribution

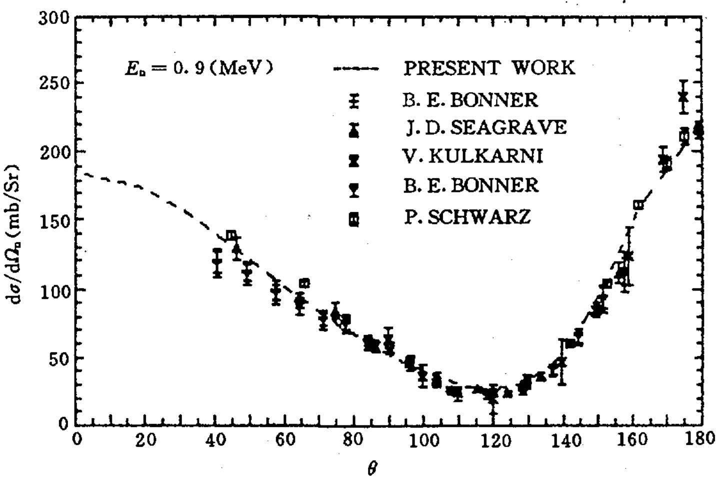

Fig. 3b The elastic angular distribution

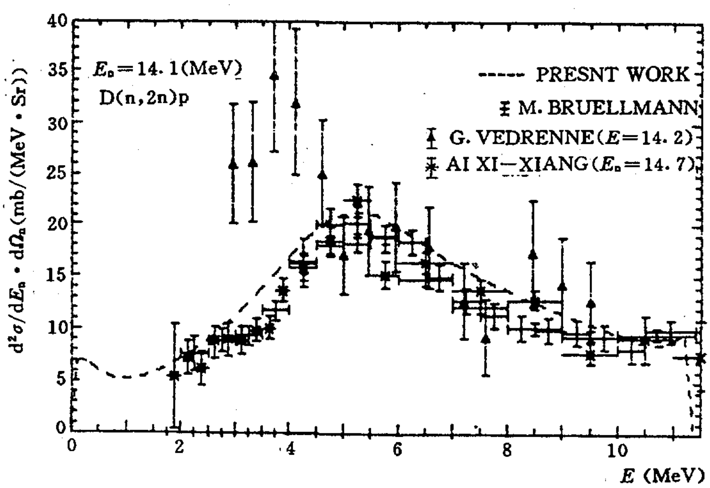

Fig. 4a Measured and calculated double-differential cross sections for (n,2n) reaction at 15°

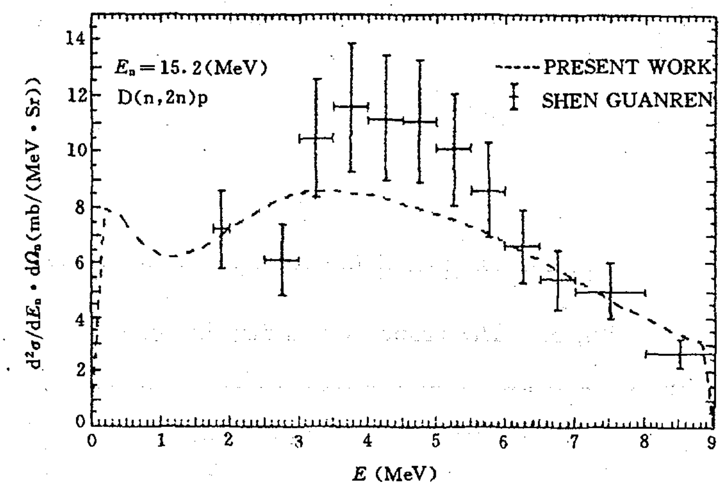

Fig. 4b Measured and calculated double–differential cross sections for (n,2n) reaction at 45°

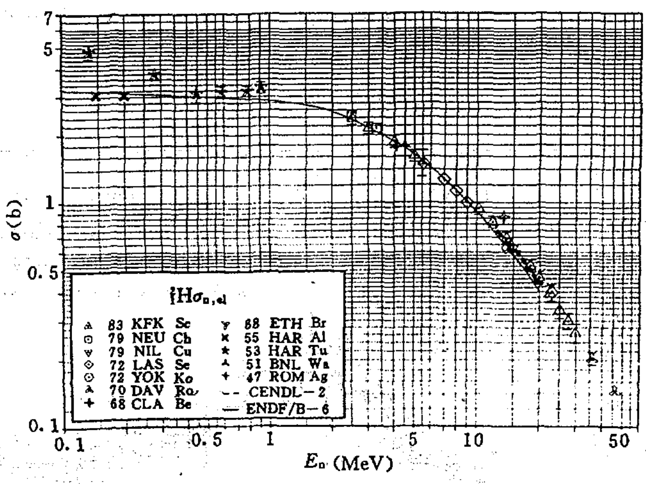

Fig. 5 The elastic scattering cross sections

REFERENCES

[1] Zhou Enchen, "Chinese Evaluated Nuclear Data Library, version–1", P. 38, 1980

[2] Chu Lianyuan et al, Commun. Theor. Phys., 11, 411(1989)

[3] Bratenahl et al., PR 110, 927(1958)

[4] Peterson et al., PR 120, 521((1960)

[5] Willard et al., PR, 9, 339(1964)

[6] Riddle et al., NP, 61, 457(1965)

[7] J. C. Davis et al, PR, C3, 1798(1971)

[8] N. Koori, JPJ, 32, 306(1972)

[9] J. M. Clement, NP, A183, 51((1972)

[10] P. Stoler et al., PR, C8, 1539(1973)

[11] K. Gul et al., 79 Knox, 39(AB2), (1979)

[12] T. W. Phillips et al., PR, C22, 384(1980)

[13] V. J. Ashby et al., PR, 111, 616(1958)

[14] H. C. Catron et al., PR, 123, 218(1961)

[15] M. Holmberg, NP, A129, 327 & 305(1969)

[16] J. Frehaut et al., 85 Santa Fe, (IB06), 1985

[17] Shen Guanren et al., Chinese Journal of Nucl. Phys., 12, 24((1990)

[18] Bai Xixiang et al., Chinese Journal of Nucl. Phys., 2, 327((1980)

[19] K. Gul et al., J. Phys. G: Nucl. Phys. 5, 1107(1979)

[20] G. Vedrenne et al., Journal de Physique (colloque) 27, 71(1966)

[21] S. Shirato et al., NP, A120, 387((1968)

[22] E. R. Graves et al., NCSAC–42, 158(1971)

[23] G. Pauletta et al., NP, A255, 267(1975)

[24] L. Stewart et al., LA–3271(1968)

THE EVALUATION OF TRITON NEUTRON DATA

Zhuang Youxiang

(CHINESE NUCLEAR DATA CENTER, IAE)

ABSTRACT

Based on the experimental data evaluation and theoretical calculation, a complete and self–consistent set of triton neutron data has been recommended in the energy range of 10^{-5} eV ~ 20 MeV for CENDL–2, and the comparison with other evaluations has been carried out.

INTRODUCTION

The interaction of neutron on triton is of important significance in the use of nuclear energy, and can be utilized as an effective way to research nuclear force, because triton belongs to " a few nucleon system ".

The price of tritium sample is very expensive, and there are many problems such as radiation protection etc., therefore it is deficient in experimental data, especially for ^{3}H(n,2n)^{2}H and ^{3}H(n,3n)^{1}H reactions. Up to now only LANL has manufactured the better tritium samples, and measured the most data.

The possible reactions induced by neutron on triton, except radiative capture, are as follows:

$$n+{}^3H \rightarrow \begin{cases} n + {}^3H, \text{ elastic scattering;} \\ 2n + {}^2H - 6.26\ \text{MeV, (n,2n) reaction;} \\ 3n + {}^1H - 8.49\ \text{MeV, (n,3n) reaction.} \end{cases}$$

Thus $\sigma_t = \sigma_{n,n} + \sigma_{n,2n} + \sigma_{n,3n} + \sigma_{n,\gamma}$.

1 EVALUATION OF EXPERIMENTAL DATA

The experimental data evaluation is based on Ref. [1], total cross section is usually measured by means of transmission method.

The recommended values of total cross section are based on a least–squares fit to the data of Refs. [2~4]. See Fig. 1.

The (n,2n) and (n,3n) reaction cross sections were measured only at 14.06

MeV by D. S. Mather et al[5] . They are 46.8 ± 4.9 mb and 0.2 ± 1.0 mb, respectively.

The $^3H(n,\gamma)^4H$ cross sections were measured by W. L. Imhof et al.[6] in 1964. Their results are as follows:

E_n = thermal, $\sigma_{n,\gamma} < 6\ \mu b$; 0.030~1.2 MeV, $\sigma_{n,\gamma} < 0.06\ \mu b$.

Thus $\sigma_{n,\gamma}$ can be neglected, compared with the others. This cross section is assumed zero at all energies.

The elastic cross sections were taken from Refs. [7~9]. See Fig. 2.

The elastic angular distributions of Refs. [10~21] were recommended.

2 THEORETICAL CALCULATION

The elastic angular distributions in the center of mass system were calculated as normalized probabilities versus cosine of the scattering angle with the aid of phase shift analysis by Wang Yansen et al.[22] and coincide with the experimental data[10~21] as well as ENDF / B–6[23] . See Fig. 3.

3 COMPREHENSIVE RECOMMENDATION

3.1 The total cross sections of experimental evaluation were taken as recommended ones, bacause it has high precision. See Fig. 1.

The (n,2n) cross sections were taken from ENDF / B–6[23], which is based on systematics and p–^{3}He reaction studies of Rosen and Leland[24] and Anderson[25], for lack of experimental data.

The (n,3n) cross sections were evaluated on the basis of experimental data from Refs. [5] and [26].

Owing to small radiative capture cross sections, $\sigma_{n,\gamma} \approx 0$; thus $\sigma_{n,n} = \sigma_t - \sigma_{n,2n} - \sigma_{n,3n}$. Such obtained $\sigma_{n,n}$ are consistent with their experimental data[7~9]. See Fig. 2.

3.2 The elastic and (n,2n) angular distributions in the center of mass system are as normalized probabilities versus cosine of the scattering angle. The former was taken from our calculation[22] and ENDF / B–6[23] which are on the basis of experimental data of Refs. [10~21]. The latter was taken from ENDF / B–6.[23]

3.3 The (n,2n) energy distributions are given as normalized probabilities versus energy of the outgoing neutron in the laboratory system taken from ENDF / B–6[23].

3.4 The (n,3n) energy–angle distributions were taken from M. N. Nikolaev (1989).

4 COMPARISON WITH OTHER EVALUATIONS

4.1 Total and Elastic Cross Sections

Above 600 keV, CENDL–2 is the same value as ENDF / B–6; below 600 keV, CENDL–2 coincides with the new measurement of T. W. Phillips et al. (1980), but it is generally larger than ENDF / B–6, especially at thermal energy it is 31% higher then ENDF / B–6.

BROND of Soviet is similar to CENDL–2. n + T is not included in JENDL–3.

4.2 (n,2n) and (n,3n) Cross Sections

The (n,2n) cross sections of CENDL–2, ENDF / B–6 and BROND are all the same, but the (n,3n) of ENDF / B–6 equals to zero and that of CENDL–2 and BROND are small (about mb).

4.3 Elastic and (n,2n) Angular Distribution

On the basis of the same experimental data at $E_n = 10^{-5}$ eV, 0.1, 0.5, 1.5, 2.0, 3.5, 6.0, 8.5, 9.5, 10.4, 11.5, 14.0, 16.23, 20.0 MeV, CENDL–2, ENDF / B–6 and BROND have given 15 sets of recommended data. In addition CENDL–2 has added 9 sets of data at $E_n = 4.5$, 7.0, 12.0, 13.0, 14.1, 15.0, 17.0, 18.0, 19.5 MeV; and revised that at $E_n = 0.1$ MeV, because the elastic angular distribution at $E_n = 0.1$ MeV is already not isotropic.

Thus CENDL–2 has given more reasonable energy points and complete data set than the others.

4.4 (n,2n) Energy Distribution and (n,3n) Angle–Energy Distribution

CENDL–2 is the same as ENDF / B–6 and BROND, respectively.

4.5 Covariances of Neutron Cross Sections

Covariance file 33 is given in CENDL–2, it is not included in any other evaluations.

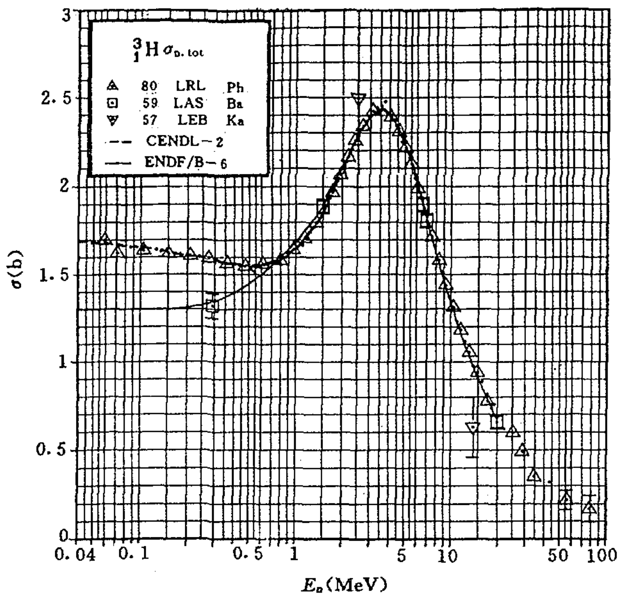

Fig. 1 Total neutron cross section of ^3H

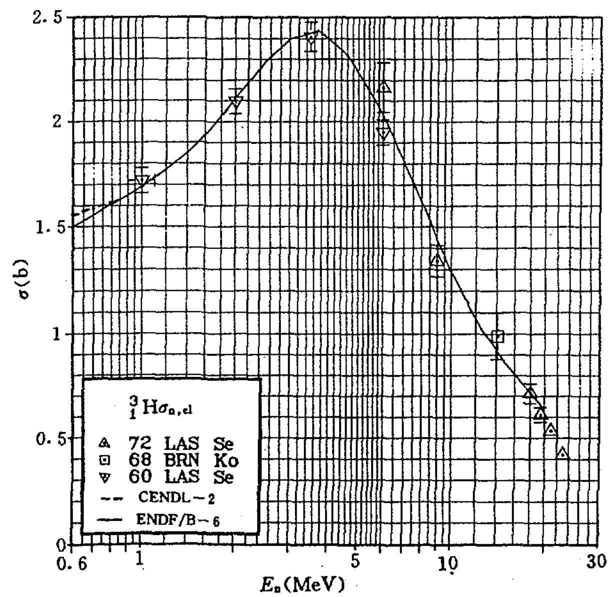

Fig. 2 Neutron elastic scattering cross section of ^3H

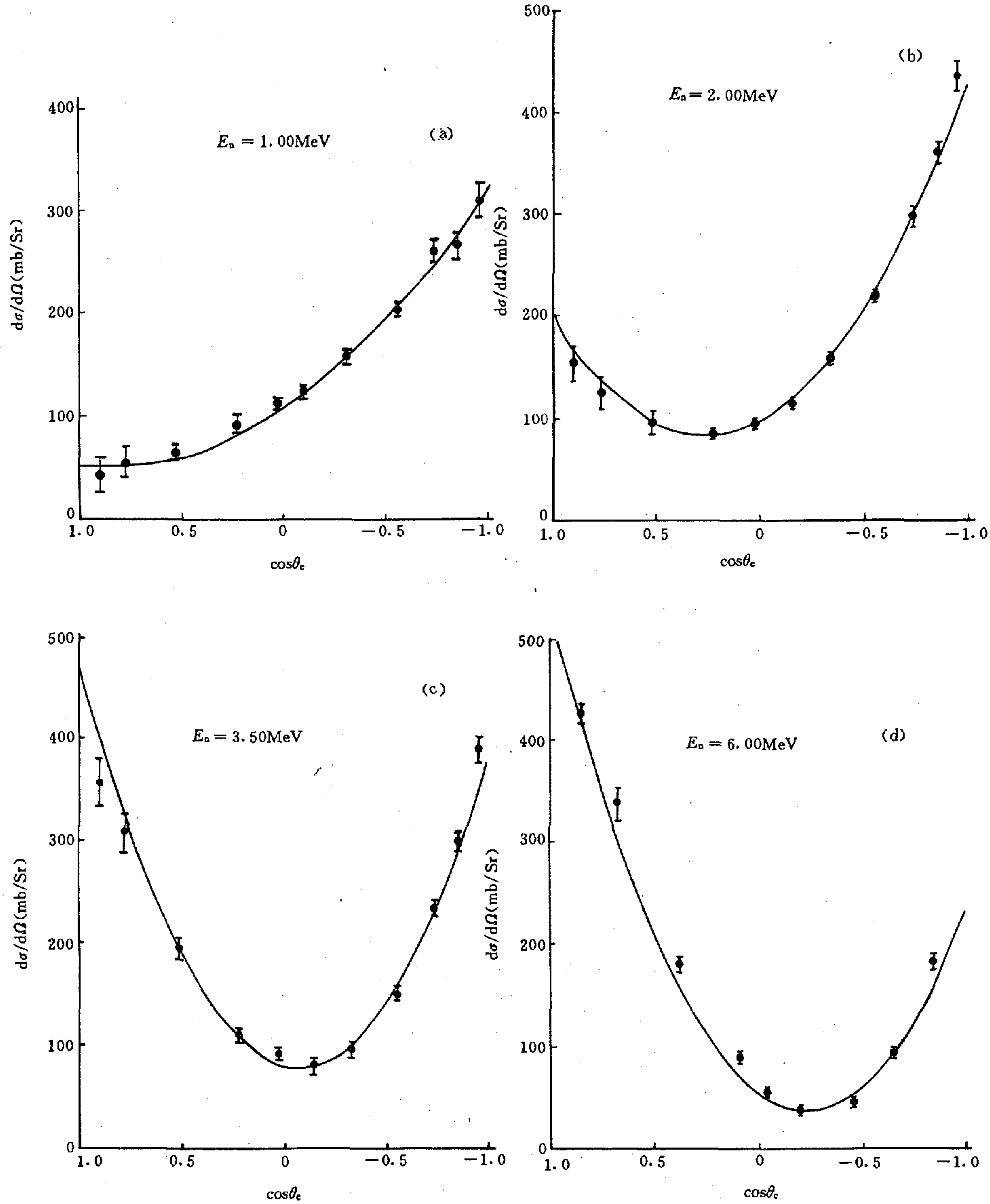

Fig. 3(a–d) The angular distributions of elastic scattering neutron from ^{3}H

Φ experimental data

——— calculated velues from phase shift analysis

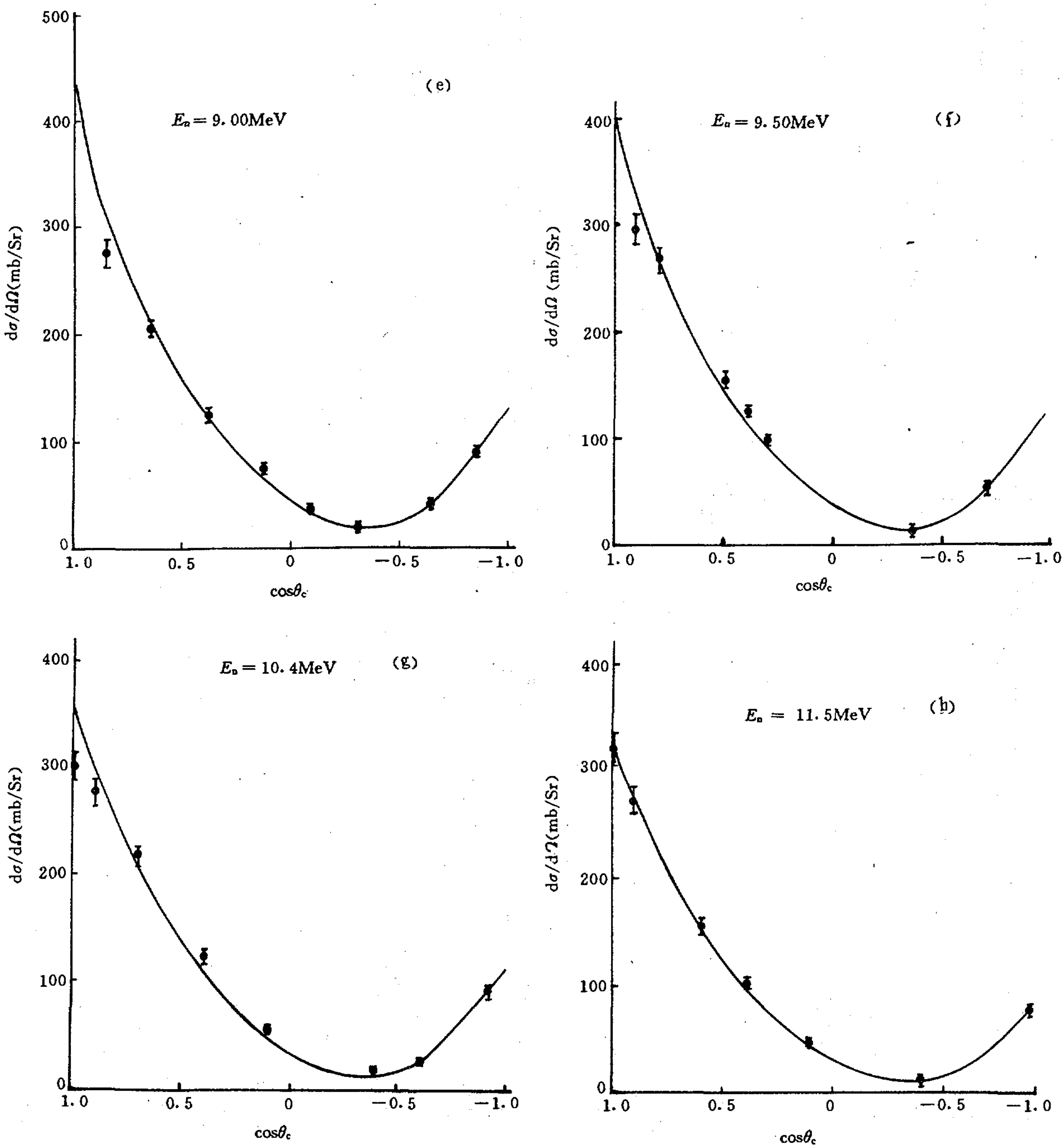

Fig. 3(e—h) The angular distributions of elastic scattering neutron from ^3H

Ⅰ experimental data

——— calculated velues from phase shift analysis

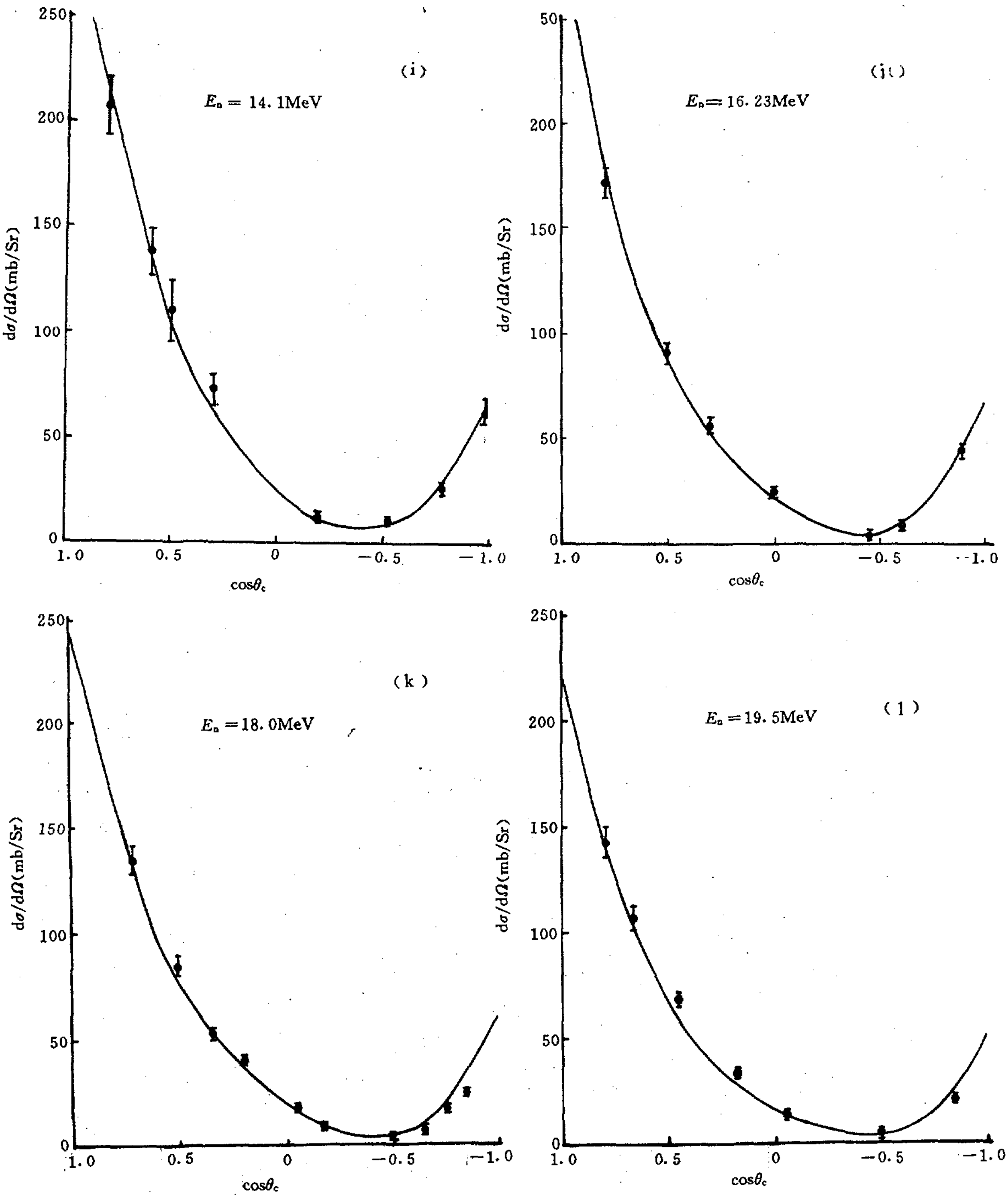

Fig. 3(i–l) The angular distributions of elastic scattering neutron from ^{3}H

experimental data

calculated values from phase shift analysis

REFERENCES

[1] Zhuang Youxiang, " The experimental evaluation of triton neutron data" , hsi–77085(bp), 1978

[2] Katsaurov et al., AE / S, 5,71(1957)

[3] Battat et al., NP, 12, 291(1959)

[4] Phillips et al., PR / C, 22,384(1980)

[5] D. S. Mather et al., AWRE–O–47 / 69, 1969

[6] W. L. Imhof et al., NP, 59,81(1964)

[7] J. D. Seagrave et al., PR, 119, 1981(1960)

[8] Kootsey et al., NP / A, 113,65(1968)

[9] J. D. Seagrave et al., AP, 74 250(1972)

[10] J. D. Seagrave et al., PR, 119, 1981(1960)

[11] J. M. Coon et al., PR, 81, 33(1951)

[12] T. B. Clegg et al., NP, 50, 621(1964)

[13] W. Haeberli et al., PR / B 133, B 1178 (1964)

[14] J. Brolley, Jr. et al., PR, 117, 1307 (1960)

[15] R. H. Lovberg, PR, 103, 1393 (1956)

[16] R. A. Vanetsian et al., Soviet J. of Atomic Energy, Trans. 2, 141 (1957), and K. P. Artemov et al., JETP, 10, 474 (1960)

[17] L. Rosen et al., WASH–1064 (EANDC(US)–79U), P. 99, 1966

[18] D. Blanc et al., Supplement Fasc. 3~4, c1–98 (1966)

[19] J. D. Seagrave et al., LA–DC–12954 (1971)

[20] J. R. Morales et al., Bull. Am. Phys. Soc. 14, 554 (1969)

[21] R. L. Hutson et al., PR / C, 4, 17 (1971)

[22] Wang Yansen et al., Private Communication (1991)

[23] L. Stewart, LA–3270 (1965) updated and revised

[24] L. Rosen and W. T. Leland, WASH–1064 (EANDS(US)–790) (Oct. 1966) p. 99

[25] J. D. Anderson et al., Phys. Rev. Letters 15, 66(1965)

[26] Ajdacic et al., Phys. Rev. Letters 14, 144(1965)

EVALUATION OF NEUTRON DATA ON ^{3}He FOR CENDL–2

Zhao Zhixiang

(CHINESE NUCLEAR DATA CENTER, IAE)

INTRODUCTION

The neutron cross sections of ^{3}He are of importance in nuclear technique and nuclear engineering. The large, nearly $1/v$ (n,p) cross section of ^{3}He has been used as a standard cross section. Moreover,this process is an important triton–making reaction.

The evaluation of ^{3}He neutron nuclear data for CENDL–1 was finished by Zhao in 1979 [1]. Since then, some significant new experimental data have become available [2~6]. So improving and updating to CENDL–1 should be made.

EVALUATION AND RECOMMENDATION

The main problem in the evaluation of CENDL–1 was that the measured neutron cross sections of ^{3}He were not self–consistent: the total cross section measured by Battat [7] and Goulding [8] were lower than the sum of partial cross sections in the incident energy region of E_n = 1 to 3 MeV.In the evaluation of CENDL–1, the elastic cross section was decreased to make self–consistency. This discrepancy is removed by Haesner's new measurement on total cross section [2]. The Haesner's data are in good agreement with the measured data of (n,p) and (n,n) reactions. The new measured data [2] of angular distribution of elastic scattering make it possible to improve File 4 of CENDL–1. Moreover, the new measured data[2~6] on (n,γ), (n,p), (n,n) and (n,d) reactions are also helpful to update and implement the CENDL–2.

Based on the new measured data mentioned above, the new evaluation for CENDL–2 is given as follows:

MF = 3 MT = 1 Total Cross Section

In the energy region of E_n < 1 MeV, the total cross sections are given by summing the elastic and nonelastic cross section. The total cross sections obtained in this way are in good agreement with those measured by Als–Nielsen [9] and King [10] in low energy. For $E_n > 1$ MeV, Evaluated cross sections are obtained through fitting Haesner's data with polynomials by least–squares method. As mentioned above, Haesner's data are consistent with the sum of (n,p) and (n,n) cross sections.

MF = 3 MT = 2 Elastic Scattering Cross Section

In the energy region of $E_n < 1$ MeV, the elastic cross sections are obtained based on Alfimenkov's new data [6] through eye–guide. For $E_n > 1$ MeV, a least–squares fit is performed based on the measured data available [3, 12~14].

MF = 3 MT = 3 Nonelastic Cross Section

The non–elastic cross sections are derived by

MT3 = MT16 + MT28 + MT102 + MT103 + MT104

MF = 3 MT = 16 and 28 (n,2n) and (n,np+pn) Cross Section

The sum of (n,2n) and (n,np+pn) cross sections is obtained by deducting the (n,n), (n,γ), (n,p) and (n,d) components from the total cross sections. Then these two cross sections are seperated from the sum simply based on the shape of the sum and the Q–values of these two reactions.

MF = 3 MT = 102 Capture Cross Section

In CENDL–1, (n,γ) cross section was neglected. This evaluation supplements MT = 102 based on Alfimenkov's measurement [3] in thermal region and Wervelman's data [4] at 24 keV. A line in log–log coordinate smoothly passes these data and is extrapolated to 20 MeV.

MF = 3 MT = 103 (n,p) Cross Section

The Borzakov's [5] and Haesner's [2] data are generally consistent with those of CENDL–1. So (n,p) cross sections of CENDL–1 remain unchanged in this evaluation.

MF = 3 MT = 104 (n,d) Cross Section

The (n,d) cross sections in CENDL–1 are higher for several millibarns than Haesner's new measured data. No measured (n,d) cross sections were available for CENDL–1 above E_n = 16 MeV. In this evaluation, an adjustment to CENDL–1 is made to fit Haesner's data.

MF = 4 MT = 2 Angular Distribution of Elastic Scattering

It is found that Haesner's new angular distribution data are in good agreement with those of Refs. [12~ 14]. The legendre coefficients of angular distributions are recommended based on these data. The transformation matrix for the coefficients is calculated from a code written by Chu et al. [15].

RESULTS AND COMPARISON

The comparisons of this evaluation with ENDF / B–6, JENDL–3 and BROND are carried out. The agreement of this evaluation with the new measured data is better than the others.

REFERENCES

[1] Zhao Zhixiang, CNDC–85010(1986)

[2] B. Haesner et al., KFK–3395(1982); Phys. Rev., C28, 995(1983)

[3] V. P. Alfimenkov et al., YF, 31, 21(1980)

[4] R. Wervelman et al., Nucl. Sci. and Eng.,102, 428(1989)

[5] S. B. Borzakov et al., YF, 35, 532(1982)

[6] V. P. Alfimenkov et al., YF, 33, 891(1981)

[7] M. E. Battat et al., Nucl. Phys., 12, 291(1959)

[8] C. A. Goulding et al., Nucl. Phys., A215, 253(1973)

[9] J. Als–Nielsen et al., Phys. Rev., B133, 925(1964)

[10] J. D. P. King et al., Phys. Rev., 75, 1366(1949)

[11] V. P. Alfimenkov et al., YF, 25, 1145(1977)

[12] J. D. Seagrave et al., Phys. Rev., 119, 1981(1960)

[13] A. R. Sayes et al., Phys. Rev., 122, 1853(1961)

[14] M. Drosg et al., USNDC–1(1972)

[15] Chu Lianyuan et al., CNDP 5, 14(1991)

THE RE–EVALUATION OF NEUTRON DATA FOR ^{10}B

Chen Qiankun Chen Zhenpeng

(DEPARTMENT OF APPLIED PHYSICS,
TSINGHUA UNIVERSITY)

The nuclear data for ^{10}B was evaluated in CENDL–1; since 1982 some new experimental data have been published. All of them are considered in this evaluation. The data in the neutron energy region from 0.1×10^{-4} eV to 1 MeV were calculated with R–matrix theory. The parameters of R–matrix were obtained from the simultaneous analysis of the experimental data of ^{11}B system.

In the neutron energy region between 1 MeV and 20 MeV, the evaluated data from various libraries have been comparaed with the experimental data. The data of JENDL–3 coincide with the experimental data very well. So those data were adopted in CENDL–2.

The average cosine of elastic scattering angle in the Lab. system (MT=251, MF=3), the average logarithmic energy reduction (MT=252, MF=3) and the zero degree G. G. parameters of the target nuclei in the elastic scattering (MT=253, MF=3) were added in CENDL–2 which are calculated from the data of MT=2, MF=4.

THE RE–EVALUATION OF NEUTRON DATA FOR ^{11}B

Qi Huiquan

(DEPARTMENT OF APPLIED PHYSICS,
TSINGHUA UNIVERSITY)

The ^{10}B was evaluated in CENDL–1, since 1982 some new experimental data have been published. All of them are considered in this evaluation, especially, the (n,n′γ) cross sections. Some recommended data based experimental data were improved, such as the total cross sections. They were obtained from spline function fitting in the last evaluation, some structure were lost.

The (n,γ) reaction was added. The data of (n,2n), (n,n′α), (n,n′p), (n,n′2α), (n,n′d) and (n,n′t) reactions were added too, which were calculated with GNASH code[1] and obtained from JENDL–3.

The average cosine of elastic scattering angle in the Lab. system (MT=251, MF=3), the average logarithmic energy reduction (MT=252, MF=3) and the zero degree G. G. parameters of the target nuclei in the elastic scattering (MT=253, MF=3) were added in CENDL–2, which were calculated from the data of MT=2, MF=4.

REFERENCE

[1] P. G. Young et al., GNASH, a prequilibrium, statistical nuclear –model code for calculation of cross section and emission spectra LA–6947 (1977)

EVALUATION OF NEUTRON INDUCED DATA ON ^{19}F

Zhao Zhixiang

(CHINESE NUCLEAR DATA CENTER, IAE)

C. Y. Fu D. C. Larson

(ORNL, U. S. A.)

INTRODUCTION

Flurine is an important material in fusion reactor. The neutron induced data on F are very useful in fusion reactor design and other nuclear engineering application. The evaluation in ENDF / B–5 for ^{19}F was finished by Larson et al. in 1979. Since then, several new measurements are available. In ENDF / B–5 evaluation, energy distribution of the recoil nuclei was not given and the theory calculation was not used to give the γ–ray production data to ensure the energy balance.

This evaluation is performed based on the new measured data and a comprehensive theory calculations. The optical model code GENOA[1] was used to determine the optical model parameters and calculate the angular distribution of elastic scattering. The Distorted Wave Born Approximation code DWUCK[2] was used to calculate cross sections and angular distribution of direct–interaction contribution for inelastic scattering. H–F and pre–compound code TNG[3] provided cross sections and energy–angular distribution for emitted particles.

1 THEORETICAL CALCULATION

The calculation includes the following reactions: (n,n′), (n,2n), (n,np), (n,nα), (n,p), (n,pn), (n,α) and (n,αn) reactions.

1.1 Procedures to Adjust Parameters

Much effort was spent on adjusting parameters so that a good simultaneous fit to measured data could be obtained. To ensure consistency of the calculation, a set of optical model parameters (OMP) was obtained through an iteration process. Firstly, using a set of OMP from Ref. [4] as input to DWUCK, the contribution of direct–interaction was obtained. Then, using same OMP and the output of DWUCK as input to TNG, the compound elastic cross sections were calculated after adjusting level density parameters to fit measured data. The level density parameters for ^{19}F, ^{19}O and ^{16}N were adjusted to fit the measured data of (n,n′), (n,p), (n,α) and (n,2n) reactions. Finally, with compound elastic cross sections given by TNG and measured elastic angular distribution, GENOA was used to obtain a new set of OMP as input to DWUCK to begin the next iteration. To reduce the number of iterations, we mainly adjusted the depth of the spin–orbit potential in GENOA because the results calculated from TNG and DWUCK results were insensitive to this parameter.

1.2 Model Parameters Used in the Calculation

The OMP for n + ^{19}F were taken from Ref. [4] and adjusted to fit measured data as described above and given in Ref. [5]. For n + ^{18}O, the OPM of Ref. [6] were used. The OPM for n + ^{18}F were taken as those of n + ^{19}F and the OMP of n + ^{15}N taken from Ref. [7]. The charged particle OMP were taken from Refs. [7~9] and given in Ref. [5].

The Gilbert–Cameron composite level density formulae as described by Fu[10] were used in TNG. The initial level density parameters were obtained based on the information of descrete levels compiled by Ajzenberg–Selove [11~13]. To fit the measured cross sections of (n,n′), (n,p), (n,α) and (n,2n) reactions, the level density parameters for ^{19}F, ^{19}O and ^{16}N were adjusted. The cross sections for tertiary reactions are insensitive to level density parameters of the residual nuclei because the main contribution to the cross sections for these reactions come from discrete levels. The level density parameters used in the calculation were given in Ref. [5].

The energy, spin, parity of discrete levels and the branching ratios of the γ– ray decays from the excited levels of the residual nuclei were taken from the compilation of Ajzenberg– Selove[11~13] and given in Ref. [5].

The deformation parameters used in DWUCK were taken from Ref. [14]. The γ– ray transmission coefficient was calculated by the giant–dipole resonance model in TNG. The absorption cross section for giant resonance was assumed to have a Lorentzian shape. The resonance energy, peak cross section and full width at half maximum were taken from the empirical formulas[15].

1.3 Results and Comparisons

The comparisons of calculated cross sections, angular distributions, double differential cross sections and γ–production data with collected measured data and ENDF / B–5 were carried out. It is found that the results of this calculation are in good agreement with the measured data and obviously improved the ENDF / B–5 (see Figs.1 ~ 38 of Ref. [5]).

2 EVALUATION

2.1 Reaction Cross Sections (File 3)

The total and capture cross section in the resonance region were calculated from a set of resonance parameters which were adjusted to fit the high resolution measured data[16] by using multi–level R–matrix analysis code SAMMY[17]. In the smoothing region, the total cross sections were obtained through smoothing the measured data of Ref. [16]. The cross sections of (n,p), (n,α), (n,2n), (n,np+pn) and (n,nα+αn) reactions were taken from TNG calculation. For inelastic cross sections of discrete levels, the TNG and DWUCK calculations were adopted. TNG is not capable of calculating the cross sections of (n,d) and (n,t) reactions. For these two reactions, the evaluated cross sections were obtained by using Zhao's systematics[18] normalized to the limited measured data[19~21].

2.2 Angular Distribution (File 4)

The Legendre coefficients of elastic scattering were calculated by GENOA with adjusted OMP and compound elastic contribution given by TNG. For inelastic scattering, the Legendre coefficients were obtained by summing directinteraction contribution given by DWUCK and compound contribution calculated by TNG.

2.3 Double Differential Cross Section (File 6)

The double differential cross sections of emmited particles, γ–rays production and recoil nuclei for all reactions were evaluated based on TNG calculation. In the calculation, the angular distributions for second outgoing particles and γ– rays were assumed isotropic.

3 EVALUATION OF COVARIANCE DATA

The covariance data for cross sections for total interaction, (n,γ),(n,p),(n,α)

and inelastic scattering of 1st and 2nd excited states were evaluated based on the uncertainties of measured data used. For non–elastic and elastic cross sections, which were derived from other cross sections, the covariance data were given by using NC–type sub–subsection. The covariance data of (n,d) and (n,t) cross sections were calculated from the uncertainties of the regional parameters in the systematics used. The covariance matrix of (n,2n), (n,np+pn) and (n,nα+αn) cross sections were calculated from the covariance matrix of the model parameters in TNG. The method to obtain the covariance matrix of thoery model parameters given by this work was described in Ref. [5]. By using this method, the covariance matrix for several most sensitive parameters was obtained and given in Table 1.

Table 1 Covariance matrix of model parameters

Parameter	St. Error, %	Correlation Matrix					
A_n = 4.00 MeV	8.12	1.00					
A_a = 3.68 MeV	4.96	−0.10	1.00				
W_o = 6.20 MeV	56.2	−0.67	0.38	1.00			
V_o = 45.8 MeV	29.9	−0.48	0.03	0.68	1.00		
R_v = 1.26 fm	9.39	0.49	−0.20	−0.80	−0.92	1.00	
R_d = 1.30 fm	26.5	0.48	−0.25	−0.92	−0.67	0.79	1.00

* A_n and A_a are the level density parameters for ^{19}F and ^{16}N;
W_o and V_o are the depths of real and imaginary well for n+ ^{19}F;
R_v and R_d are the diffuseness of real and imaginary potential.

4 SUMMARY

The evaluation of neutron induced data on ^{19}F from 10^{-5} eV to 20 MeV has been performed and accepted as ENDF / B–6 and CENDL–2. The cross sections, angular distributions, double differential cross sections and covariance data have been given by this evaluation.

REFERENCES

[1] F. G. Perey, Computer Code GENOA, unpublished (1967)

[2] P. D. Kunz, "Distorted Wave Code DWUCK72", University of Colorado, 1972

[3] C. Y. Fu, Nucl. Sci. and Eng., 100(1988)61

[4] D. C. Larson, ORNL–5682(1980)

[5] Z. X. Zhao et al., ORNL / TM−11672(1990)
[6] P. Grabmayr et al., Nucl. Phys., A350, 167(1980)
[7] E. Fabrici et al., Phys. Rev., C21(1980)830
[8] S. Sen et al., Nucl. Phys., A219(1974)429
[9] H. Oeschler et al., Nucl. Phys., A202(1972)513
[10] C. Y. Fu, Atomic Data and Nucl. Data Tab., 17(1976)127
[11] F. Ajzenberg−Selove, Nucl. Phys., A449(1986)1
[12] F. Ajzenberg−Selove, Nucl. Phys., A460(1986)1
[13] F. Ajzenberg−Selove, Nucl. Phys., A475(1987)1
[14] T. R. Krick et al., Nucl. Phys., A216, 549(1973)
[15] E. G. Fuller and E. Hayward, Nuclear Reactions, Vol. 2, p. 113(1962)
[16] D. C. Larson et al., ORNL / TM−5612(1976)
[17] N. M. Larson, ORNL / TM−9179(1987)
[18] Z. X. Zhao et al., Nucl. Sci. and Eng., 99(1988)367
[19] M. Fazio et al., Nucl. Phys., A111(1968)255
[20] D. Rendic et al., Nucl. Phys., A117(1968)113
[21] S. M. Qaim et al., Nucl. Phys., A295(1978)150

RE−RECOMMENDATION FOR NATURAL MAGNESIUM

Tang Guoyou

(IHIP. PEKING UNIVERSITY)

Cai Chonghai

(PHYSICS DEPARTMENT, NANKAI UNIVERSITY , TIANJIN)

We have re−evaluated natural Mg data, Main advancement of our re−recommended data is that MUP2 program[1] was used to calculate every reaction channel cross section, and (n,n′p), (n,n′α), (n,2α) reaction channels were divided from (n,p), (n,α) reactions.

Besides total cross section (MT = 1), radiative capture cross section and elastic scattering angular distribution, all other reaction channel cross sections, angular distributions of secondary neutron and energy distributions of secondary neutron were calculated by MUP2 program[1].

Total cross sections were taken from experimental data[2~5].

Radiative capture cross sections, from thermal energy up to about 1.0 keV are obtained based on $1/v$ law, between 1.0 keV and 500 keV from ENDF / B–5, from 500 keV up to about 3.0 MeV based on $1/E$ law, above 5 MeV, they were kept as a constant from recommended data of 14.0 MeV[6], and at thermal energy was evaluated on the basis of experimental data[7~11].

Elastic scattering angular distributions, from 25 keV up to 8.5 MeV, 11.0 MeV and 14.0 MeV were based on the measured data[12~19], at all other energy points were calculated by AUJP program[1].

Our recommended data of some cross sections are compared with ENDF / B–6, JENDL–3, shown in Figs. 1~8.

For inelastic scattering cross section of first level (–0.5851 MeV) theoretical calculation quite agrees with measured data.

ACKNOWLEDGMENTS

Much thanks for Chinese Nuclear Data Center, from which we got some financial and technical support.

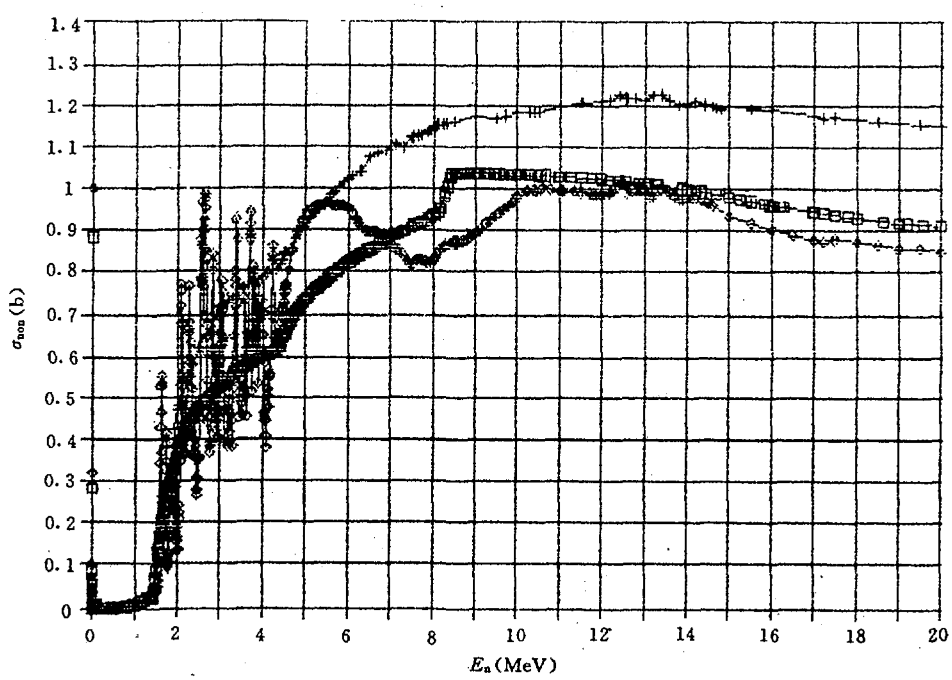

Fig. 1 Mg nonelastic scattering cross section

□ Our data + JENDL–3 ◇ ENDF / B–6

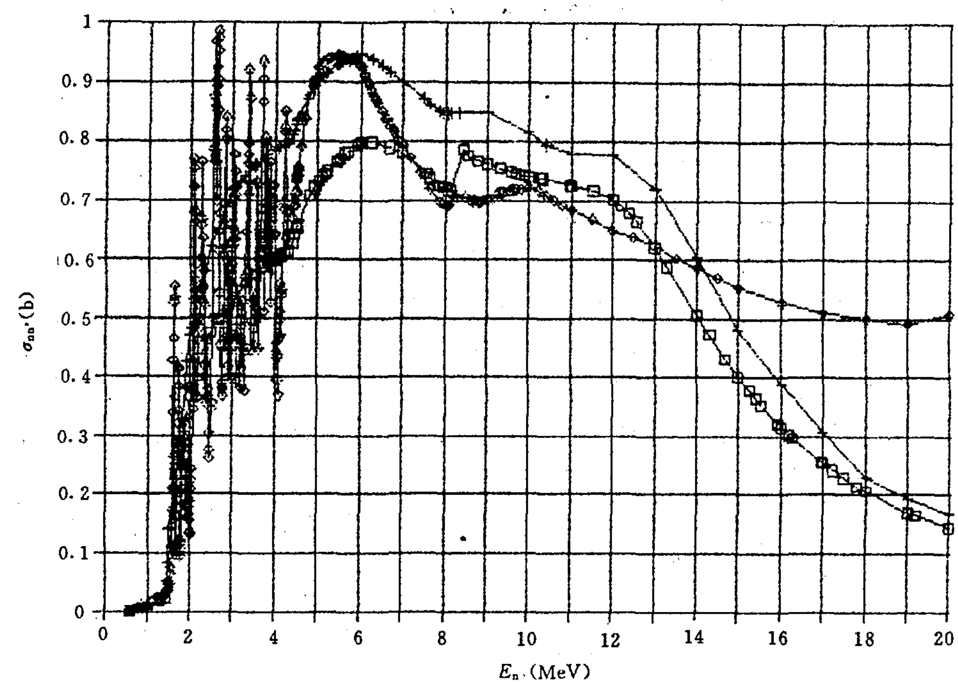

Fig. 2 Mg (n,n′) cross section

□ Our data + JENDL−3 ◇ ENDF / B−6

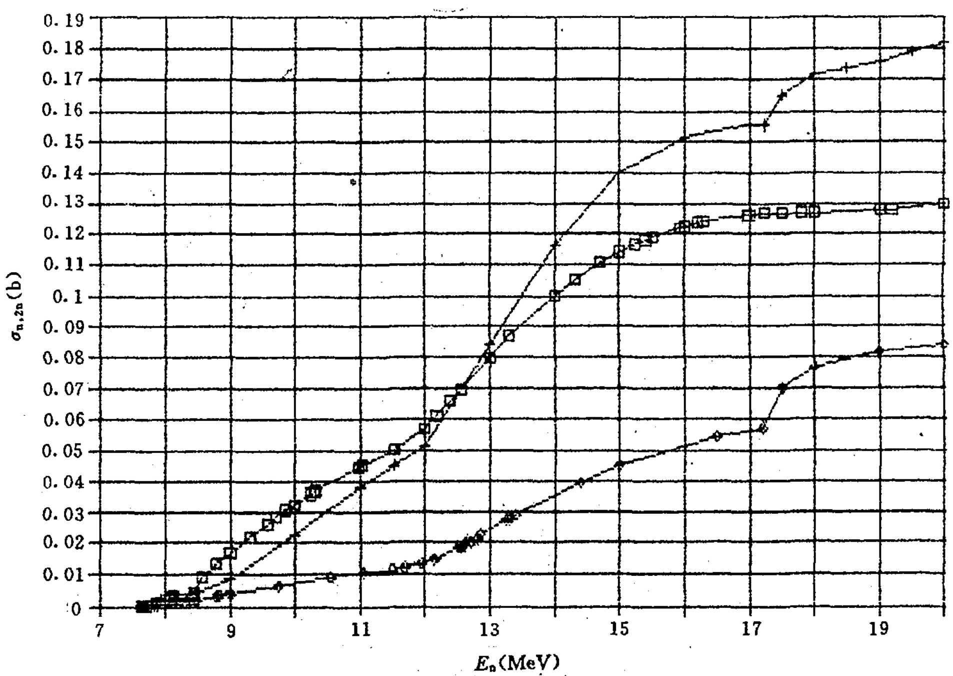

Fig. 3 Mg (n,2n) cross section

□ Our data + JENDL−3 ◇ ENDF / B−6

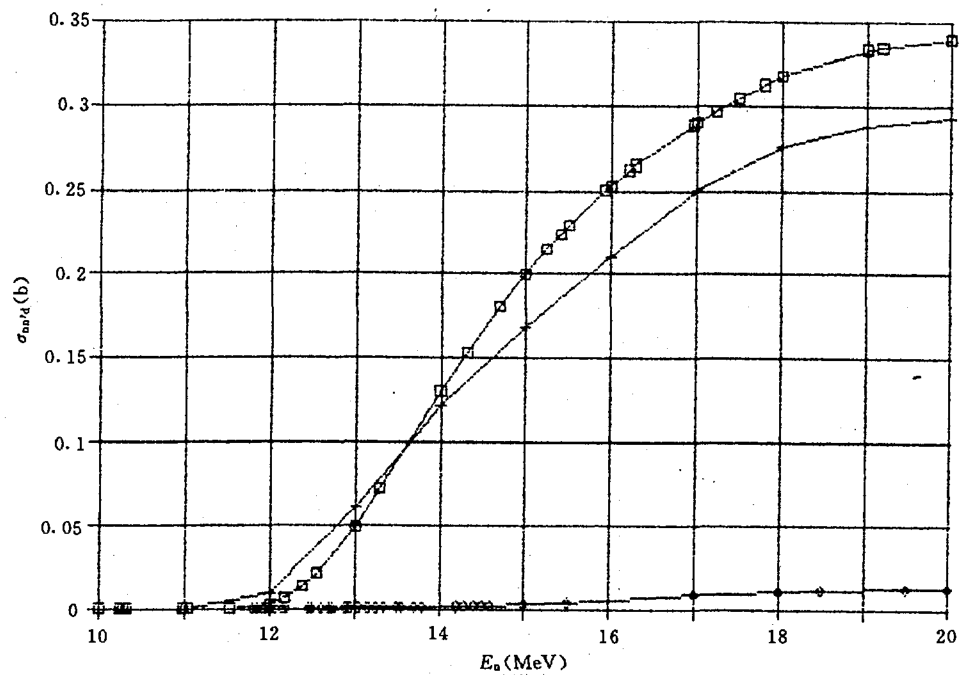

Fig. 4 Mg (n,n′d) cross section

□ Our data + JENDL−3 ◇ ENDF / B−6

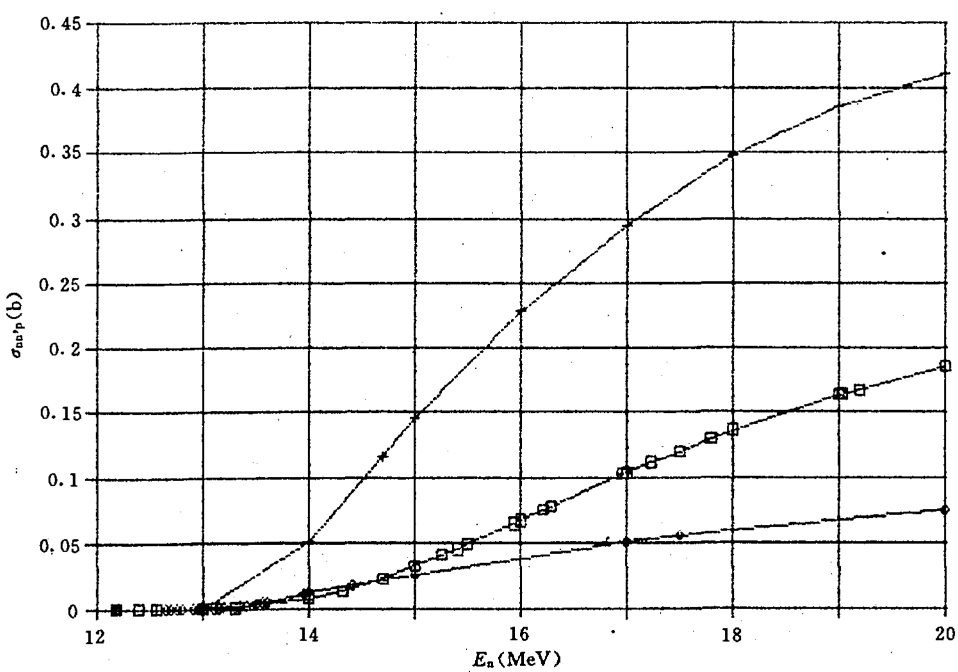

Fig. 5 Mg (n,n′p) cross section

□ Our data + JENDL−3 ◇ ENDF / B−6

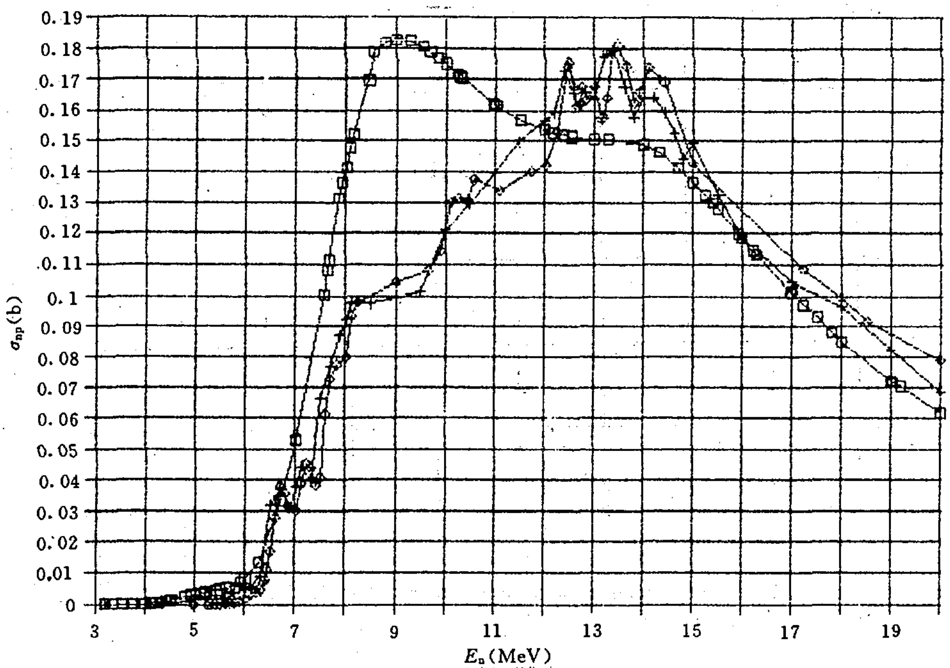

Fig. 6 Mg (n,p) cross section

□ Our data + JENDL-3 ◇ ENDF / B-6

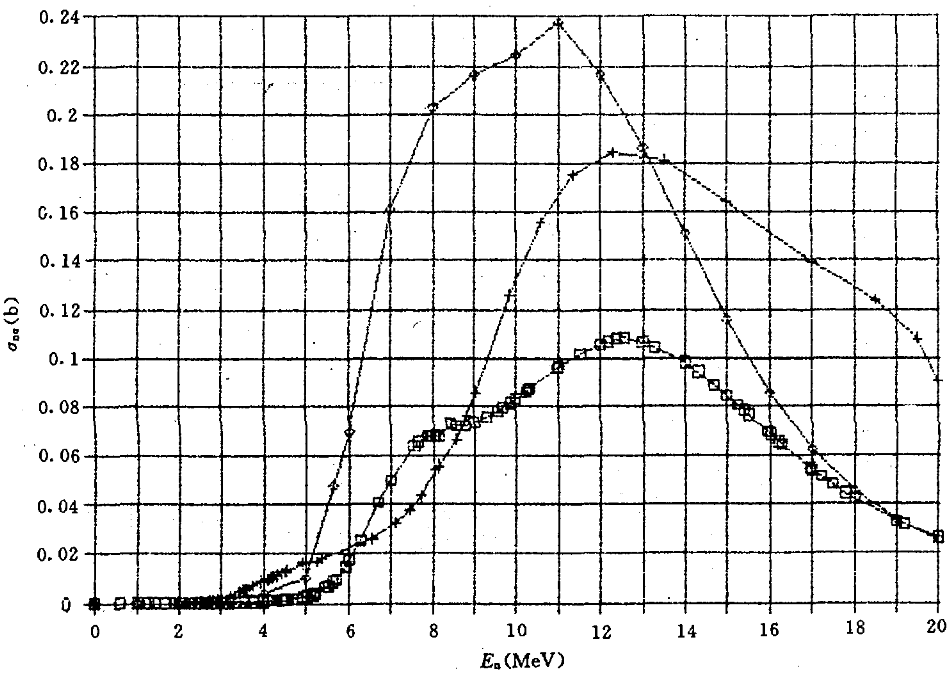

Fig. 7 Mg (n,α) cross section

□ Our data + JENDL-3 ◇ ENDF / B-6

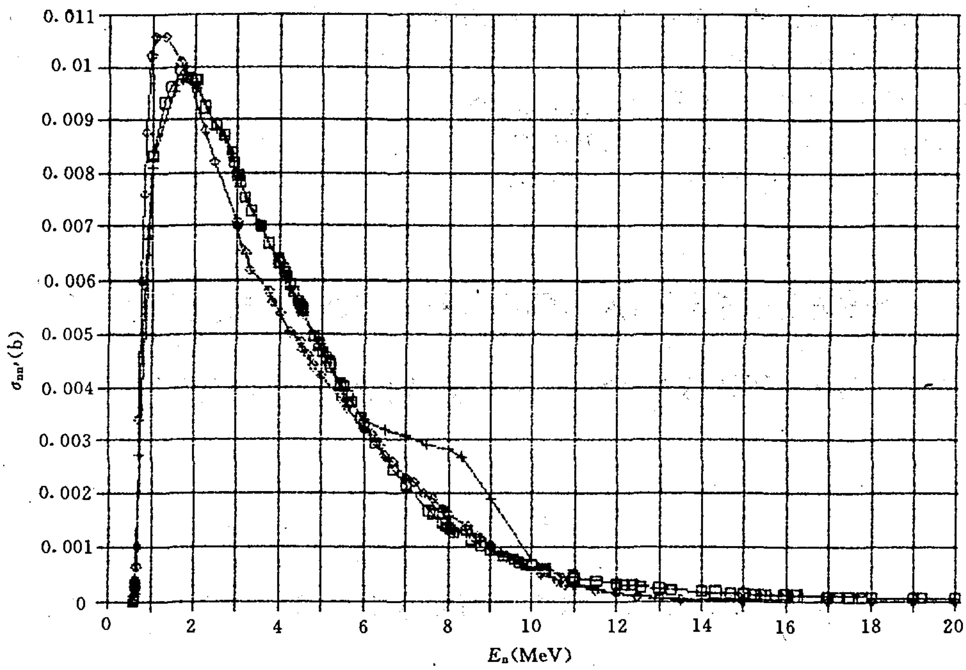

Fig. 8 The cross section of inelastic scattering to first level for Mg

□ Our data + JENDL–3 ◇ ENDF / B–6

REFERENCES

[1] Cai Chonghai, et al., report of AUJP and MUP2 program

[2] Rainwater, et al., Phys. Rev., 73, 733(1948)

[3] U. N. Singh et al., Phys. Rev., C10, 2150(1974)

[4] UCRL–50400 Vol. 10, Tabulated Experimental Data for Neutron –Induced Interactions (1976)

[5] D. C. Larson et al., ORNL / TM–6420 (1978)

[6] M. Budnar, INDC (YUG) – 6

[7] Huttel et al., Kernenergie, 6, 366(1963)

[8] A. Stefanescu, Rev. Roum. Phys., 311, 6(1961)

[9] H. Rose AERE–R / R–2516(1959)

[10] Pomerance et al., Phys. Rev., 83, 641(1951)

[11] Colmer and Litter, Proc. Phys. Soc., A63, 1175(1950)

[12] A. Langsdorf, et al., ANL–5567(1956)

[13] S. A. Cox, et al., B. A. P., 12, 1186(CB5)(1967)
B. A. P. 10, 576(AC6)(1965)

[14] W. Kinny, F. G. Perey, ORNL–4550,(1970)

[15] D. B. Thomson, et al., Phys. Rev., 125, 2049(1962)
[16] J. C. Ferrer, et al., Nucl. Phys / A, 275, 325(1977)
P. L / B, 62, 399(1976)
[17] P. H. Stelson, et al., Nucl. Phys., 68, 97(1965)
[18] R. C. C, et al., Nucl. Phys., 53, 177(1965)
[19] S. Berko, et al., Nucl.Phys., 73, 561(1965)

EVALUATION FOR THE COMPLETE NEUTRON DATA OF ALUMINIUM

Liu Jicai

(HENGYANG TECHNOLOGIC COLLEGE)

Cai Chonghai

(DEPARTMENT OF PHYSICS, NANKAI UNIVERSITY, TIANJIN)

INTRODUCTION

Al is a stable element and very important for nuclear industry as it is provided with good physical and chemical nature.

Xia Yijun[1] has recommended a set of neutron data for Al in 1978 for CENDL−1. But there were some obvious defects: experimental data are not enough, consistency of experimental and theoretical data are not well and neutron energy region is only from 4 keV ~ 20 MeV.

In this new evaluation, the new experimental data up to 1986 were supplemented, and a new theoretic program was used to calculate the complete neutron data of Al. The calculated data are good in agreement with the experimental ones. Neutron energy region was extended to 10^{-5} eV ~ 20 MeV. So that, the new recommended data would be more reasonable, reliable and usable in comparison with the former[1].

1 ANALYSIS EVALUATION

1.1 Total Cross Section

4 keV~ 20 MeV, the data is based on EXFOR10515 and EXFOR20010. As there are too many points of data, only some of them were selected.

10^{-5} eV~4 keV, based on Moxonand[2], Koester[3] and taking account of capture cross section changing as $1/v$, a average value of elastic cross section was obtained. It is a constant in this energy region. Then the total cross section was deduced, as shown in Fig. 1.

1.2 Elastic Cross Section

There are a few experimental data of total and differential elastic cross section before 1978, and no new data have been found after that time. A set of differential elastic cross section was given by theoretical calculation. The elastic cross section was obtained by subtracting the nonelastic cross section from the total cross section.

1.3 Nonelastic Cross Section

Only one set of new experimental data has been published since 1978. It is in agreement with the data measured previously. The sum of all nonelastic reaction channels was taken as the recommendation of nonelastic cross section, as shown in Fig. 2.

1.4 (n,p) Cross Section

Some new experimental data have been found. But there are obvious differences amoung them and no information of error was given, so they are not adopted, and the data of ENDF / B–5[4] was adopted in our evaluation.

1.5 (n,t) Cross Section

Qaim[5] has measured the (n,t) cross section for four energy points in energy range 16~ 19 MeV with error ~8%. Our recommendation from theoretical calculation is in a good agreement with them, as shown in Fig. 3.

1.6 (n,α) Cross Section

There are two evaluations[4,6] supported by experimental data. On account of consistency of format, the data of ENDF / B–5[4] was selected as our recommendation. It is noticed that Kneff's value at 14.8 MeV is by ~26% higher than the recommendation. It remains to be proved.

1.7 (n,γ) Cross Section

The data of ENDF / B–5[4] was adopted in our evaluation. It would be pointed out that, although the recommended value at the thermal energy agrees well with experimental results, but at ~14 MeV the recommended value (36 μb) is much less than experimental data (420 μb)[7]. However both are rather small. It needs to be improved in future.

1.8 (n,2n) Cross Section

The recommendation was obtained by combining the experimental data and the theoretical calculation, as shown in Fig. 4.

1.9 The Others

(n,n′), (n,d) and (n, ^{3}He) cross section, angular distribution and spectra of secondary neutron were taken from the theoretical calculation, as shown in Figs. 3 and 5.

2 THEORETICAL CALCULATION

First the program AUJP–1[8] was used to adjust automatically the optical model parameters according to the experimental data of total, nonelastic and differential elastic cross sections. Then the cross section, angular distribution and spectra of secondary neutron were calculated by using the program MUP–2[9]. Most of the results are satisfactory. But some of the results are in disagreement with experimental data, especially (n,p), (n,α) and (n,2n). The improvement could be expected from using the program MUP–3 in the near future.

3 CONSISTENCY TREATMENT

In order to meet the consistency of the data in physics, (n,p), (n,d), (n,t), (n,α), (n,n′), (n,2n), (n,np), (n,nd) and (n,nα) cross sections were recommended respectively. The sum of them was taken as nonelastic cross section. It is in good agreement with the experimental data. The elastic cross section was obtained by subtracting the nonelastic cross section from the total cross section.

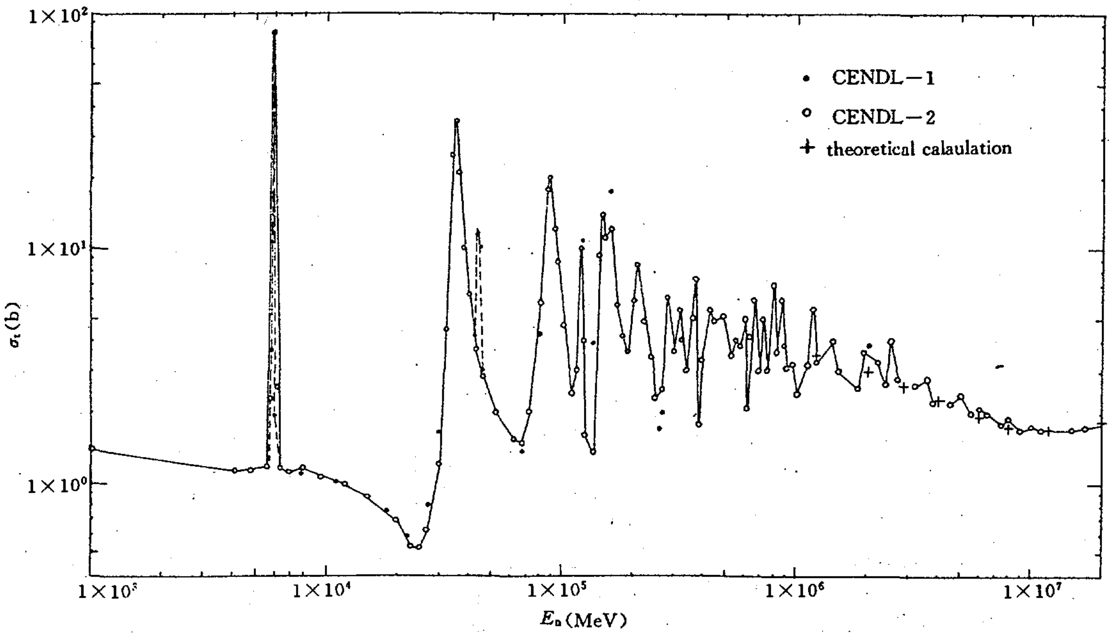

Fig. 1 Total cross section

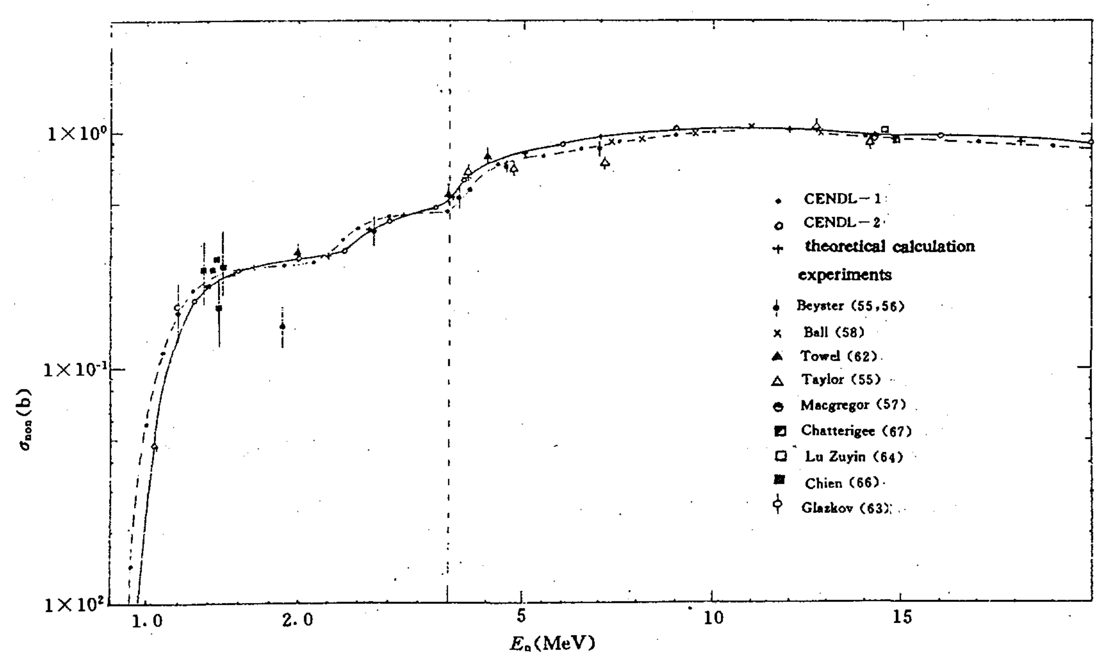

Fig. 2 Nonelastic cross section

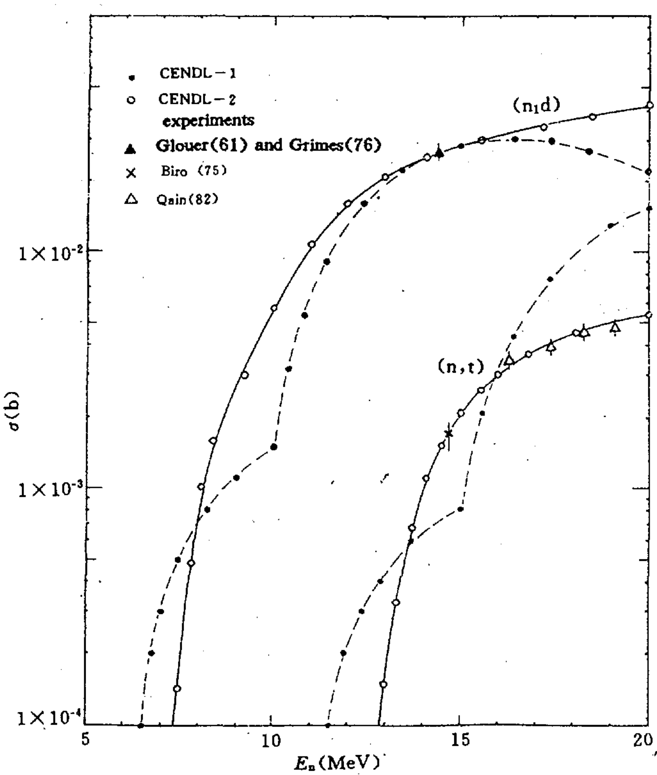

Fig. 3 (n,d), (n,t) cross section

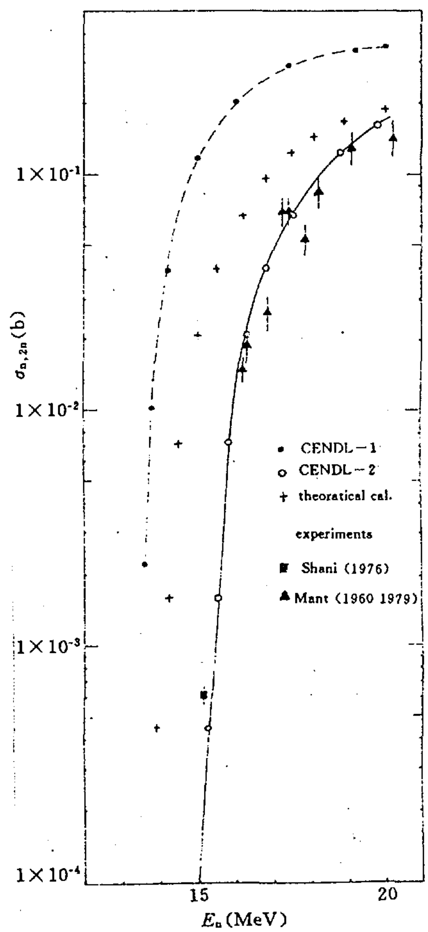

Fig. 4 (n,2n) cross section

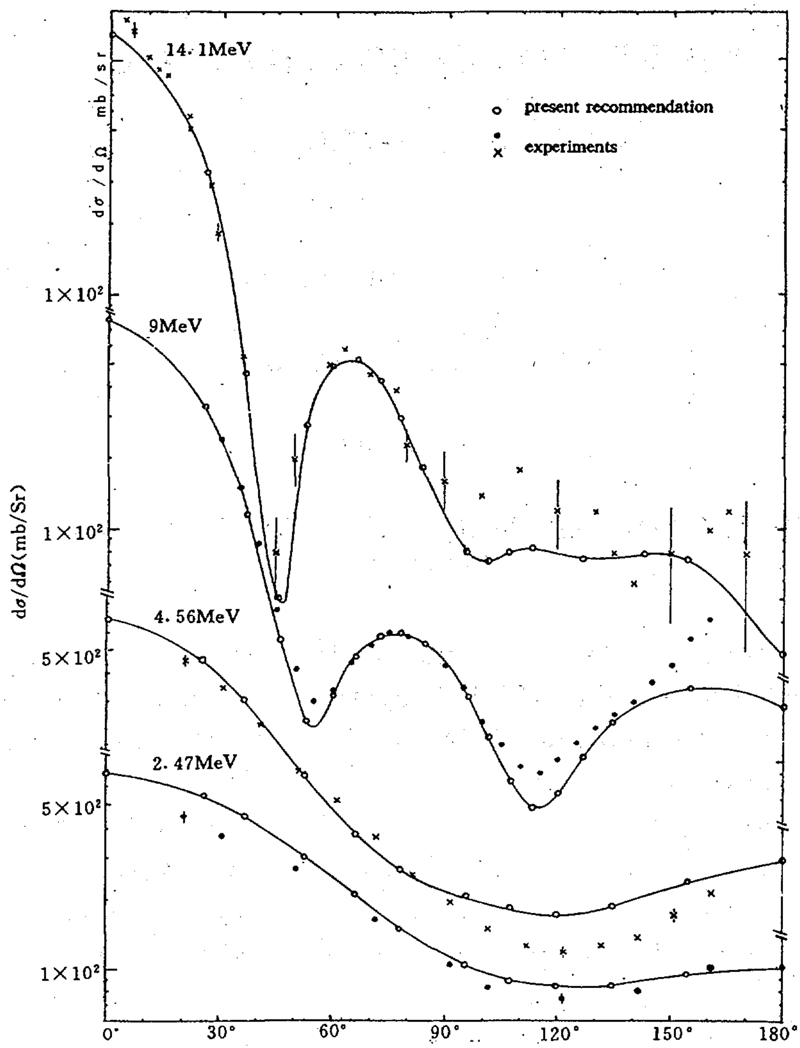

Fig. 5 Differential elastic cross section

REFERENCES

[1] CNDC, Collection of Evaluation Nuclear Data, Atomic Energy Press, 1978

[2] M. C. Moxon et.al., AERE–PR / NP–20

[3] L. Koester et. al., ZP / A, 292, 95(1979). or EXFOR 21676.003

[4] P. G. Young, D. G Foster, Jr., ENDF / B–5, MAT6313

[5] S. M. Qaim, EXFOR21837.002(1983)

[6] IAEA, Nuclear Data Standards for Nuclear Measurements, TRS No. 227, 59

[7] M. Budner et. al., EXFOR 30532.004(1980)

[8] Zhou Hongmo et.al., Matterials of AUJP–1 Test Meeting, 1986

[9] Cai Chonghai et.al., Matterials of MUP–2 Test Meeting, 1986

RE–RECOMMENDATION FOR NATURAL SILICON

Tang Guoyou Shi Zhaomin

(IHIP. PEKING UNIVERSITY)

Cai Chonghai

(PHYSICS DEPARTMENT, NANKAI UNIVERSITY , TIANJIN)

We have been reevaluated natural Si data. Main advancement of our re–recommended data is that MUP2 program [1] was used to calculate every channel cross section, and (n,n′p), (n,n′α), (n,2α) re action channels were divided from (n,p), (n,α) reactions.

Besides total cross section, radiative capture cross section (n,p) reaction cross section, (n,α) reaction cross section and the elastic scattering angular distribution, all other cross sec tion, angular distribution of secondary neutron and energy distribution of secondary neutron were calculated data by MUP2 program.

1 TOTAL CROSS SECTIONS (MT = 1)

Recommended data were based on measured data by M. Adib[2], W. Larson[3], R. B. Schwarz[4].

2 RADIATIVE CAPTURE CROSS SECTIONS (MT = 102)

The thermal cross section (0.166 b) was the measured data of L. Koester[5] and A. M. Spits[6]. From 0.00254 eV to 20 keV data were got based on $1/v$ law. For 30 keV, 65 keV, 14 MeV data were taken from measured data of R. L. Macklin[7], F. Rigaud[8], F. Cvelbar[9].

Other data were taken from theoretical calculation by MUP2 and normalized to measured data.

3 (n,p) REACTION CROSS SECTION (MT = 103)

Threshold to 9 MeV data were the measured data of J. B. Marion [10], B. Mainsbridge[11], R. Bass[12], A. M. Ghose[13], M. Herman[14]. Jeronymo [15], J. Sight[16].

From 9 MeV to 20 MeV data were calculated by MUP2 based on preequilibrium statistical.

4 (n,α) REACTION CROSS SECTION (MT = 107)

Threshold to 9 MeV data were based on the measured data of M. Birk[17], B. Mainsbridge[20], M. Herman[14], U. Garuska[18]. From 10 MeV to 20 MeV data were calculated by MUP2.

5 ELASTIC SCATTERING ANGULAR DISTRIBUTION (MF = 4, MT = 2)

0.5 MeV to 3.0 MeV data were taken from the measured data of W. E. Kinney[19], 3.0 MeV to 12 MeV from H. H. Knitter[20], D. M. Drake[21], S. Tanaka[22], W. E. Kinney[19], J. Bandenberger[23], W. Pilz[24], D. Velkley[25], 14.0 MeV data from S. Kliczewski[26], and 20 MeV data was taken from data of J. Rapaport[27].

15 MeV to 19 MeV data calculated by AUJP[1]. Our recommended data of some cross sections are compared with ENDF / B–6, JENDL–3, shown in Figs. 1~5.

ACKNOWLEDGMENTS

Much thanks for Chinese Nuclear Data Center, from which we got some finan cial and technical support.

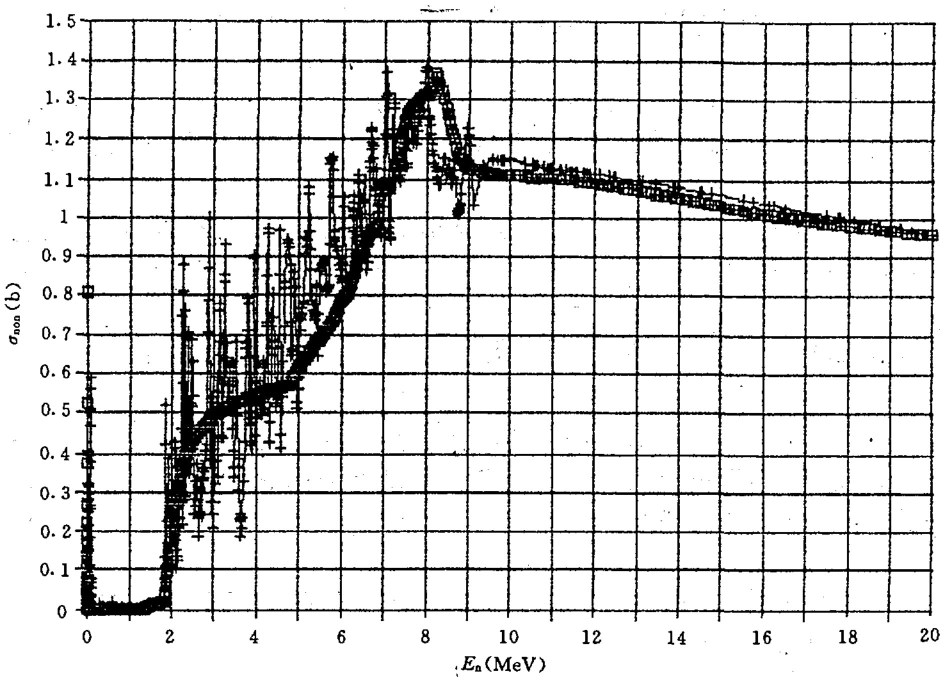

Fig. 1 Si nonelastic scattering cross section

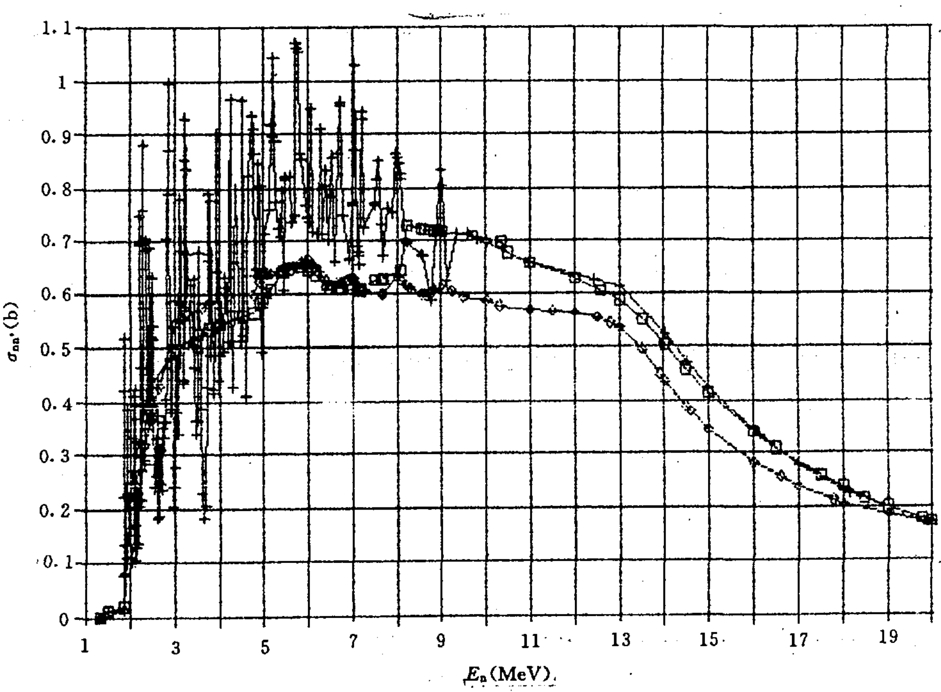

Fig. 2 Si(n,n′) cross section

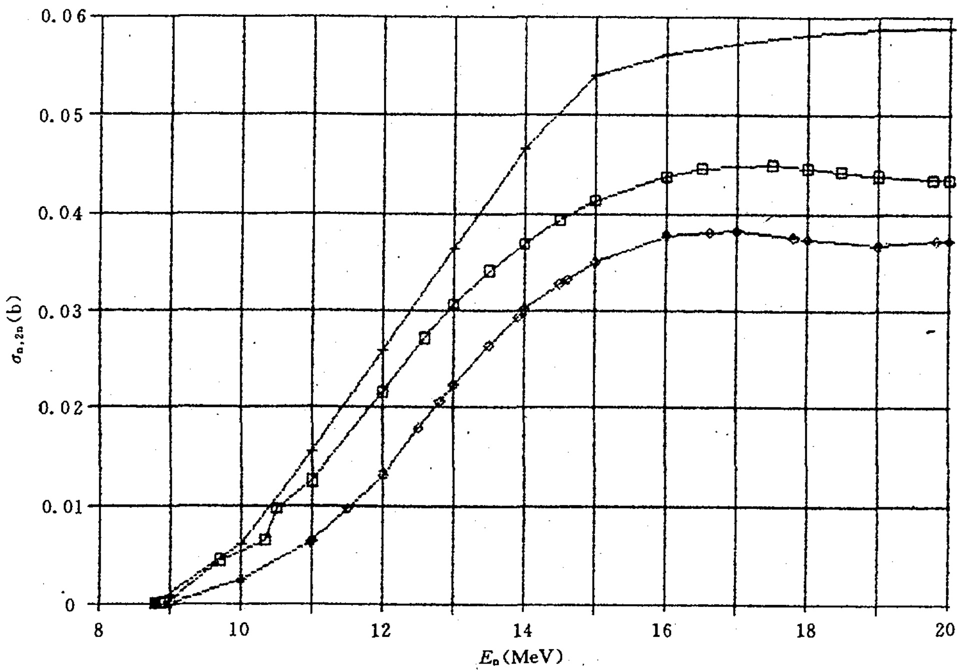

Fig. 3 Si(n,2n) cross section

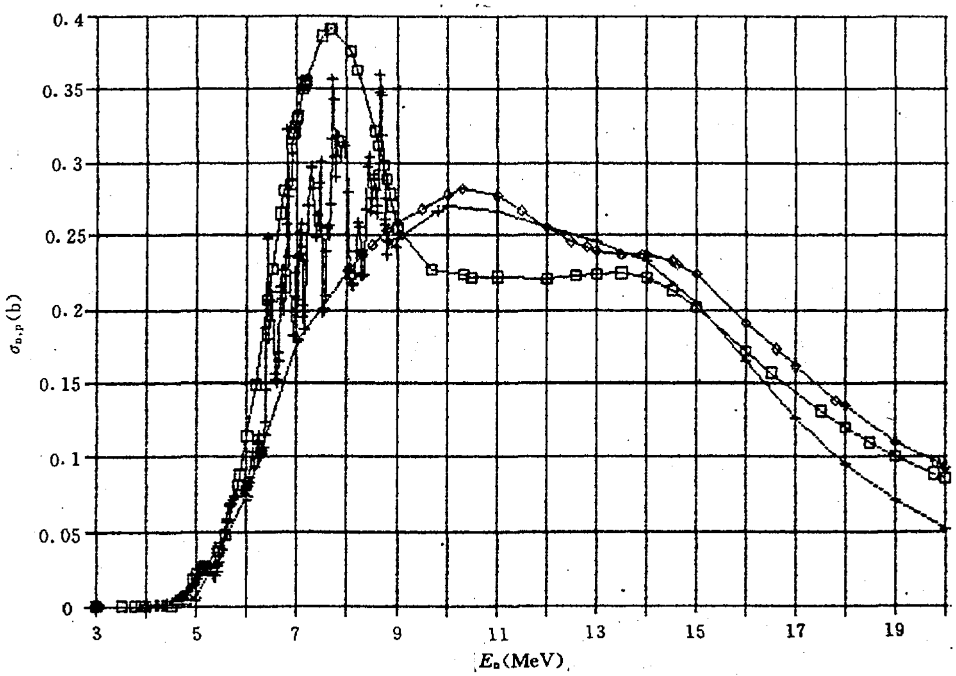

Fig. 4 Si(n,p) cross section

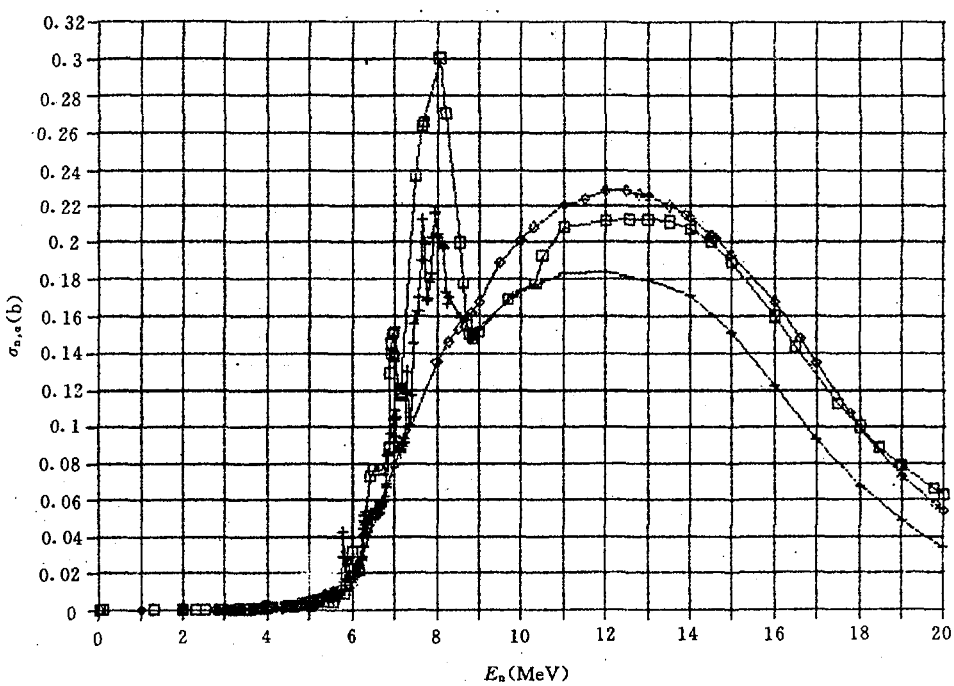

Fig. 5 Si(n,α) cross section

REFERENCES

[1] Cai Chonghai, Yu Ziqiang, Internal report of Nankai University for MUP2 program

[2] M. Adib et al., Atomkerenergie 27 (2), 117(1976)

[3] D. C. Larson et al., ORNL / TM–5618(1976)

[4] R. B. Schwartz et al., BAP, 16,495(1971)

[5] L. Koester et al., ZP / A, 289(4), 399(1979)

[6] A. M. Spits et al., NP / A, 224, 517(1974)

[7] R. L. Macklin et al., PR, 129, 2695(1963)

[8] F. Rigaud et al., NP / A, 154, 243(1970)

[9] Cvelbar et al., NP / A, 138, 412(1969)

[10] J. B. Marion et al., PR, 101, 247(1956)

[11] B. Mainsbridge et al., NP, 48, 83(1963)

[12] Bass et al., EANDC (E) 66, 64

[13] A. M. Ghose et al., IAEA / TA–1390, 7810

[14] M. Herman et al., INR–1871 / I / PL / A, 13, 8007

[15] Jeronymo et al., NP, 47, 157(1963)

[16] J. Sight et al., BAP, 15, 1328(1970)

[17] M. Birk et al., NIM, 21, 197(1963)

[18] U. Garuska et al., P,INR–1773 / I / PL / A, 16, 7809
[19] W. E. Kinney et al., 76, LOWELL, 2, 1319, 7607
[20] H. H. Knitter et al., ZP, 207, 56(1967)
[21] D. M .Drake et al., NP / A, 128, 209(1969)
[22] S. Tanaka et al., 70, HELSINK, 2, 317(1969)
[23] J. Bandenberger et al., NP / A, 196, 65(1972)
[24] W. Pilz et al., NIM, 169, 533(1980)
[22] D. Velkiey et al., PR / C, 9, 2181(1974)
[26] S. Kliczewski et al., NP / A, 304, 269(1978)
[27] J. Rapaport et al., NP / A, 286, 232(1977)

EVALUATION OF NEUTRON REACTION DATA OF NATURAL SULFUR

Shi Yi Liu Shengkang Zhou Yongyi

(DEPARTMENT OF PHYSICS, NANJING UNIVERSITY)

Complete neutron data evaluation has been finished for natural sulfur in the incident neutron energy range from 10^{-5} eV to 20 MeV. Measured data up to 1985 were collected and fitted with spline function after careful analyses. The theoretical calculations were performed with code MUP–2, which was based on the optical model, the Hauser–Feshbach theory with width fluctuation correction and the unified treatment of exciton model and evaporation model, the neutron optical potential parameters were adjusted by means of code AUJP. The complete evaluated data were checked in physics and format.

There are four isotopes of element sulfur, ^{32}S, ^{33}S, ^{34}S and ^{36}S. Both the abundances of ^{33}S and ^{36}S are less than 0.01 and their contributions were attributed to isotope ^{32}S.

1 RESONANCE PARAMETERS

The resolved resonance parameters for isotope ^{32}S up to 1.092 MeV were based on the data of Jungmann[1], with supplement of the data of Halperin[2], and for isotope ^{34}S, Carlton's[3] data were adopted up to 1.017 MeV. Negative resonance parameters were determined according to the thermal cross sections given by Mughabghab[4].

2 NEUTRON CROSS SECTION

2.1 Total Cross Section

There are a large number of experimental data for the total cross section of sulfur. More than 40 of them were collected in this evaluation. The data carefully measured by Cierjacks[5] were recommended in the energy range from 1.092 to 5 MeV. Above 5 MeV, 14 experimental data were selected and the spline function fitted curve of these data was recommended (Fig. 1).

2.2 Elastic Cross Section

The elastic cross sections measured by 30 authors were collected in the energy region 0.05~20 MeV, most of which were merely given in differential cross sections. These data were used to adjust the optical potential parameters. The recommended elastic scattering cross sections were given by the difference of the total cross section and the nonelastic cross section (Fig. 2).

2.3 Nonelastic Cross Section

There were only five sets of measured data for nonelastic cross section at 2.5, 7 and 14 MeV. Those data were used for adjusting the optical model parameters. The recommended nonelastic cross section is the sum of the cross sections of all nonelastic channels.

2.4 Inelastic Cross Section

Most of the experimental data were measured for the inelastic scattering to excitation energy of 2.23 MeV. These data were fitted to give the recommended curve of the first excitation energy level. For the inelastic to other 22 discrete energy levels and to the continuum, the theoretical data were used due to the lack of experimental data. Total inelastic cross section is the sum of all the partial inelastic cross sections.

2.5 (n,2n) Cross Section

The carefully measured data of Bormann[6] and Arnold[7] for ^{32}S were fitted and recommended, and theoretical results were adopted for ^{34}S.

2.6 (n,n′α), (n,n′p) Cross Section

Theoretical calculation was used as recommended ones for (n,n′α) of natural sulfur and (n,n′p) of ^{34}S, due to the lack of experimental data. For ^{32}S, the calculated (n,np) cross section was about double of the experimental data of Allan[8] and Antolkovic[9] at 14 MeV. Thus the theoretical curve were normalized to the experimental data and recommended.

2.7 (n,p) Cross Section

For ^{32}S, due to the complex structures in 2~5 MeV energy region, experimental data of Allan(1957) and Hurllman(1954) were used. Above 5 MeV, spline function fitting was done based on a number of experimental data. Theoretical results were well consistent with the experimental data such as Rormann'[10] and used for recommendation.

2.8 (n,t) Cross Section

There are 9 measurements of ^{32}S (n,t) cross section, all of which are given at one energy point around 14 MeV except that of Bormann[10], who measured in energy region from 14.0 to 19.6 MeV. The calculated data are in good agreement with the experimental data and the latter is used for recommendation. Calculated data were adopted for ^{34}S due to the lack of measurement.

2.9 (n,α) Cross Section

From 1.3 to 4 MeV, experimental data measured by Schmitt[11] and Hurlimann[12] were recommended with structure remained and theoretical results are adopted in other energy regions for ^{32}S. For ^{34}S, experimental data were used in 4.5~14 MeV energy region and theoretical results were used above 14 MeV.

2.10 Capture Cross Section

There are 3 measurements of capture cross section, two of which are at 14 MeV, while Lindholm[13] measured from 3 to 15 MeV. The theoretical results agree well with the experiments below 14 MeV, but dropped rapidly in higher energy. The theoretical data were recommended in present evaluation.

3 SECONDARY NEUTRON ANGULAR DISTRIBUTION

3.1 There are 30 measurement data of the angular distribution for the elastic scattering in the energy range from 0.05 to 20 MeV, the theroretical results are consistent well with these data and used for recommendation (Fig. 3).

3.2 Isotropic angular distributions of (n,2n), (n,n'α), (n,n'p) and inelastic continuum were assumed.

3.3 Angular distributions of inelastic scattering to 23 discrete levels were taken from theoretical calculation.

4 SECONDARY NEUTRON ENERGY DISTRIBUTIONS

Secondary neutron energy distributions for the inelastic continuum, (n,2n), (n,n') and (n,n'p) reactions were taken from theoretical calculation.

The present evaluation is compared with ENDF / B–5. Total cross section, inelastic cross sections and ^{32}S (n,n'p) cross section of present evaluation are almost the same as those of ENDF / B–5. The charged particle emitted reaction cross sections, such as (n,p), (n,t), (n,α) of ^{32}S and (n,α) of ^{34}S are not much difference with that recommended in ENDF / B–5. But new experimental data of resonance parameters were used so that the present recommended data are more accurate and complete than those of ENDF / B–5, e. g. the highest resonance energy is extended to 1.017 MeV and much higher than that in ENDF / B–5.

The authors would like to thank Drs. Cai Dunjiu, Liu Tingjin and Cai Chonghai for their great help in theoretical calculation and data evaluation.

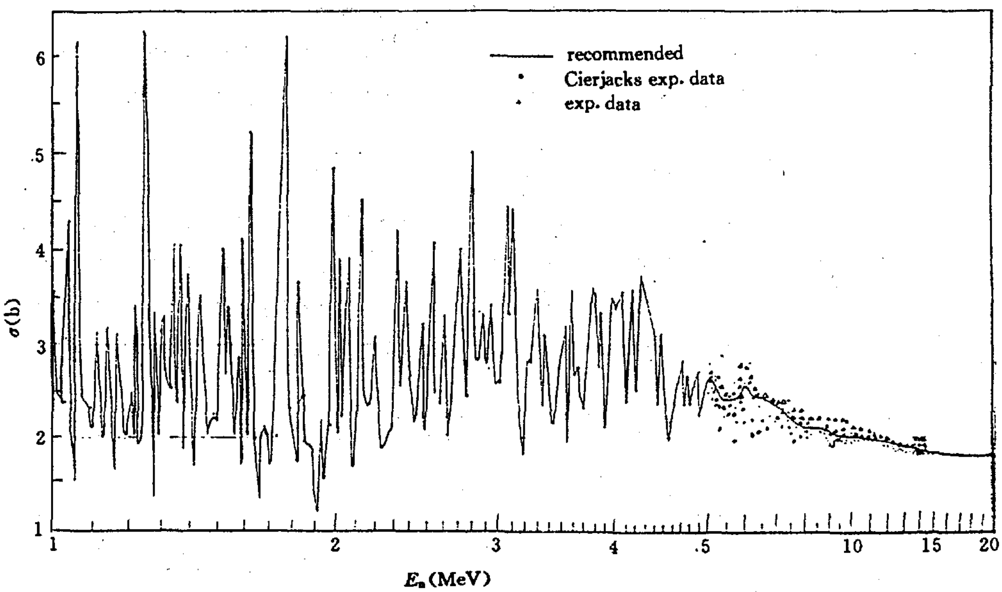

Fig. 1 Total cross section

—— recommended • Cierjacks exp. data ▲ exp. data

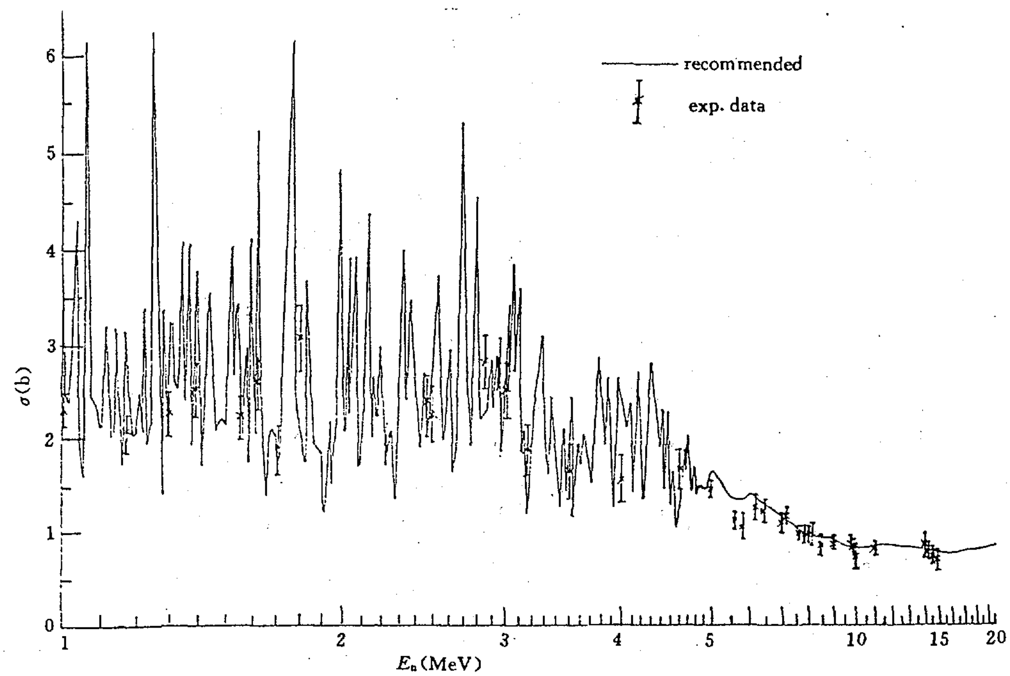

Fig. 2 Elastic scattering cross section

——— recommended ɸ exp. data

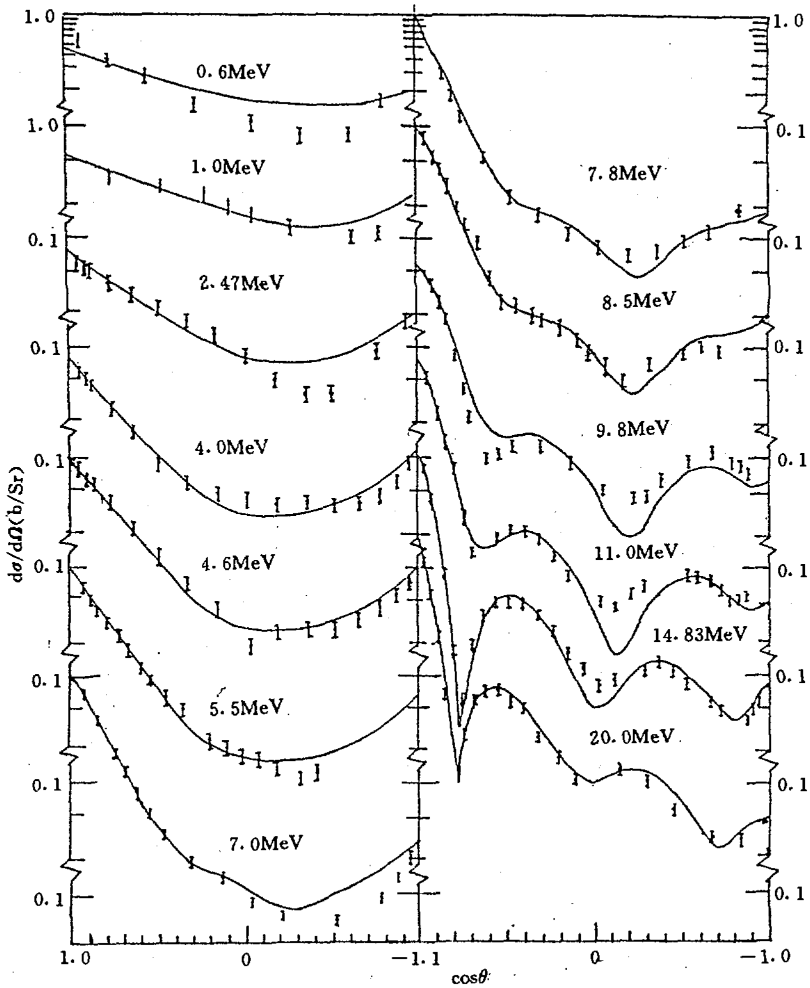

Fig. 3 Elastic scattering differential cross section

—— recommended ♦ exp. data

REFERENCES

[1] C. R. Jungmann et al., Nucl. Phys., A386, 287(1982)
[2] J. Halperin et al., Phys. Rev., C21, 545(1980)
[3] R. F. Carlton et al., Phys. Rev., C29, 1980(1984)
[4] S. F. Mughabghab et al., Neutron Cross Section Vol. 1, Part, A(1980)
[5] S. Cierjacks et al., KFK–1000(1968)
[6] M. Bormann et al., EANDC (E)–66, 42(1966)
[7] W. Arnold et al., J. DA., 26, 3425(1965)
[8] D. L. Allan, Nucl. Phys., 24, 274(1961)
[9] B. Antolkovic, Nucl. Phys., 44, 123(1963)
[10] M. Bormann et al., Conf. 66 Paris, 1, 255(1967)
[11] H. W. Schmitt, Bull. Amer. Phys. Soc., 3, 37(1958)
[12] T. Hurtlmann et al., Helv. Phys. Acta., 28, 33(1954)
[13] A. Lindholm, Nucl. Phys., A279, 445(1977)

EVALUATION OF NEUTRON REACTION DATA OF NATURAL POTASSIUM

Han Min Zhou yongyi

(DEPARTMENT OF PHYSICS, NANJING UNIVERSITY)

Complete neutron data evaluation has been finished for natural potassium in the 10^{-5} eV to 20 MeV incident neutron energy region. Experimental data up to 1988 were collected and fitted with spline function after careful analyses. The theoretical calculations were performed with code MUP–2, which is based on the optical model, the Hauser–Feshbach theory with width fluctuation correction and the unified treatment of exciton model and evaporation model. The neutron optical parameters were adjusted by means of code AUJP. The complete evaluation data were checked in physics and format.

There are three isotopes of element potassium, ^{39}K, ^{40}K and ^{41}K, with abundances of 93.26%, 0.0117% and 6.7% respectively. The contributions of isotope ^{40}K were attributed to ^{39}K for its much lower abundance. Just as ENDF / B–4, 5, no resonance parameters were given in present evaluation, because of the less accuracy of measured results, although the resolved resonances exist up to 200 keV. The recommended neutron cross sections in 0.1 ~ 20 MeV energy region is shown in Fig. 1.

1 NEUTRON CROSS SECTION

1.1 Total Cross Section

The total cross section was very poorly measured up to 0.01 eV and between 10 eV and 1 keV, so the sum of (n,p)+(n,α)+(n,γ)+(n,n) was recommended. From 0.01 to 10 eV the data measured by Joki(1955)[1] was smoothed and used. The up–to–date careful measurements of Singh(1973)[2] and Cierjacks(1969)[3] were recommended from 1.0 to 360 keV and between 360 keV and 1.6 MeV, respectively. All structures were retained. Above 3.6 MeV, there are a lot of experimental data, and the present recommended curve was obtained from the fitting of the data of 8 authors : Foster(1971)[4], Johnson(1962)[5], Reber(1967)[6], Coon(1952)[7], Cierjacks(1969)[3], Guarrini(1968)[8], Angeli(1968)[9] and Bacon(1967)[10] (Fig. 2).

1.2 Elastic Scattering Cross Section

The elastic cross section in present evaluation was obtained from the difference between total cross section and nonelastic cross section. There are no available measured data up to 0.3 MeV. Above 0.3 MeV, the recommended data are consistent with the experimental data of Langsdorf(1975)[13], Reber(1967)[6], Frasea(1966)[15], Towle(1965)[16], Kent(1962)[17], Korzh(1963)[14] et al. (Fig. 3).

1.3 Nonelastic Cross Section

There are only five experimental data with poor accuracy for this cross section. These data were corrected and adjusted according to the sum of all the reaction cross sections and used to adjust the optical potential parameters. The recommended nonelastic cross section was obtained from the sum of all the nonelastic channels (Fig. 3).

1.4 Inelastic Cross Section

There are limited measurements for the first 4 exciting levels (E_x = 2.52, 2.81, 3.02, 3.60 MeV) of ^{39}K and for the first 2 exciting levels (E_x = 0.978, 1.291 MeV) of ^{41}K, with incident neutron energy range from threshold (1.0058 MeV) to 4.0 MeV (Fig. 4). Partial cross sections of inelastic scattering up to 30th exciting states and to the continuum were recommended for natural K. Theoretical results were used and the lst, 2nd, 12th, 17th, 18th and 21th excitation cross sections were normalized to Lind's(1961)[18] experimental results below 4 MeV. For the total inelastic cross section, experimental data measured by Lind(1961)[18], Towle(1965)[16], and Nichol(1968)[20] were used from threshold to 4.0 MeV, and theoretical result was adjusted to fit the experimental results of Lind(1961)[18] at 4.0 MeV and of Towle(1967)[21] at 7.0 MeV and was taken as recommended data for the energy region above 4.0 MeV.

1.5 (n,2n) Reaction Cross Section

Two smooth curves corresponding to $^{39}K(n,2n)^{38g}K$ and $^{39}K(n,2n)^{38m}K$ were fitted to the experimental results of 16 authors[22~38] respectively. The $^{39}K(n,2n)^{38}K$ cross section was the sum of the two partial cross sections. Theoretical curve was used for $^{41}K(n,2n)^{40}K$ due to the lack of measurement (Fig. 5).

1.6 (n,nα) Reaction Cross Section

For ^{39}K, theoretical result normalized to the experimental data of Bormann[40] was used from threshold to 12.0 MeV. Above 12.0 MeV, a smooth curve was fitted to Bormann's data. Theoretical data were used for ^{41}K due to the lack of measurements.

1.7 (n,np) Reaction Cross Section

This cross section was obtained from theoretical result normalized to Foland's[39] experimental data at 14 MeV region.

1.8 Capture Cross Section

Up to 1.0 keV, the capture cross section is $1/v$ variation with 1.93 b at energy 2200m / s. From 1.0 to 120 keV, the cross section was obtained from a resolved resonance calculation based on two sets of resonance parameters of Macklin[41] and Mughabghab[42]. Above 120 keV, theoretical result, which agreed with Stupenia's[43] experimental data, was used.

1.9 (n,p) Cross Section

For ^{39}K, up to 300 keV, the (n,p) cross section is $1/v$ variation with 0.051 b at energy 2200m / s (taken from ENDF / B–4). From 300 keV to 1 MeV, theoretical result was used. Above 1 MeV, curve was obtained from fitting Bass's[45] experimental data till 8 MeV and Foland's[39] data at 14 MeV region. The structure between 1.4 and 3 MeV was retained. Smooth curve was also obtained from fitting experimental data of 9 authors including Bass[45] for ^{41}K.

1.10 (n,α) Cross Section

Up to 750 keV, the cross section was taken according to $1/v$ law with value of 0.004 b at energy 2200m / s taken from Mughabghab[42]. Above 750 keV, (n,α_0) data till 8 MeV[44] and (n,α) data[46] at 14 MeV measured by Bass[45] as well as (n,α) data measured by Bormann[12] between 12 and 14 MeV, together with theoretical result in 8~ 12 MeV and 14~ 20 MeV were used for ^{39}K. Measured data of 9 authors including Bass[45] were used for ^{41}K. A smooth curve was got by fitting these data.

1.11 (n,d), (n,t), (n, ^{3}He), (n,3n), (n,nd), (n,nt) Cross Section

Theoretical results were used for them due to the lack of measurements.

2 SECONDARY NEUTRON ANGULAR DISTRIBUTION

2.1 Theoretical results were used for the elastic scattering angular distributions. The optical potential parameters were adjusted to make the angular distributions agree with the experimental data of Reber[6], Frasca[15], Towle[16], Kent[17], Korzh[14] and Popov[11] (Fig. 6).

2.2 Isotropic angular distribution of (n,2n), (n,n′α), (n,n′p) and inelastic continuum were assumed.

2.3 Angular distributions of inelastic scattering to 30 discrete levels were taken from theoretical calculation.

3 SECONDAY NEUTRON ENERGY DISTRIBUTIONS

Secondary neutron energy distributions for the inelastic continuum, (n,2n), (n,n′α) and (n,n′p) reactions were taken from theoretical calculation.

4 CONCLUSION REMARKS

In our present work, some of the main cross sections such as total, elastic, (n,2n), (n,α) are well consistent with those of ENDF / B–5. However, some improvements have been made.

4.1 Our resolved resonance cross section region is given up to 120 keV, while those in ENDF / B–5 was lower than 10 keV, and in ENDL / 1983, smooth curve was used in whole energy region.

4.2 There are some important improvements for (n,nα), (n,np), and (n,p) cross sections in higher energy regions compared with ENDF / B–5. For example, the emitted proton spectra were not distinguished in ENDF / B–5, so that the (n,p) cross section is too large due to the inclusion of (n,n′p), while the (n,np) cross section was too small due to the exclusion of (n,pn).

The author would like to thank Drs. Cai Dunjiu, Liu Tingjin, Cai Chonghai and Liang Qichang for their great help in theoretical calculation and data evaluation.

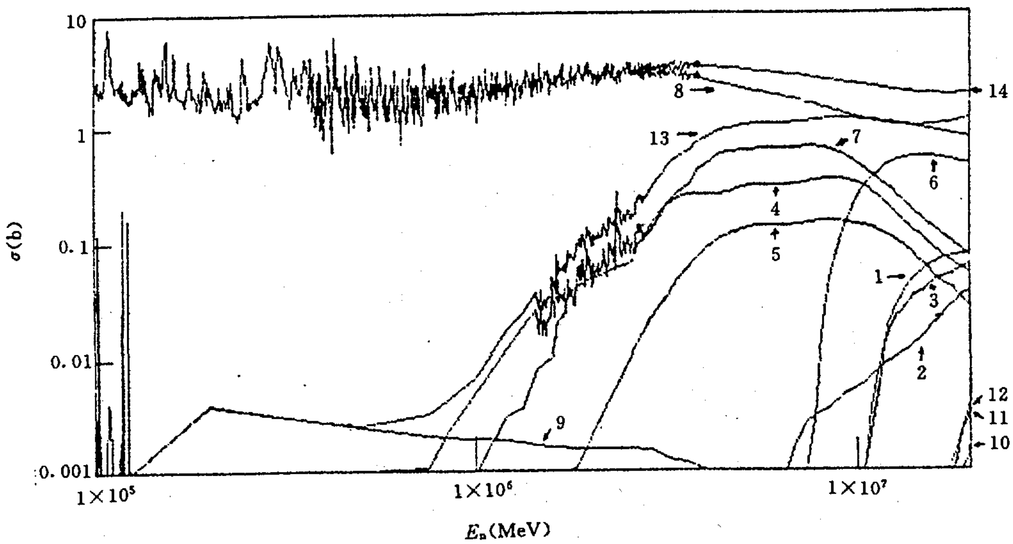

Fig. 1 Neutron cross sections of natural potassium

1. $\sigma_{nn'\alpha}$, 2. σ_{nd}, 3. σ_{n2n}, 4. σ_{np}, 5. $\sigma_{n\alpha}$, 6. σ_{nnp}, 7. σ_{inl}

8. σ_{el}, 9. $\sigma_{n\gamma}$, 10. σ_{nnd}, 11. σ_{nt}, 12. σ_{n^3He}, 13. σ_{non}, 14. σ_{tot}

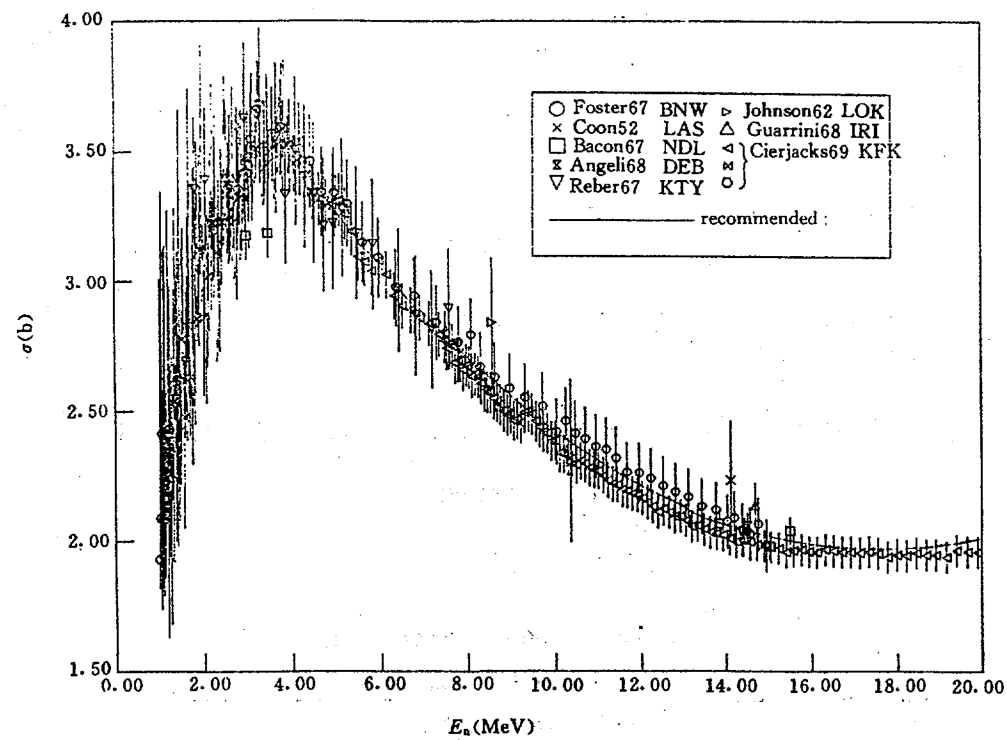

Fig. 2 Total cross sections

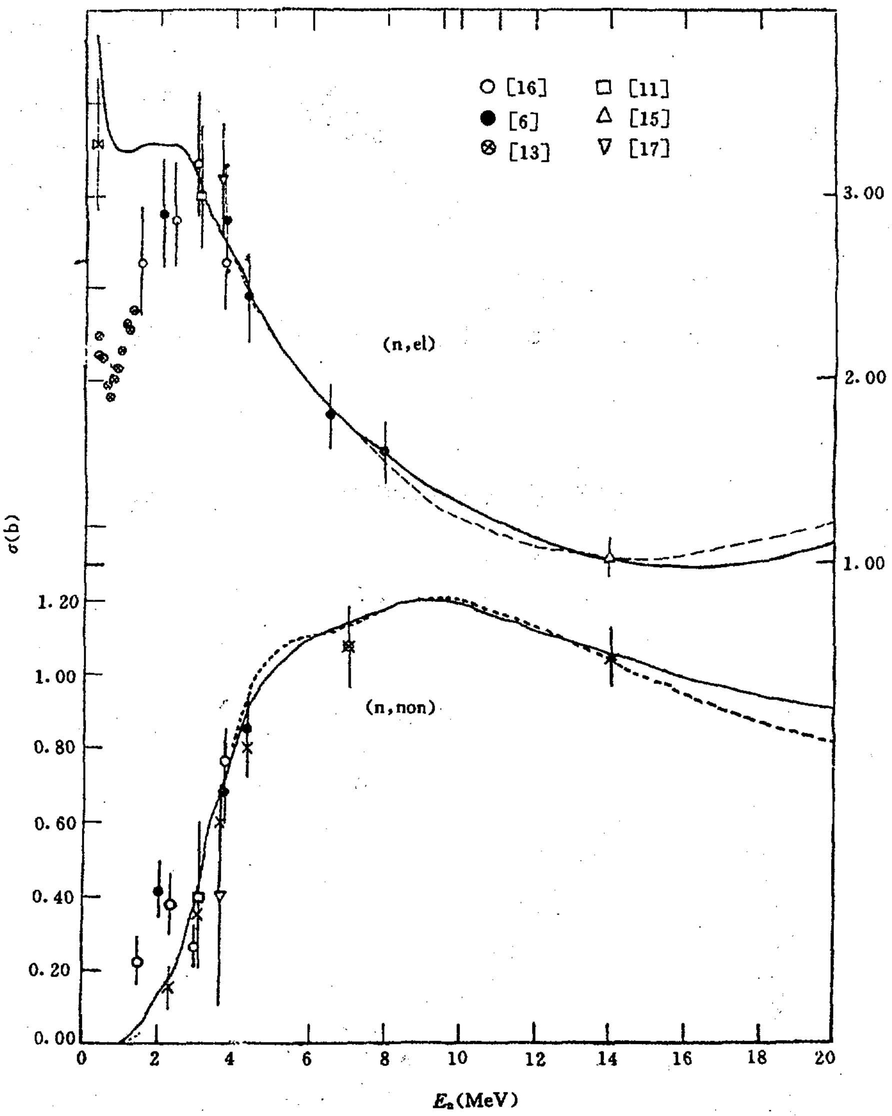

Fig. 3 Elastic and nonelastic cross sections

——— theorectical calculation

- - - recommended

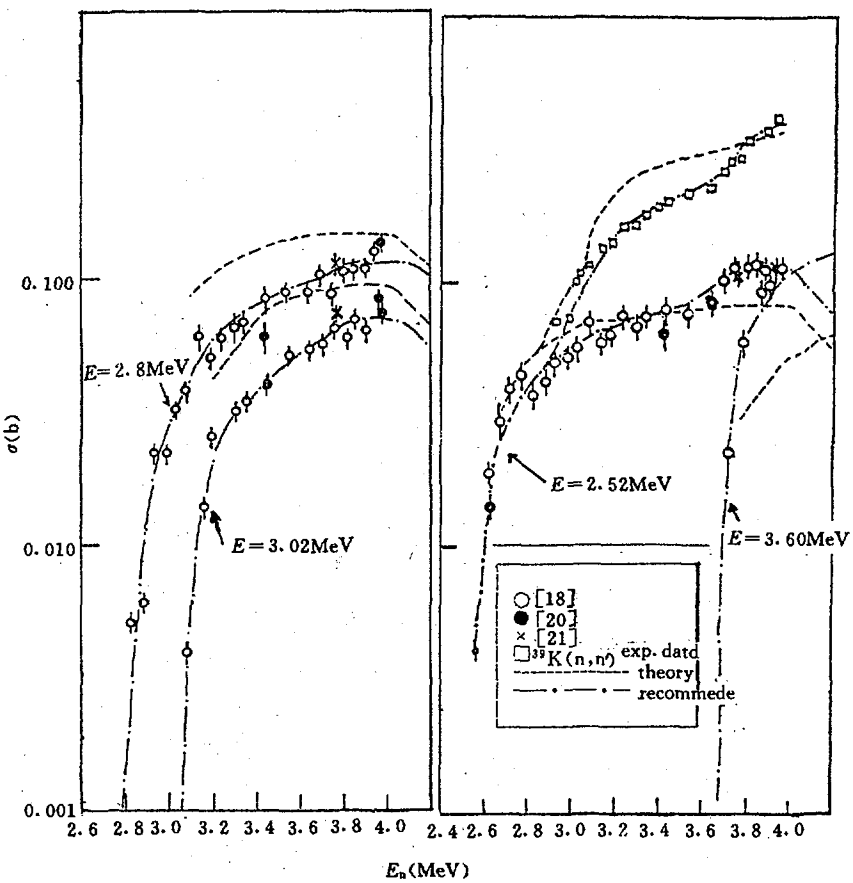

Fig. 4 Discrete level inelastic cross sections

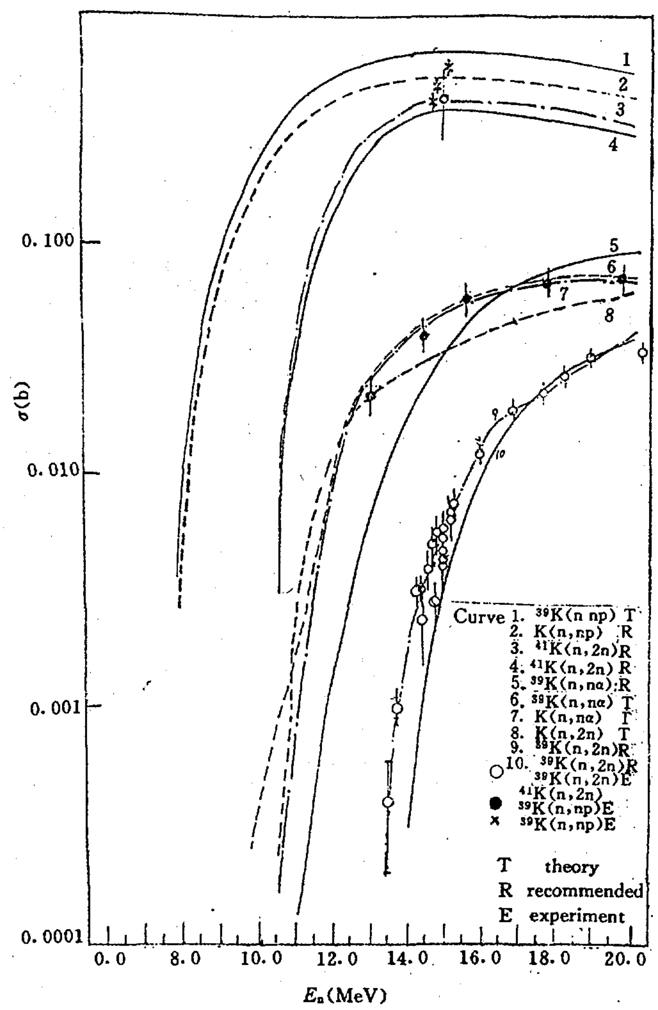

Fig. 5 (n,2n) cross sections

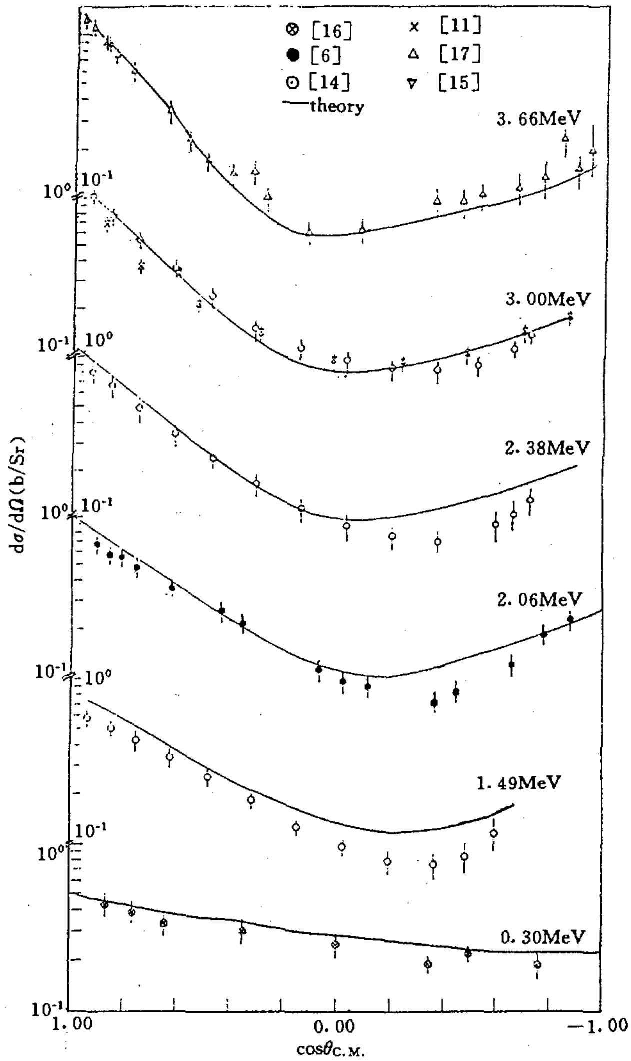

Fig. 6 (1) Elastic scattering differencial cross sections

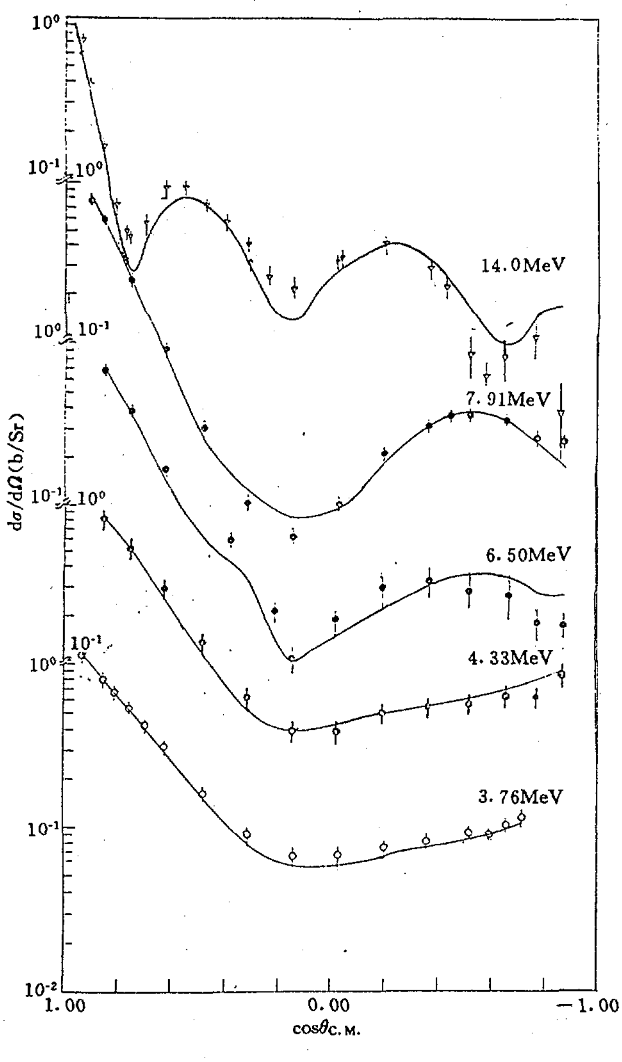

Fig. 6 (2) Elastic scattering differencial cross sections

REFERENCES

[1] Joki. E. G., Phys. Rev., 99, 610(1955)
[2] Singh. U. N., Phys. Rev., C8, 1883(1973)
[3] Cierjacks S. Report KFK−1000, (Supp. 2) (1969)
[4] Foster D. G., Phys. Rev., C3, 576(1971)
[5] Johnson R. G., Report IMSC−4−50−62−1, 22(1962)
[6] Reber. J. D., Phys. Rev., 1673, 1077(1967)
[7] Coon. J. H., Phys. Rev., 88, 562(1952)
[8] Guarrini. F., Nucl. Sci. & Eng., 31, 341(1968)
[9] Angeli. I., Nucl. Phys., A119, 525(1969)
[10] Bacon. E. G., Nucl. Sci. & Eng., 28, 293(1967)
[11] Popov. V. I. Sov. Progr. In Neutr. Phys., New York(1961)
[12] Bormann. M., Z. Maturforsch., A15, 200(1960)
[13] Langsdorf A., Phys. Rev., 107, 1077(1957)
[14] Korzh. I. A., J. UFZ., 8, 1389(1963)
[15] Frasca. A., J. Phys. Rev., 144, 854(1961)
[16] Towle. J. H. et al., Nucl. Rev., 144, 854(1961)
[17] Kent. D. W., Phys. Rev., 125, 331(1962)
[18] Lind. D. A., Ann. Phys., 12, 485(1961)
[19] Cai C. H., Nankai Univ. Rep.(1985)
[20] Nichols D. B., Phys. Rev., 166, 1074(1968)
[21] Towle J. H., Nucl. Phys., A100, 257(1967)
[22] Strain J. E., Report ORNL−3072
[23] Rayburn L. A., J. Phys. Soc. Jap., 122, 168(1961)
[24] Valkinen M., JU−PR−1 / 1976
[25] Bormann M., Nucl. Phys., 63, 438(1965)
[26] Pasquarelli A. Nucl. Phys., A3, 218(1967)
[27] Bass R., EANDC (CE)−57U, 1(1965)
[28] Pepelink R., Nucl. Data for Basic & Applied Science, Santa Fe, p. 1211(1985)
[29] Misra S. C., BARC−693, 7(1973)
[30] Tiwari D. N., Phys. Rev., 167, 109(1968)
[31] Peto G., Act. Phys. Acodemice., 24, 93(1968)
[32] Araminowicz J., INR−1464, 14(1973)
[33] Shani G., INIS−MF−3663, 83(1976)
[34] Srinivasarao C. V., 78Bombay., 2, 113(1978)
[35] Khurana C. S., Nucl. Phys., 28, 560(1961)
[36] Bass R., EANDC (E)−57U, 1(1965)
[37] Janczyszyn J., J. of Radioanal. Chem., 14, 201(1973)

[38] Adam A., Nucl. Phys., 180, 587(1972)
[39] Foland K. A., Nucl. Sci. & Engineer, 95, 128(1987)
[40] Bormann M., Z. Naturforsch, A15, 200(1960)
[41] Macklin R. L., Nucl. Sci. & Engineer, 88, 129(1984)
[42] Mughabghab S. F., Neutron Cross Section, Vol. 1(1981)
[43] Stupegia O., J. Nucl. Energy, 22, 267(1968)
[44] Bass R., Nucl. Phys., 28, 478(1961)
[45] Bass R., EANDC (E)–57U, 1(1965)
[46] Bass R., Nucl. Phys., 56, 569(1964)

EVALUATION OF NEUTRON DATA FOR NATURAL TITANIUM

Yao Lishan

(INSTITUTE OF NUCLEAR RESEARCH,
LANZHOU UNIVERSITY)

ABSTRACT

The complete neutron nuclear data of natural titanium have been evaluated for CENDL–2 in neutron energy range from 10^{-5} eV to 20 MeV. Some of the data have been calculated by means of theoretical model. A good agreement is obtained with measured values. The recommended data are compared with JENDL–3 and ENDF / B–6.

INTRODUCTION

Natural titanium (Ti) consists of stable isotopes ^{46}Ti, ^{47}Ti, ^{48}Ti, ^{49}Ti and ^{50}Ti. The abundances of them are as 8.2, 7.4 73.8, 5.4 and 5.2 percent respectively. It's one of fission and fusion reactor structure materials. All reaction threshold energies of titanium with neutrons are given in Table 1.

The complete neutron nuclear data of natural titanium have been evaluated. The evaluated quantities include reaction cross sections (σ_{tot}, σ_{nn}, σ_{non}, $\sigma_{nn'}$, σ_{n2n}, σ_{n3n}, $\sigma_{n,\gamma}$, σ_{nx} (x = p, t, ^{3}He, d), $\sigma_{nn'x}$), angular and energy distributions of secondary neutrons etc.

1 RESONANCE PARAMETERS

In File 2, only a potential scattering radius is described. The resonance parameters of natural titanium haven't been included. The evaluated data of the resonance cross sections are given in the relative sections of File 3.

Table 1 Reaction threshold energies of Ti with neutrons

Reaction channels	Threshold energies (MeV)
n,n′	0.16282
n,2n	8.311
n,3n	19.466
n,p	(Q=0.1822)
n,t	10.965
n, ^{3}He	9.7209
n,d	8.2953
n,α	(Q=2.181)
n,n′ p	10.568
n,n′ t	> 20.0
n,n′ ^{3}He	18.782
n,n′ d	17.357
n,n′ α	8.1782
n,γ	(Q=8.5207)

2 REACTION CROSS SECTIONS

2.1 Total Cross Section

Below 200 keV, total cross section data were taken from the work of Trochon (77) [1]. In 200 keV to 5 MeV, recent data were mainly measured by Guenther (77) [2] from 0.944 to 4.371 MeV, with total errors 2.5 percent. In the work of Barnard(73) [3], besides total cross section , elastic scattering cross section was also given. The data measured by Foster(71) [4] were a good experimental results. It not only extended the measured energy range (2.253 to 14.864 MeV), but also improved the accuracy of measurement (1 to 3 percent). In addition, the data measured by Schwartz(73,74) [5] were also adopted. The evaluated results together with ENDF / B–6 are shown in Fig. 1. The evaluated curve of the JENDL–3 shows a complicated structure, the resonance parameters were in 10^{-5} eV to 100 keV. Above 5 MeV, the data measured by

Refs. [6~8] were also adopted, besides the work of Foster(71) [4]. The evaluated curve is shown in Fig. 2. From these results, it can be seen that the evaluated results between ours and JENDL–3 are well consistent. But, when $E_n > 10$ MeV, the evaluated data of ENDF / B–6 are higher than ours.

2.2 Elastic, Nonelastic and Inelstic Scattering Cross Sections

Elastic scattering cross sections are obtained by subtracting nonelastic scattering from the total cross sections. Above 5 MeV, the evaluated curve is also shown in Fig. 2. The evaluated results are well consistent with ENDF / B–6, and, it is seems to be improved compared with JENDL–3. For nonelastic scattering cross sections, experimental data were all measured in 50's. The recommended data are basically consistent with ENDF / B–6 (see Fig. 3). For inelastic scattering cross sections, the data of three works[9~11] were adoped. Because experimental data are insufficient, the sum of the discrete levels for Ref. [2] is used. The evaluated results are shown in Fig. 4 together with JENDL–3 and ENDF / B–6. The recommended data are taken from theoretical calculations with the model code.

2.3 (n,2n), (n,3n) Reaction Cross Sections

For (n,2n) reactions, the data were measured by Frehaut(80)[12] and Auchampaug(77)[13] systematically. In addition,the older measured data of Ref. [14] are adopted for 14 MeV neutrons. The evaluated results are shown in Fig. 5. For (n,3n) reaction, no measured data are available. Therefore, the recommended data were taken from calculated results by means of the model code.

2.4 Radiative Capture Cross Section

For (n,γ) reaction, below 200 keV, the data were taken from Ref. [1]. In 200 keV to 20 MeV region, experimental data are very insufficient, no new data are available. The recommended data were then taken from theoretical calculations by means of the model code.

2.5 (n,p) Reaction Cross Section

For natural titanium, no experimental data are available, the data obtained in terms of weighted sum of its isotopes are shown in Fig. 6. The (n,p) reaction cross sections for the isotopes from 13.6 to 19.5 MeV were measured systematically by Pasechnik (66)[15]. In addition, the data given by Refs. [16~18] are also adopted for 14 MeV neutrons. The recommended data were taken from theoretical calculations, and normalized to the experimental data.

2.6 Other Reaction Cross Sections

For (n,t) and (n,d) reactions, there is only a value measured by Biro(75)[19] and Grimes(77)[20] at 14 MeV, respectively. Recommended data were taken from theoretical calculations and normalized to experimental values. For (n, ^{3}He) and (n,t) reactions, the calculated results are recommended. For (n,n′x) (x = p, t, ^{3}He, d,α) reactions, because no experimental data are available, therefore the recommended data are given by using model calculations.

2.7 Inelastic Scattering Cross Sections of Discrete Levels

The recommended 20 level′s paramters are given in Table 2. The experimental data were mainly measured by Guenther(77)[2] for 10 levels, Barnard(73)[3] for 3 levels and Kinney(73)[21] for 9 levels. Because the measured levels were overlapped each other and the measured errors were quite large, the experimental results are treated as a reference for theoretical calculations. The recommended data were then taken from the calculated results by means of the model code.

Table 2 Discrete level parameters of Ti

U (MeV)	J^π	U (MeV)	J^π	U (MeV)	J^π
0.0	0^+	1.5499	$3/2^-$	2.2856	4^+
0.1594	$7/2^-$	1.5860	$3/2^-$	2.4210	2^+
0.889	2^+	1.6229	$5/2^-$	2.6100	0^+
0.9835	2^+	1.7235	$1/2^-$	2.6742	4^+
1.2521	$9/2^-$	1.7620	$5/2^-$	2.9973	0^+
1.3818	$3/2^-$	1.7941	$1/2^-$	3.2240	3^+
1.4422	$11/2^-$	1.9857	2^+	2.3688	3^-

3 ANGULAR DISTRIBUTIONS OF SECONDARY NEUTRONS

For angular distributions of elastic scattering cross sections, the adopted data are ones of Refs. [2, 21, 22]. The evaluated results obtained by fitting to experimental data, or by calculating with the model code.

For angular distributions of inelastic scattering and other reactions, isotropic in the center of mass system is assumed.

4 ENERGY DISTRIBUTION OF SECONDARY NEUTRONS

For (n,n′), (n,2n) and (n,3n) etc., no experimental data of the secondary neutron energy distributions are available, and the calculated data are recommended.

5 THEORETICAL CALCULATION

The theoretical models for calculating neutron data consist of the optical model (OPM), Hauser–Feshbach theory with width fluctuation correction (WHF) and evaporation model including the pre–equilibrium emission (PEM). The neutron nuclear data of Ti were calculated with AUJP code [22] and MUP2 code [23]. The calculated quantities were the cross sections, angular and energy distributions of emitted neutrons for all reactions.

The optimal optical model parameters used are given in Table 3.

Table 3 Optical model parameters of various reaction channels

Channels / Parameters	n	p	t	^{3}He	d	α
AR	0.735	0.75	0.98	0.72	0.86	0.59
AS	0.456	0.24	2.85	0.88	1.59	0.11
AVV	0.58	0.24	2.85	0.88	1.59	0.11
AS0	0.75	0.75	0.98	0.72	0.86	0.59
XR	1.190	1.15	1.75	1.20	1.07	1.05
XS	1.287	1.04	2.88	1.40	1.78	1.20
XVV	1.26	1.04	2.88	1.40	1.78	1.20
XS0	1.17	1.15	1.75	1.20	1.07	1.05
XC	1.25	1.25	1.30	1.30	1.30	1.54
U0	0.884	0.0	36.833	45.37	0.0	0.0
U1	0.039	0.0	−0.33	−0.33	0.0	0.0
V0	54.129	54.0	165.0	151.9	91.13	186.6
V1	−0.169	−0.32	−0.17	−0.17	0.0	0.0
V2	−0.014	0.0	0.0	0.0	0.0	0.0
V3	−24.0	24.0	−6.4	50.0	0.0	0.0
V4	0.0	0.40	0.0	0.0	2.2	0.0
VS0	6.2	6.2	2.5	2.5	7.0	0.0
W0	9.421	11.8	0.0	0.0	16.21	36.43
W1	−0.277	−0.25	0.0	0.0	0.0	0.0
W2	−12.0	12.0	0.0	0.0	0.0	0.0
A2S	0.70					
A2V	0.70					

6 CONCLUDING REMARKS

In the present work, the neurton nuclear data of natural titanium were evaluated. Due to using the newly measured data in this evaluation the previous evaluation was modified. Comparing our evaluated data with JENDL–3 and ENDF / B–6, it can be seen that the total, (n,2n), (n,p) cross sections were improved. And the nonelastic, inelastic scattering and capture cross sections were modified more or less; (n,x) reaction cross sections (x = p, t, ^{3}He, d, α) were also evaluated. The recommended data are given in ENDF / B–5 format and stored in CENDL–2, (MAT = 2220).

ACKNOWLEDGEMENTS

The author would like to thank Profs. Yuan Hanrong, Liang Qichang and Cai Dunjiu for their warm support and help of this work. He also thanks Dr. Cai Chonghai, Dr. Ma Gonggui for their help in the calculation.

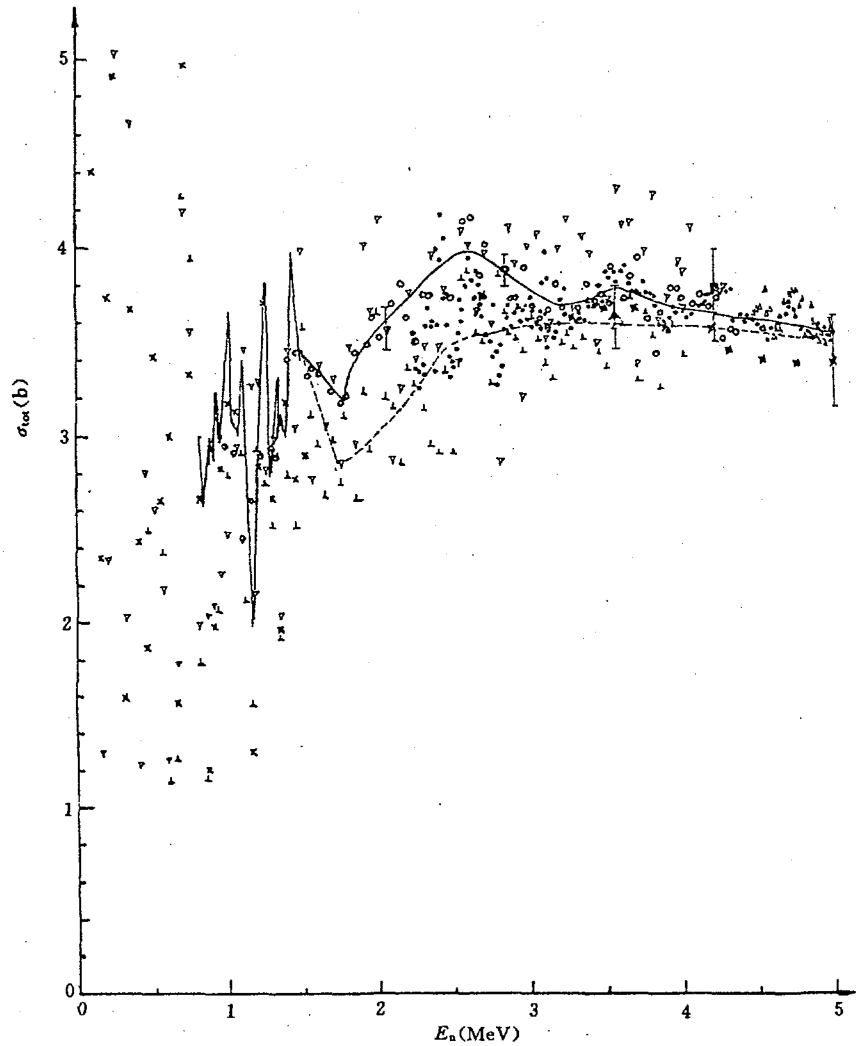

Fig. 1 The comparison between evaluated results with experimental values for total cross sections of Ti

○ [2], × [3], • [4], ⊥ ∇ [5], △ [6]

---- ENDF / B-6 ——— Present work

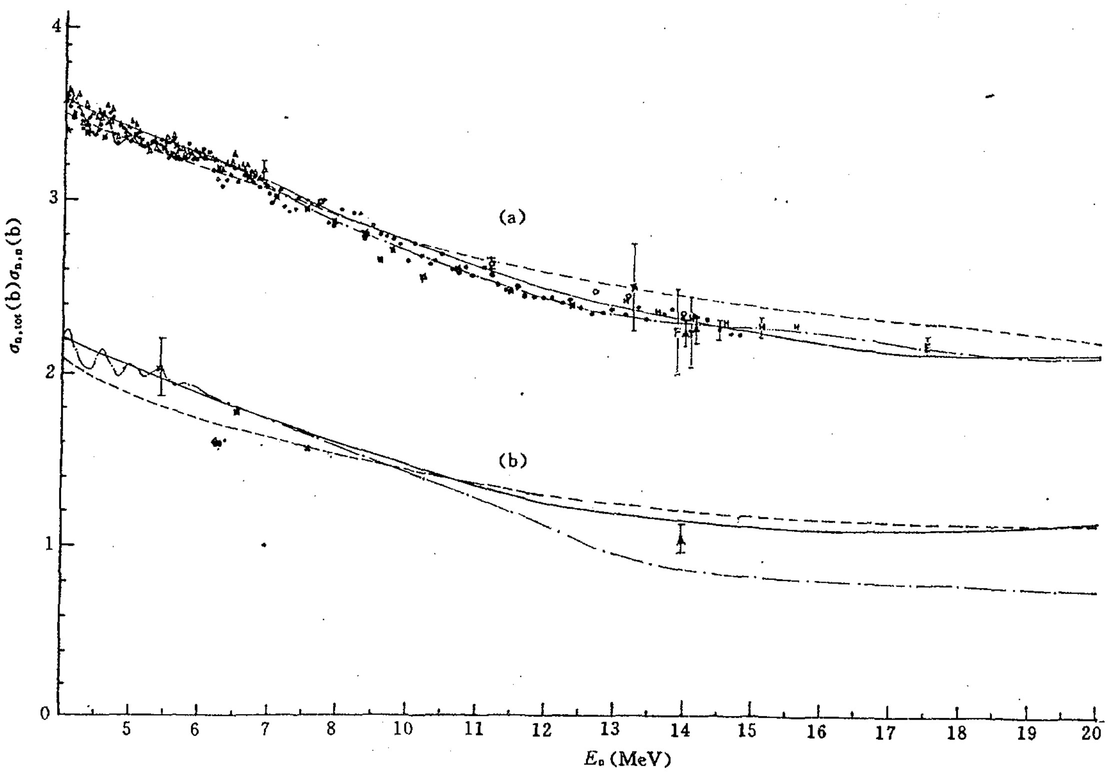

Fig. 2 The comparison between evaluated results with experimental values

(a) Total cross section, (b) Elastic scattering cross section

• [4], △ [6], H [7], E [8]

—·—·— JENDL-3 ---- ENDF / B-6 ——— Present work

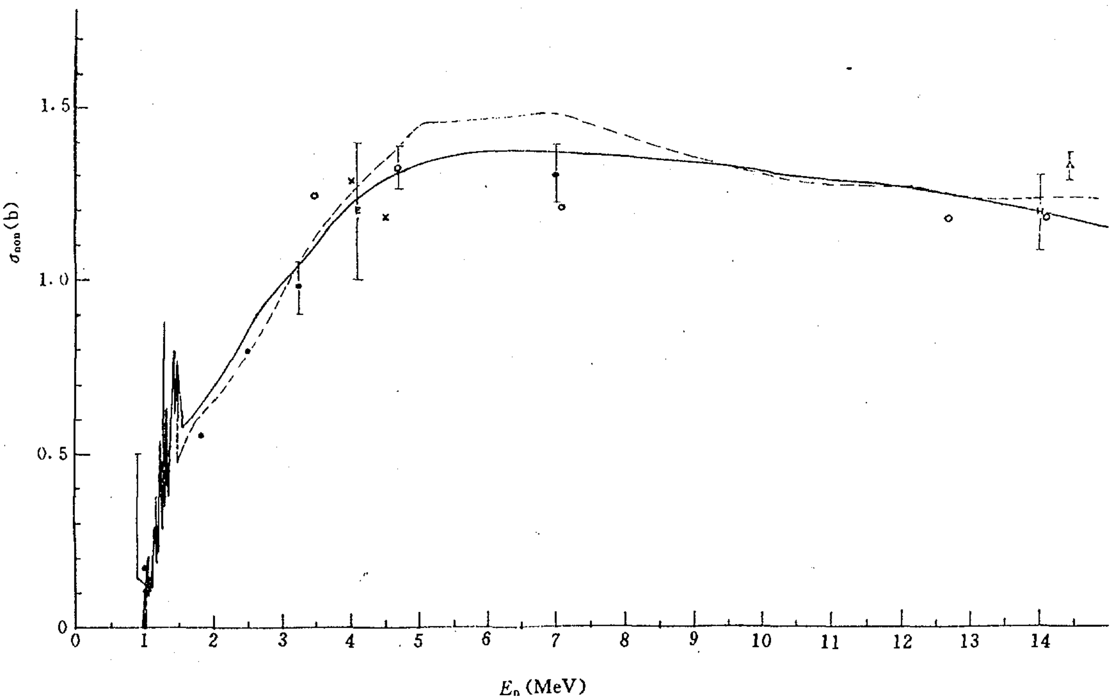

Fig. 3 The comparison between evaluated results with experimental values for nonelastic scattering cross sections of Ti

The experimental values of recommendation were taken from EXFOR data

---- ENDF / B–6 ——— Present work

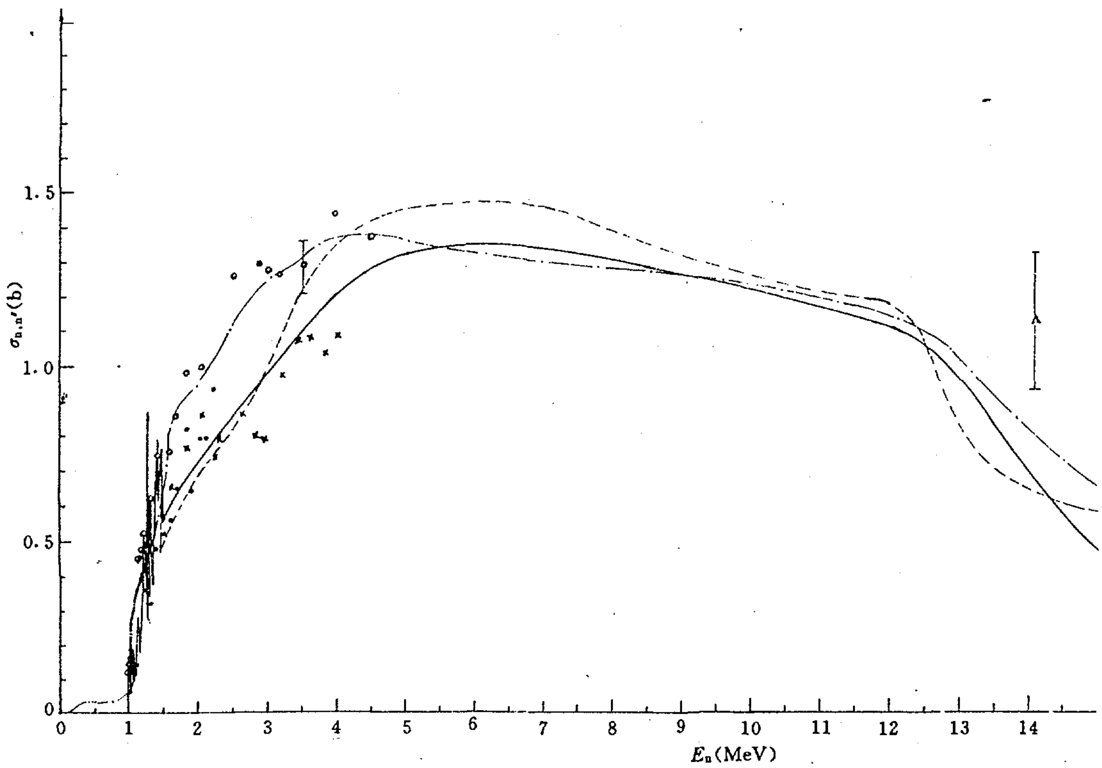

Fig. 4 The comparison between evaluated results with experimental values for inelastic scattering cross sections of Ti

× [2], △ [9], ○ [10], · [11]

—·— JENDL-3, - - - ENDF / B-6, —— Present work

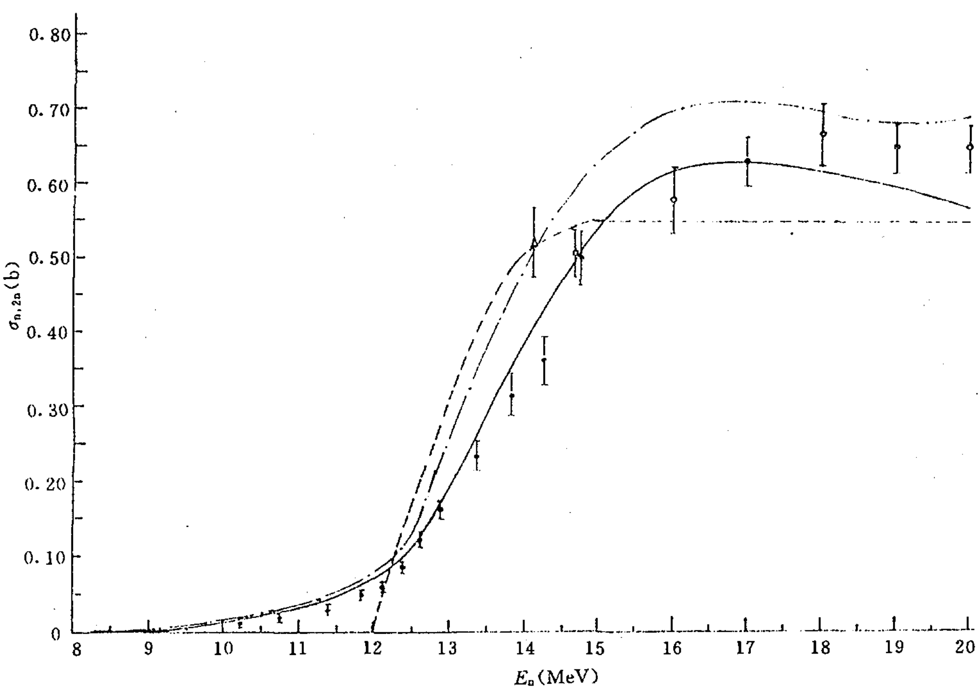

Fig. 5 The comparison between evaluated results with experimental values for Ti(n,2n) reactions cross sections

• [12], ○ [13], △ [14], —•— JENDL-3, - - - ENDF / B-6, —— Present work

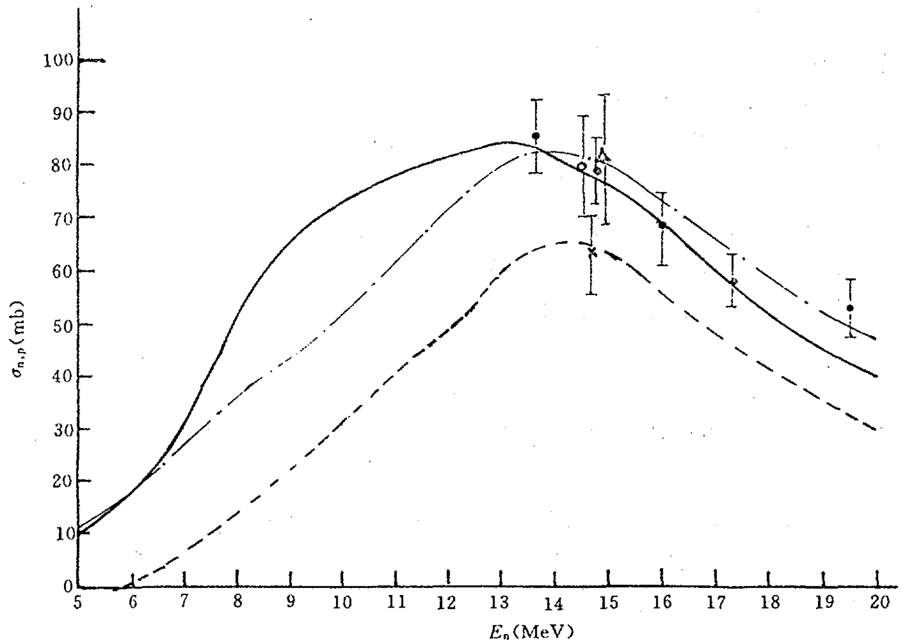

Fig. 6 The comparison between evaluated results with experimental values for Ti(n,p) reactions cross sections

• [15], × [16], △ [17], ○ [18]

—•— JENDL-3, - - - ENDF / B-6, —— Present work

REFERENCES

[1] J. Trochon et al., CEA–R–4883(1977)

[2] P. Guenther et al., ANL–NDM–31, (1977)

[3] E. Barnard et al., ANL–NDM–3, (1973)

[4] D. G. Foster et al., Phys. Rev., C–3, 576(1971)

[5] R. B. Schwartz et al., NBS–MONO–138 (1974). CEA–R–4524(1973)

[6] A. D. Carlson et al., Phys. Rev., 158, 1142(1967)

[7] J. P. Conner, Phys. Rev., 109, 1268(1958)

[8] J. M. Peterson et al., Phys. Rev., 120, 521(1960)

[9] I. Fujita et al., Nucl. Sci. Techn., 9, 301(1973)

[10] D. L. Broder et al., YK–10, 13(1972)

[11] D. L. Broder et al., FEI–32, (1965)

[12] J. Frehaut et al., Frehaut(80), (1980)

[13] Auchampaug et al., BNL–NCS–50681, 231(1977)

[14] V. J. Ashby et al., Proc. Second UN Conf. the Peaceful Uses of Atomic Energy, Geneva, 1 ~ 13 Sept. 1958, 15, 3(1958)

[15] M.V.Pasechnik et al., Can. J. Phys., 44, 2337(1966)

[16] S. M. Qaim et al., Nucl. Phys., 283, 269(1977)

[17] V. N. Levkovskij et al., Jadernaja Fizika, 10, 44(1969)

[18] W. G. Cross et al., EANDC(CAN)–16, 1(1963)

[19] T. Biro et al., J. Inorg. Nucl. Chem., 37, 1583(1975)

[20] S. M. Grimes et al., Nucl. Sci. Eng., 62, 187(1977)

[21] W. E. Kinney et al., ORNL–4810, (1973)

[22] M. E. Gurtovoj et al., Atomnaya Energiya, 30(5), 455(1971)

[23] Zhou Hongmo et al., AUJP(CNDC0011)(1989)

[24] Cai Chonghai et al., MUP2(CNDC0013)(1989)

EVALUATION OF NEUTRON NUCLEAR DATA OF NATURAL VANADIUM

Zou Yiming Ma Gonggui Wang shiming

(INSTITUTE OF NUCLEAR SCIENCE AND TECHNOLOGY OF SICHUAN UNIVERSITY, CHENGDU)

ABSTRACT

A comprehensive evaluation of neutron nuclear data and theoretical calculation for vanadium is described. It contains neutron cross sections of all reaction channels, angular distribution and energy distribution of secondary neutrons in the incident energy range from 1.0^{-5} eV to 20 MeV.

INTRODUCTION

The natural vanadium consists of two isotopes, ^{50}V and ^{51}V. But in this evaluation, there was no consideration for very minor isotope ^{50}V (0.25% abundance)

The reaction Q value and threshold energy for all pessible reactions below 20 MeV are indicated in Table 1.

Table 1 Reaction Q value and threshold energy of ^{51}V

Reactions	Q value (MeV)	Threshold energy (MeV)
$^{51}V(n,n)^{51}V$	0	
$^{51}V(n,\gamma)^{51}V$	7.3110	–
$^{51}V(n,n')^{51}$	−0.3200	0.3263
$^{51}V(n,p)^{51}Ti$	−1.6754	1.7085
$^{51}V(n,\alpha)^{48}Sc$	−2.0554	2.0961
$^{51}V(n,d)^{50}Ti$	−5.8282	5.9436
$^{51}V(n,t)^{49}Ti$	−10.518	10.727
$^{51}V(n,\ ^{3}He)^{49}Sc$	−12.505	12.753
$^{51}V(n,2n)^{50}V$	−11.052	11.271
$^{51}V(n,n'p)^{50}Ti$	−8.0528	8.2122
$^{51}V(n,n'\alpha)^{47}Sc$	−10.293	10.497

The present evaluation was based on experimental data available up to June 1989 and theoretical calculation using MUP–2[1] code. It contains important neutron cross sections : total, elastic scattering, nonelastic scattering, inelastic, (n,2n), (n,γ), (n,p), (n,n′p), (n,α), (n,n′α), (n,t) and (n,d) cross sections. They are considerably improved, compared with CENDL–1[2] and ENDF / B–5[3], and are in essentially agreement with ENDF / B–6[4] and JENDL–3[9].

This evaluation was accepted by CENDL–2 in the ENDF / B–5 format.

1 THEORETICAL CALCULATION AND THE PARAMETERS

The theoretical calculation was done with two programs, AUJP[5] and MUP–2[1].

AUJP is an automatic–adjusting–parameter optical model code. MUP–2 code includes optical model, H–F statistical model and pre–equilibrium evaporation model.

In this theoretical calculation, original optical potential parameters were taken from the work of Lu Hanlin[6], nuclear level information taken from Ref. [7], level density parameters taken from Ref. [8]. The level density formula is defined by

$$a = \{\, 0.00917\, [\, S(z) + S(n) + QB] \,\}\, A$$

$$V = 2.5 + 150 / A$$

Where $QB = 0.12$, $S(z) + S(n)$ are shell correct.

The level density parameter used in this work are given in the following:

PZ	0.0	1.73	0.0	1.73	0.0
PN	0.0	1.30	0.0	1.54	0.0
SZ	−13.93	−13.24	−12.55	−11.85	−11.15
SN	12.60	12.13	13.00	13.50	13.83

To obtain the better calculation result in the whole energy range, the first term coefficient U_1 (E) varing with energy was intruduced in adjusting real optical potential parameters.

$$U = U_0 + U_1 (E)E + U_2 E^2 + U_3 (N-Z)/A$$

where $$U_1 (E) = 1 - (1 + EA^{1/3} / 82)^{-2}$$

The adjusted optical model parameters (unit : MeV or Fermi) are given in the following:

Real well depth $V = 54.29 - 0.36\ E - 0.023E^2 - 24(N-Z)/A$

$$r_0 = 1.20, \qquad a_0 = 0.69$$

Imaginary volume absorption well depth

$$W = 0.81E - 9.6$$

Imaginary surface absorption well depth

$$W_d = 10.1 - 0.13E - 12(N-Z)/A$$

$$r_w = r_d = 1.16, \qquad a_w = a_d = 0.50$$

$$V_{so} = 6.2, \qquad r_{so} = 1.16, \qquad a_{so} = 0.69$$

The adjusted double giant resonance peak parameters of photonuclear reaction are given in the following:

SAO 0.250 0.249 0.249 0.249 0.249 0.249 0.249 0.249 0.120 0.144 0.144 0.144 0.144 0.144 0.144 0.144

GM 4.42 4.42 4.42 4.42 4.42 4.42 4.42 4.42 5.10 5.10 5.10 5.10 5.10 5.10 5.10 5.10

EG 17.86 17.86 17.86 17.86 17.86 17.86 17.86 17.86 21.22 21.22 21.22 21.22 21.22 21.22 21.22 21.22

The adjusted $DK = 390$.

The calculated results by AUJP code are in agreement with the evaluated data based on experimental value, as illustracted in Table 2.

Table 2 The comparison between calculated and evaluated measured data

(MeV)	tot			elastic			non		
	eval.	cal.	* %	eval.	cal.	* %	eval.	cal.	* %
1.0	3.20	3.35	4.7	3.02	2.97	1.6	0.46	0.43	6.5
2.0	3.80	3.75	1.3	2.81	2.87	2.1	0.91	0.87	4.4
3.0	3.90	3.76	3.6	2.88	2.75	4.5	1.07	1.02	4.7
4.0	3.80	3.67	3.4	2.53	2.51	0.8	1.20	1.16	3.3
5.0	3.70	3.55	4.1	2.18	2.30	5.5	1.23	1.24	0.8
6.09	3.50	3.41	2.6	2.00	2.12	6.0	1.25	1.29	3.2
7.05	3.35	3.26	2.7	1.96	1.95	0.5	1.27	1.31	3.1
8.56	3.10	3.02	2.6	1.82	1.71	6.0	1.27	1.31	3.1
11.0	2.70	2.64	2.2	1.34	1.36	1.5	1.27	1.29	1.6
14.7	2.35	2.27	3.4	0.95	0.95	1.0	1.27	1.31	3.1
16.0	2.23	2.21	0.9	0.95	0.90	5.3	1.27	1.31	3.1
20.0	2.10	2.20	4.8	0.95	0.92	3.2	1.27	1.28	0.9

* = [|cal.−eval.| / eval.] × 100

Note: The evaluated nonelastic cross sections were replaced by total inelastic cross section below 7 MeV, and assumed to be an constant above 7 MeV.

The calculated results by MUP−2 code are in agreement with the evaluated data based on experimental value, except that the cross sections at high energy are somewhat low.

2 RECOMMENDED NEUTRON CROSS SECTIONS

2.1 Total Cross Sections

Between 2 keV and 100 keV, the total cross section were given by resonance parameters.

The total cross section below 2 keV and the resonance parameter between 2 keV and 100 keV for ^{51}V were taken directly from the recommended data of Smith[4]. Between 100 keV and 4 MeV, the resonance fluctuations of the higher resolution total cross sections become increasingly larger as the energy decreases. Therefore, the "best" high resolution experimental results were recommended respectively in this energy regions. In this way, Garg's data[10] up to 102 keV, Rohr's data[11] from 102 to 220 keV, Smith's data[12] from 220 to 360 keV, Cierjacks's data[13] from 0.36 to 4.0 MeV were adopted. As there are some differences in energy scales between the results of Rohr, Smith and Cierjacks, amounting to as much as 4 keV, so the energy scales of Smith's result were removed 4 keV towords low energy. From 4 to 20 MeV, the orthogonal polynomial fit result based on the experimental data of Cierjacks[13], Doodman[14], and Peterson[15] was adopted.

The present evaluation is in very good agreement with that of ENDF / B–6 and JENDL–3[9]. The evaluation of ENDF / B–5 appears higher above 5 MeV, as illustrated in Fig. 1.

2.2 Elastic Scattering Cross Sections

The recommended elastic scattering cross sections were obtained by subtracting the nonelastic cross sections from the total cross sections in the entire energy range. The comparison between the recommended elastic scattering cross sections and experimental data [12, 17~19] shows that the recommended data are reasonable. Especialy, the recommended data is in very good agreement with the experimental data of Western[20] within experimental error at 14.7 MeV. The recommended data have larger improvement than that of CENDL–1 and ENDF / B–5 above 11 MeV, and somewhat lower than that of ENDF / B–6 and JENDL–3.

2.3 Nonelastic Scattering Cross Sections

Nonelastic scattering cross sections were taken from the sum of all partial cross sections within nonelastic scattering process. The recommended nonelastic scattering cross sections is essentially a constant from 7 to 20MeV, and is in agreement with the total inelastic cross section below 7 MeV (because of smaller (n,γ) cross section) and the data of Graves[67] at 14.7 MeV.

The present evaluation is essentially in agreement with that of ENDF / B–6 and JENDL–3, as illustrated in Fig. 2.

2.4 Inelastic Scattering Cross Sections

(1) Inelastic Scattering Cross Sections Discrete of Levels

The discrete inelastic scattering cross sections are given for 10 discrete levels. The excitation energy and spin parity, summarized in Table 3, were taken from Ref. [7].

Table 3 Energy levels of ^{51}V

Level	Energy (MeV)	Spin Parity	Levle	Energy (MeV)	Spin Parity
1	0.0	3.5⁻	7	2.547	0.5⁻
2	0.320	2.5⁻	8	2.677	1.5⁻
3	0.929	1.5⁻	9	2.699	7.5⁻
4	1.609	5.5⁻	10	3.085	2.5⁻
5	1.813	4.5⁻	11	3.150	1.5⁻
6	2.411	1.5⁻			

For 0.32, 0.929, 1.609 and 1.813 MeV levels, due to the more experimental data, their inelastic scattering cross sections were given combining experimental data and the calculation results. From threshold to 5 MeV, the orthogonal polynomial fitting result of the data of Refs. [18, 19, 22~ 23] was adopted. Above 5 MeV the calculation results were normalized to the data of Ref. [18] at 6.44 MeV. For less experimental data levels, 2.4157 and 2.5470 MeV, and the levels of no experimental data levels, the calculated results were directly adopted.

The comparison between the present recommended data,ENDF / B–6, JENDL–3 and the experimental data was made, as illustrated in Figs. 10~ 11.

(2) Continuum Inelastic Scattering Cross Sections

Continuum inelastic scattering cross sections were obtained by subtracting the sum of the discrete inelastic scattering cross sections from the total inelastic scattering cross sections.

(3) Total Inelastic Scattering Cross Sections

The recommended total inelastic cross section is taken from the theoretical calculation result.

The recommended total inelastic cross sections are in agreement with the data of Refs.[19, 24~26], ENDF / B–6 and JENDL–3, as illustrated in Fig. 4.

2.5 (n,2n) Cross Sections

For the recommended (n,2n) cross section, the experimental data of Frehaut were used in the energy region from threshold to 13 MeV. Above that the theoretical calculated result was adopted.

The present evaluation is in good agreement with that of ENDF / B–6. Above 15 MeV the evaluation of JENDL–3 appears somewhat low, as illustrated in Fig 5.

2.6 Capture Cross Sections

The data of Macklin[29] from 100 to 184 keV was adopted. From 184 keV to 4 MeV,the various experimental data[30~35] agree each other. Therefore, the orthogonal polynomial fitting result of these data was used.

From 4 to 20 MeV the evaluated values of Smith[4] were used, which goes through the weighted average value of the data[36~39] near 14 MeV.

The present evaluation is in very good agreement with that of ENDF / B–6, and the evaluation of JENDL–3 appears lower at high energy range, as illustrated in Fig 3.

2.7 (n,p) and (n,n′p) Cross Sections

(1) (n,p) cross sections

From threshold to 9.27 MeV, the only experimental data of Smith[40] were adopted. They are in good agreement with the calculation results. In 13~ 20 MeV energy range, except the extensive measurements of Borman[41], there are a number of experimental data near 14.5 MeV. These data are scattered. However the newer results[42~46], measured in the past decade, are fairly consistent and have small uncertainties. Selecting the newer results, the weighted average value of 28.45 mb was obtained at 14.5 MeV. Then the excitation function of Bormann was normalized to this value.

From 9.27 to 13.0 MeV, due to lack of experimental data, the shape of theoretical calculation curve was adopted.

The comparison between the present recommended data, ENDF / B–6, JENDL–3 and the experimental data were made, as illustrated in Fig. 6.

(2) (n,n′p) cross sections

Due to lack of experimental data, the theoretical calculation result was adopted.

2.8 (n,α) and (n,n′α) Cross Sections

(1) (n,α) cross sections

From threshold to 9.27 MeV, the only experimental data of Knno[47] were adopted. They are in good agreement with the calculation results. There are four extensive measurements in 10~ 20 MeV energy region. The data of Bormann[48] were abandoned, as the curve trend is not consistant with the others. The experimental data of Paulsen [49] indicate a gross structure near 10.0 MeV. It may be not physical one, as the calculation indicates that there is no such structure in the cross sections.

The recommended excitation function shape was determined by orthogonal polynomial fitting of the data[49~51], and then normalized to the weighted average value of the experimental data[52~56] near 14.8 MeV, because these data not only have high precision, but also are fairly consistent.

The comparison between the present recommended data,ENDF / B–6, JENDL–3 and the experimental data were made, as illustrated in Fig. 7.

(2) (n,n′α) cross sections

There are some older experimental results[57~59] near 14.0 MeV. All of them were obtained using activation technigues. They generally indicate an upper limit of the cross section at this energy of several mb or less. The extensive measurements of Bormann ranging from 13.2 to 19.4 MeV was abandoned due to the use of unreliable reference standard.

The calculated results indicate that the cross section rises rapidly above 16.0 MeV, and this behavior is supported by the experimental data trend of Bormann. Meantime the calculated results are also in agreement with the newer experimental results of Qaim[60] and Pepelink[54] near 14.0 MeV.

The cross section was taken directly from the calculation result. It is somewhat smaller than ENDF / B–6, and larger than ENDF / B–5 and JENDL–3.

2.9 (n, ^{3}He) Cross Sections

There are only two experimental results[61,62] near14.0 MeV. They only indicate an upper limit of the cross section, and the calculated result is very small. Therefore, the cross section was ignored.

2.10 (n,d) Cross Sections

There is only one experimental result[63] at 15.0 MeV.It is in agreement with the calculation result. Therefore, the cross section was directly taken from the calculation results.

2.11 (n,t) Cross Sections

The (n,t) cross sections were taken from the calculation results, due to lack of experimental data.

3 ANGULAR DISTRIBUTION OF SECONDARY NEUTRONS

The angular distributions of secondary neutrons, of elastic scattering and inelastic scattering to discrete levels are represented by Legendre coefficients in the center of mass system. The angular distributions of secondary neutrons for (n,n′ continuum), (n,2n), (n,n′p) and(n,n′α) process are assumed isotropic.

The angular distributions of elastic scattering neutrons were taken from the calculation. They are in agreement with the experimental data [12, 16~20, 64~66], as illustrated in Figs. 8~9.

4 THE ENERGY DISTRIBUTIONS OF SECONDARY NEUTRONS

The energy distributions of secondary neutrons from (n,n′ continuum), (n,2n), (n,n′p) and (n,n′α) reactions were taken from the calculation.

5 SUMMARY

The recommended total cross section, (n,γ) and (n,α) cross sections are completely based on the experimental data, and the recommended other cross sections were taken from the calculation and are in agreement with the experimental data if there are experimental data available.

The present evaluation is considerably different from that of CENDL–1 as the following, due to new experimental data and improved MUP–2 code:

(1) Resonance parameters are included .
(2) Nonelastic scattering cross sections are essentially a constant from 7 to 20 MeV.
(3) Above 15.0 MeV, the (n,2n) cross sections become increasingly larger with energy.
(4) The particle–emitting cross sections agree with the experimental data.

The present evaluation is in agreement with ENDF / B–6 and JENDL–3, except that the nonelastic cross section, (n,γ) and (n,2n) cross section at high energy range have some differences.

ACKNOWLEDGMENTS

The authors are very grateful to Prof. Liang Qichang and Prof. Liu Tingjin for much help in this work, in the meantime, also to Prof. Cai Dunjiu et al. of CNDC.

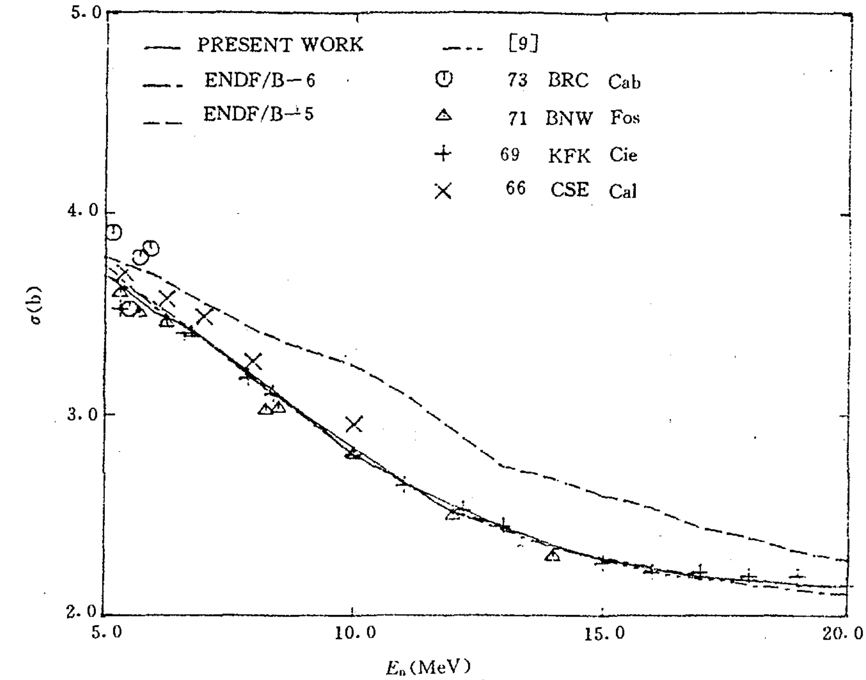

Fig. 1 Neutron total cross section of V

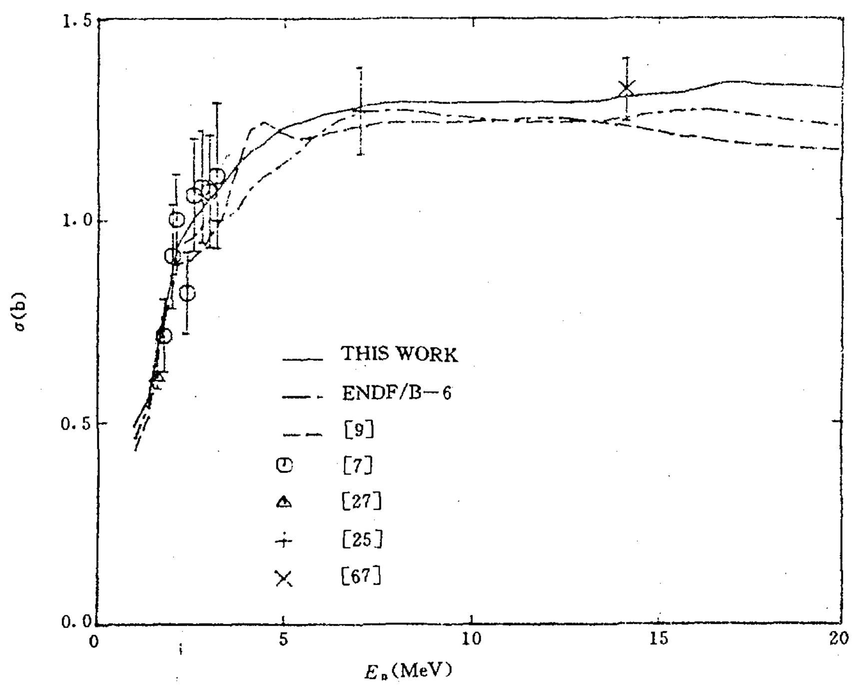

Fig. 2 Neutron nonelastic cross section of V

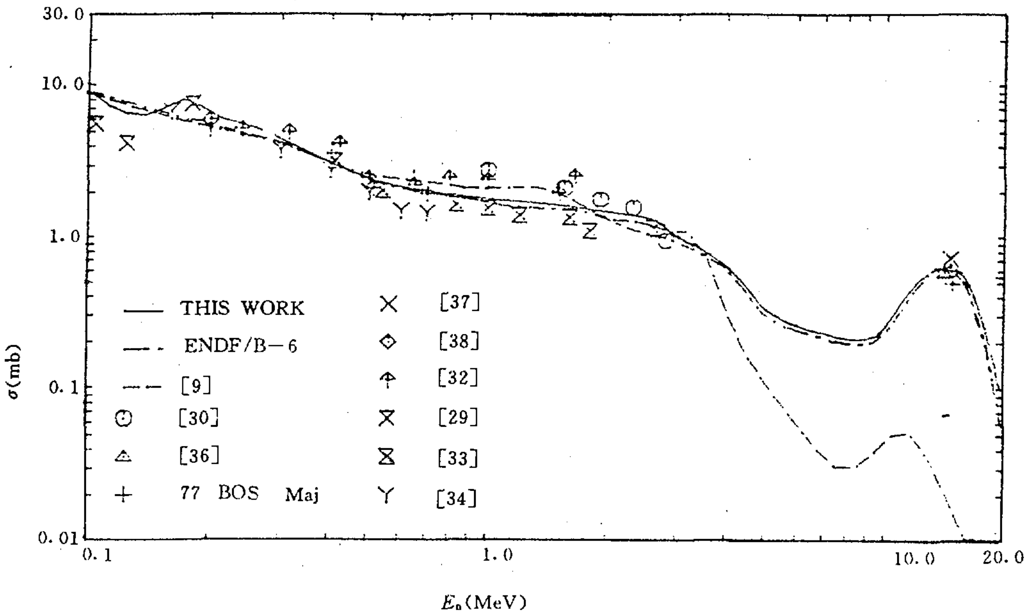

Fig. 3 Neutron capture cross section of V

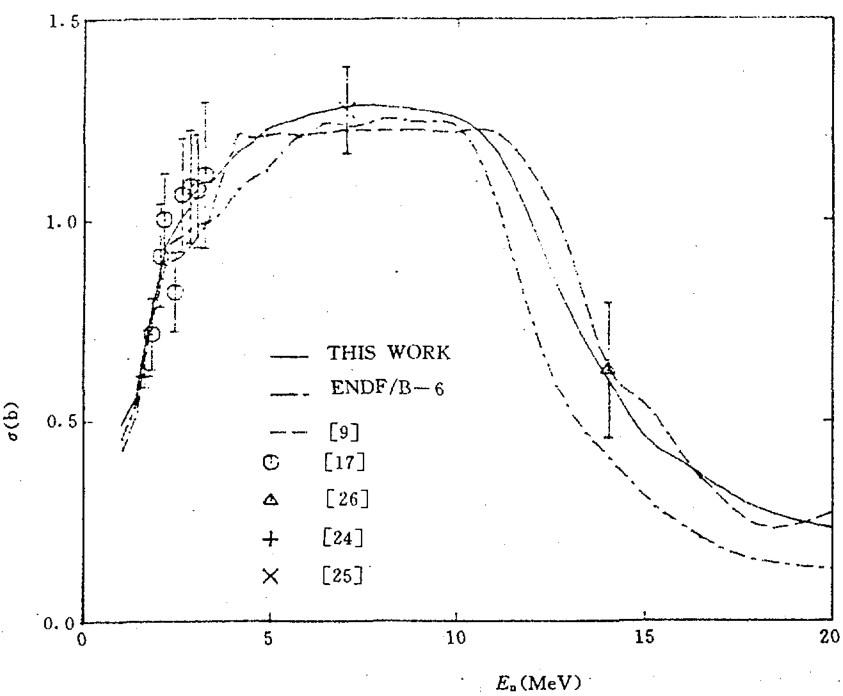

Fig. 4 Neutron total inelastic cross section of V

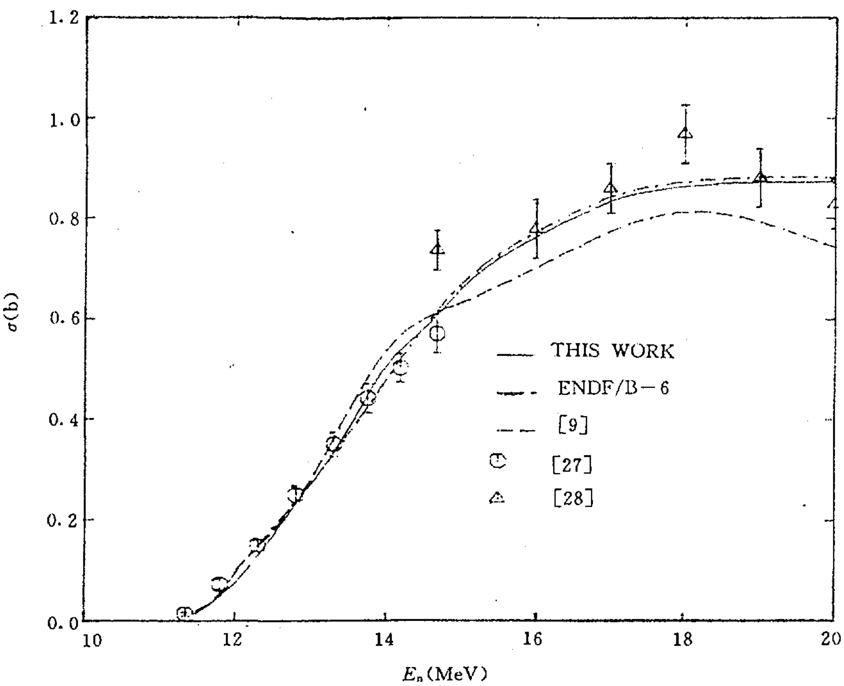

Fig. 5 (n,2n) cross section of V

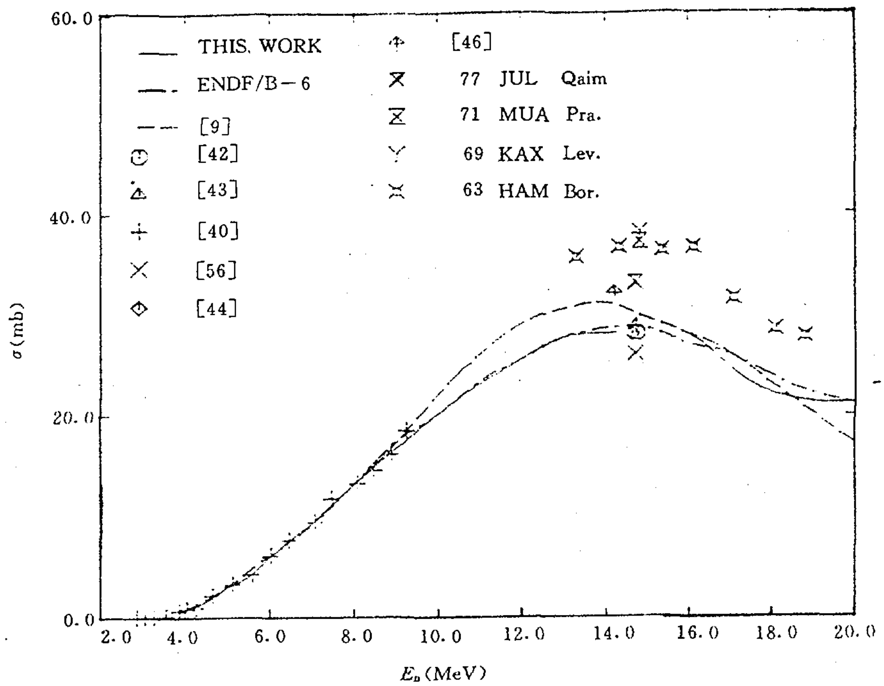

Fig. 6 (n,p) cross section of V

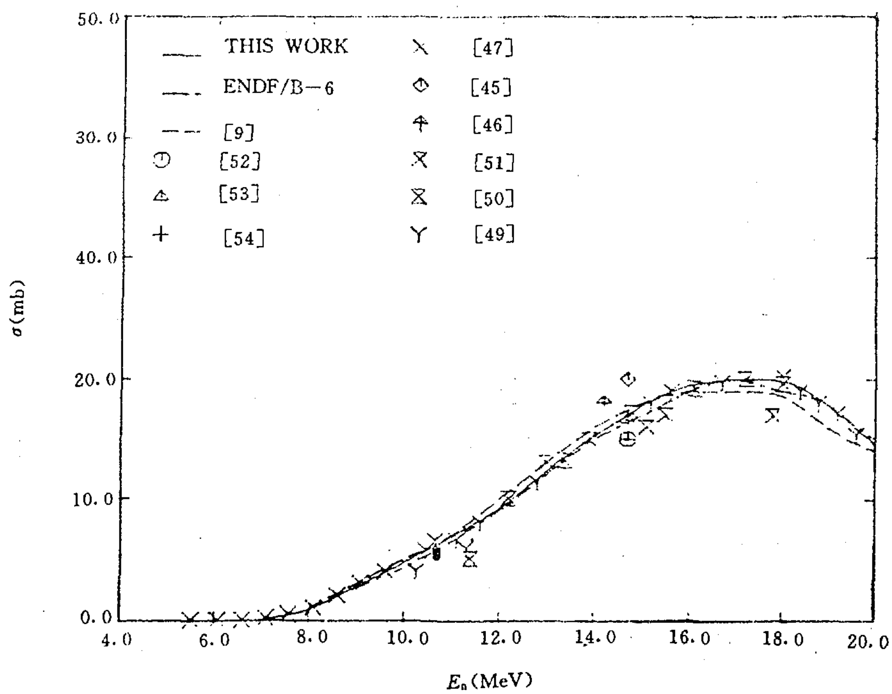

Fig. 7 (n,α) cross section of V

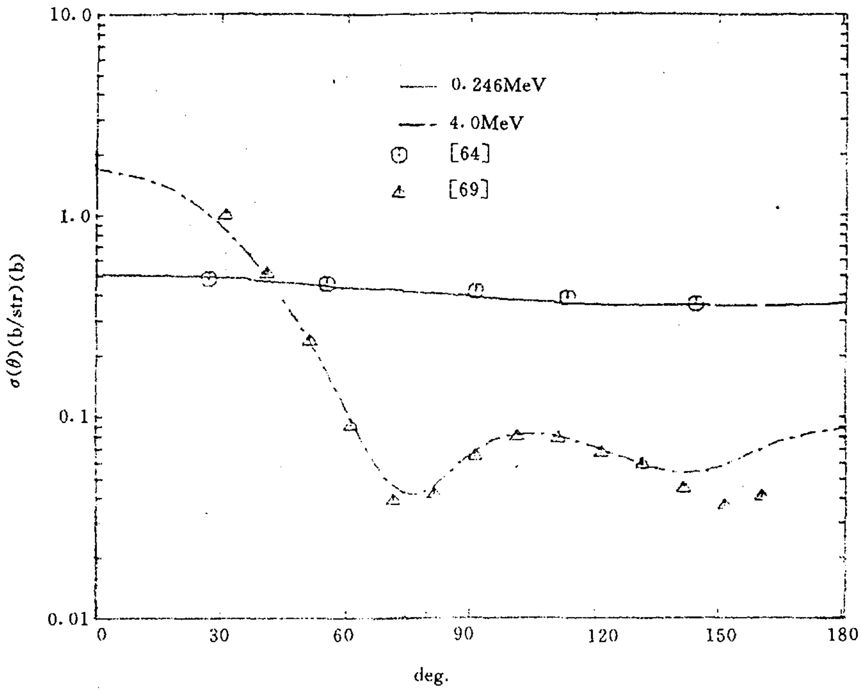

Fig. 8 Differential elastic scattering cross section of V

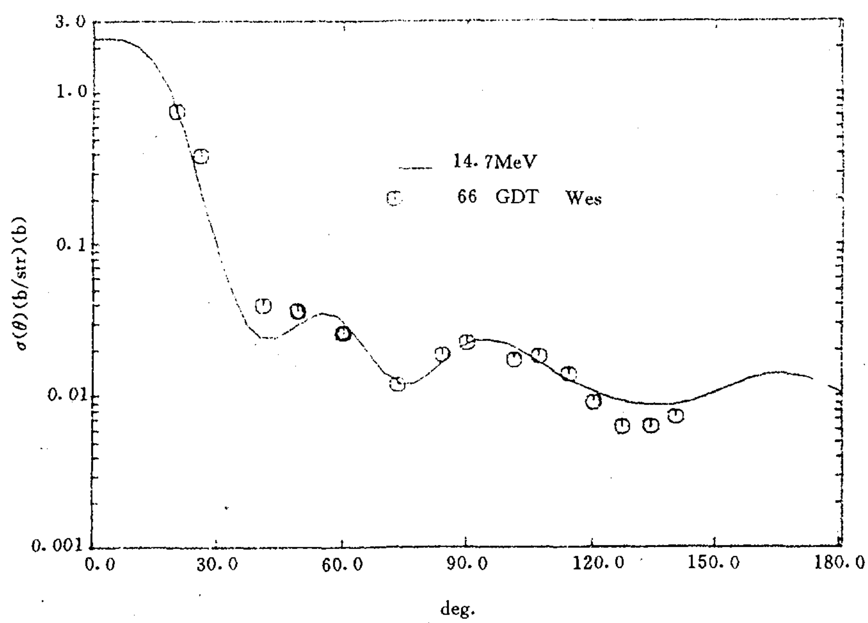

Fig. 9 Differential elastic scattering cross section of V

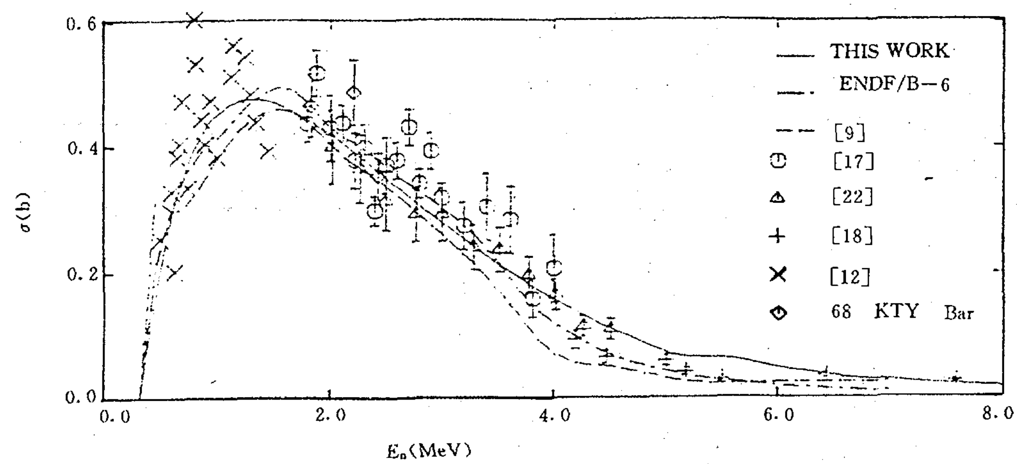

Fig. 10 0.32 MeV level inelastic scattering cross section of V

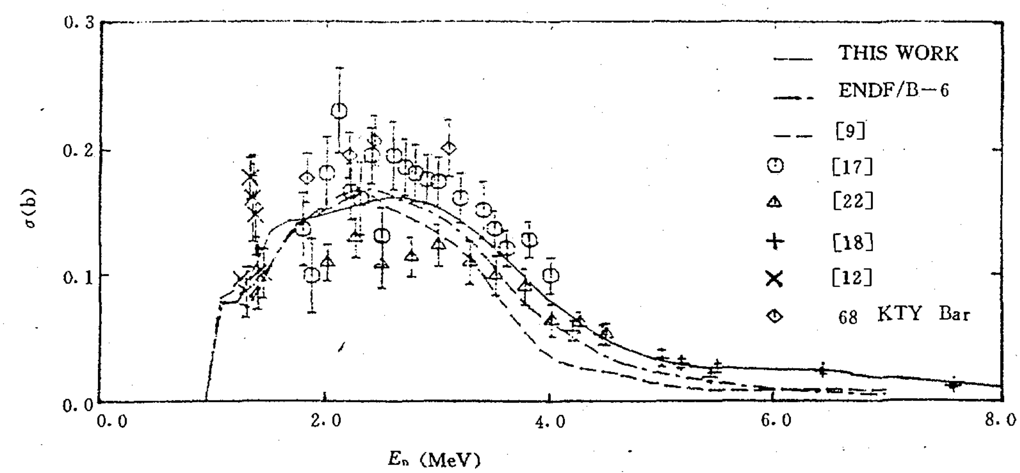

Fig. 11 0.929 MeV level inelastic scattering cross section of V

REFERENCES

[1] Yu Ziqiang, Cai Chonghai et al., Theoretical calculated program MUP–2 for medium and heavy nuclear, internal report (1986)

[2] Xia Yijun, Chinese Evaluated Nuclear Data Library, Version 1 (CENDL–1) CNDC–85010 P.60 (1986)

[3] P. Guenther et al., ANL / NDM–24 May (1977)

[4] A. B. Smith et al., ANL / NDM–105 May (1988)

[5] Zhou Hongmu, Yu Zhijian et al., Auto–parameter ajusting optical model calculated program AUJP, internal report (1978)

[6] Lu Hanlin et al., Theoretical calculation of the neutron reaction cross section for vanadium, CNDC–85011 p.93(1986)

[7] Zhou Chunmei et al., Nuclear Data Sheets 48 111 (1986)

[8] A. Gibert et al., Can. J. Phys., 43, 1446(1965)

[9] T. Watanabe, JENDL–3 (1990)

[10] J. B. Garg et al., Nucl. Sci. and Eng. 65, 76(1978)

[11] G. Rohr et al., Nucl. Phys. A 104, 1(1967)

[12] A. B. Smith et al., Phys. Rev. C 1, 581(1970)

[13] S. Cierjacks et al., KFK–1000 (1968)

[14] L. S. Goodman, Phys. Rev. 88, 686(1952)

[15] J. M. Peterson et.al., Phys. Rev. 120, 521(1960)

[16] J. C. Ferrer et al., Nucl. Phys. A 275, 325(1977)

[17] B. Holmgvist et al., AE–430 (1971)

[18] F. G. Perrey et al., ORNL–4551(1970)

[19] P. Guenther et al., Nucl. Sci. and Eng. 64, 733(1977)

[20] G. T. Western et al., AFWL–TR–65–216 2(1966)

[21] A. V. Poljakov et al., J. Jadernye Konstanty, (3) 21(1986)

[22] E. Alman–Ramstrom AE–503(1975)

[23] A. W. Brrows et al., Nucl. Phys. A107, 153(1968)

[24] J. H. Jowle, Nucl. Phys. A117, 657(1968)

[25] D. B. Thomson et al., Phys. Rev. 129, 1649(1963)

[26] Iwao–Fujita et al., Nucl. Scie. Techn. 9, 301(1972)

[27] J. Frehaut et al., CEA report, CEA–N–1875 (1976); See also proceedings of the 1980 Gaussig Conference

[28] G. Auchampaugh et al., BNL–NCS–50681(1977)

[29] R. L. Macklin et. al., Phys. Rev. 159, 1007(1967)

[30] Afzal Ansari et al., Annals of Nucl. Energy, 11, 173(1984)

[31] Yu. Ya. Stavisskii Atomnaja Energija 9, 401(1960)

[32] N. D. Dudey et al., J. Nucl. Energ, 23, 443(1969)

[33] G. Zaikin et al., Atomnaja Energija 23(1), 67(1967)
[34] A. E. Johnsrud et al., Phys. Rev. 116, 927(1959)
[35] A. Lejpunskij et al., Proceeding of the Second Interna tional Conference on the Peaceful Uses of Atomic Energy, Geneva, Vol. 15, p50 New York(1958)
[36] M. Budner et al., INDC–(YUG)–6(1979)
[37] O. Schwewer et al., Nucl. Phys. A264, 105(1976)
[38] M. Valkonen, JU–RR–1 / 1976
[39] F. Rigard et al., Nucl. Sci. and Eng. 55, 17(1974)
[40] D. Smith et al., Annals of Nucl. Energy, 11, 623(1984)
[41] M. Bormann et al., Zeitsch. F. Physik, 174, 1(1963)
[42] J. W. Meadows et al., Annals of Nucl. Energy, 14, 489(1987)
[43] P. Pepelink et al., NEANDC(E)–262U, (5) (1985)
[44] B. Anders et al., Int. Conf. on nuclear data for Science and Technology, Antwerp, 859(1982)
[45] N. A. Khan et al., Nucl. Instr. and Methods, 215, 193(1983)
[46] W. H. Warren et al., Annals of Nucl. Energy, 9, 369(1982)
[47] I. Kanno et al., Annals of Nucl. Energy. 11,623(1984)
[48] M. Bormann et al., J. Phys. Rev., 22, 602(1961)
[49] A. Paulsen et al., Atomkern Energie, 22, 291(1974)
[50] Lu Hanlin et al., Physica Energiae Fortis Physica Nucl. 3, 88(1979)
[51] Zupranska et al., Acta Physica Polonica section B 11, 853(1980)
[52] Katsuhei Kobayashi et al., Proceedings of the International Conference Nuclear Data for Science and Technology p. 261 1988 Mito, Japan.
[53] J. W. Meadows et al., Annals of Nucl. Energy. 14, 489(1987)
[54] R. Pepelink et al., Internat. Conf. on Nucl. Data for Basic and Applied Science, Santa Fe, New Mexico, May 1985(JA46)
[55] W. H. Warren et al., Annals of Nucl. Energy. 9, 369(1982)
[56] N. A. Khan et al., Nncl. Instr. and Methods, 215, 193(1983)
[57] M. Bormann et al., Zeitsch. F. Physik, 166, 477(1962)
[58] M. Hillman et al., Phys. Rev. 129, 2227(1963)
[59] E. Bramlitt et al., Phys. Rev. 131, 2649(1963)
[60] S. M. Qaim et al., Nucl. Phys. A, 458, 237(1986)
[61] I. Kumade Phys. Rev. 117, 1568(1960)
[62] E. I. Bramlitt Phys. Rev. 125, 297(1962)
[63] S. Grimes et al., Phys. Rev. C, 17, 508(1978)
[64] A. Langsdorf et al., Phys. Rev. 107, 1077(1957)
[65] J. H. Towle et al., Nucl. Phys. A117, 657(1968)
[66] B. Holmgvist et al., AE–430 (1971)
[67] E. R. Graves et al., Phys. Rev. 97, 1205(1955)

THEORETICAL CALCULATION AND EVALUATION OF NEUTRON DATA FOR NATURAL CHROMIUM

Ma Gonggui Zou Yiming Wang Shiming

(INSTITUTE OF NUCLEAR SCIENCE AND TECHNOLOGY, SICHUAN UNIVERSITY, CHENGDU)

ABSTRACT

The complete neutron nuclear data for Cr were evaluated based on both data measured up to 1989 and calculated with program MUP2[1]. The present work has been done for CENDL–2 and supersedes MAT = 1240 evaluation[2] in CENDL–1.

The follwing neutron data are given in the energy range 10^{-5} eV to 20 MeV (MAT = 2240). The cross sections included are total, elastic, non–elastic, total inelastic, inelastic cross sections to 25 discrete levels, inelastic continuum, (n,2n), (n,3n), (n,n′α) + (n,αn′), (n,n′p) + (n,pn′), (n,p), (n,d), (n,t), (n, ^{3}He), (n,α) and capture cross sections. Dirived data for MT = 251, 252 and 253 are also included.

Angular distributions and energy distribution of secondary neutron are also given.

INTRODUCTION

This is almost a completely new evaluation, in particular,the secondary neutron cross sections and angular distributions as well as the secondary neutron energy distribution have been updated. The cross sections mainly referd to BNL–325 (4th–86)[3], that also compared with ENDF / B–6(89)[4] and JENDL–3(87)[5].

We are also able to see from Ref. [6] that for the inelastic scattering to the levels almost completely new data (see Table 1) were taken.

Table 1 Discrete level scheme of Cr (Abundance %)

^{50}Cr (4.350)		^{52}Cr (83.79)		^{53}Cr (9.5)		^{54}Cr (2.36)	
0.0	0^+	0.0	0^+	0.0	$3/2^-$	0.0	0^+
0.7833	2^+	1.4341	2^+	0.5641	$1/2^-$	0.8350	2^+
1.8813	4^+	2.3696	4^+	1.0065	$5/2^-$	1.8270	4^+
2.9245	2^+	2.6470	0^+	1.2896	$7/2^-$		
3.1611	2^+	2.7677	4^+	1.5367	$7/2^-$		
3.1641	6^+	2.9648	2^+	1.9736	$5/2^-$		
3.3247	4^+	3.1138	6^+	2.1724	$11/2^-$		
		3.1617	2^+	2.2333	$9/2^-$		
		3.4152	4^+	2.3205	$3/2^-$		
		3.4722	3^+				

1 RESONANCE PARAMETERS

The resolved resonance parameters and the background used for determining the total, elastic, and capture cross sections from 10^{-5} eV to 300 keV are the same as ENDF / B–6. They are given for $^{50,52,53,54}Cr$ in File 2 along with the background in File 3.

2 RECOMMENDED NEUTRON CROSS SECTIONS

2.1 Total Cross Section

Above the resolved resonance region, it is smooth although there are some small structures. The experimental data were taken from Filippov[7], Guenther[8], Larson[9], Perey[10], Green[11], Foster[12], Cierjacks[13], Whalen[14] and Hibdon[15]. In the energy range from 0.3 MeV to 5.0 MeV there are some small structures, it was taken from corresponding experimental data in point cross sections manner; In the smooth region from 5 MeV to 20 MeV, this was mainly obtained from a spline fit to the experimental data of Guenther[8], Larson[9], Perey[10] and Cierjacks[13], shown in Fig. 1.

2.2 Elastic Scattering Cross Section

Above the resolved resonance 300 keV to 20.0 MeV, the elastic scattering cross section was obtained by subtracting the non–elastic cross section from the total cross section. In general, the agreement between the extracted cross section and available experimental data of Guenther[8], Kinney[16], Holmquvist[17], Smith[18], Stelson[19] and Sokolov[20], Malmskog[21], Pasechnik[22], Korzh[23], Kazakova[24] is good. This is shown in Fig. 2.

2.3 Non−Elastic Scattering Cross Section

This cross section is the sum of all cross sections of nonelastic channels. Below 14.1 MeV, the non elastic cross section is based on the available experimental data of Abramov[25], Strizhak[26] and Taylor[27], most of them were measured using sphere transmission method. Above 14.1 MeV, experimental data around 14 MeV were used to normalize the calculated results[28]. A plot of these data and other evaluated data is shown in Fig. 3.

2.4 Total Inelastic Cross Section

Below 7.0 MeV, the experimental data were taken from Karatzas[29], Biryukov[30], Fujita[31], Glazkov[32], Van Patter[33], Smith[34] and Border[35]; nearby 14 MeV, it was taken from Fujita[31] and Salnikov[36]. Above 7.0 MeV, the calculated results were normalized to experimental data 1.38 b at 9.1 MeV energy point[30]. From threshold to 9.1 MeV, the spline function fitting are performed based on a number of experimental results. A plot of these experimental data and the evaluated data is shown in Fig. 4.

2.5 Inelastic Cross Section to the Discrete Levels and the Continuum

The inelastic scattering cross section to 25 discrete levels were calculated with MUP−2 code[35]. For 0.5641, 0.7833, 0.835, 1.0065, 1.2896, 1.4341, 1.5367, 1.827, 1.8813, 1.9736, 2.1724, 2.2333, 2.3696, 2.647, 2.7677, 2.9245, 2.9648, 3.1138 and 3.1611 MeV levels, the calculated results are normalized to experimental data measured by Shinjiro Itagaki[37], Almen Ramstrom[38], Guenther[8], Karatzas[29], Kinney[16], Salnikov[36], and Broder[35] (Figs.5−1, 5−2).

The Continuum part was obtained by subtracting the cross section of inelastic scattering to 25 discrete levels from the total inelastic cross section.

2.6 (n,2n) and (n,3n) Cross Sections

For (n,2n) reaction, the cross section of natural Cr was measured by Auchamp[39] and Frehaut[40] in the energy range from 10.2 to 14.76 MeV and 14.7 to 21 MeV. The data were fitted with spline function (Fig. 7).

Due to no experimental data, the (n,3n) cross section data were taken from calculated results.

2.7 (n,p) Cross Section

For (n,p) reaction, there are no experimental data of natural Cr. The cross sections of the individual isotopes for $^{52,53,54}Cr$ were obtained by fitting experimental data measured by Ghorai et al.[41~57]. The (n,p) cross section of natural Cr was obtained from the sum of these curves weighted by the isotope abundance. Above 14.5 MeV, theoretical calculated data were nomalized to the fit value 90.88 mb at 14.8 MeV (Fig. 8).

2.8 (n,n'p) + (n,pn') Cross Section

Because there are no experimental data, the (n,n'p) + (n,pn') cross section was taken from calculated results.

2.9 (n,α), (n,n'α) + (n,αn') Cross Sections

For (n,α) reaction of natural Cr, the experimental data were measured by Wattecamps[58] and Paulsen[59] at 14.1 MeV and in the energy range from 4.89 to 9.97 MeV respectively. The α particles were measured at five angles with telescope detectors in a reaction chamber. Below 14.1 MeV, these data were given by fitting the experimental data. The cross section from 14.1 to 20.0 MeV was obtained from model calculation normalized to experimental data 46 mb[58] at 14.1 MeV. A plot of these data and other evaluated cross section is shown in Fig. 9.

Becaues there are no experimental data, the (n,n'α) + (n,αn') cross section was taken from calculated results.

2.10 Capture Cross Section

The capture cross section from 10^{-5} eV to 300 keV is given by the resonance parameters and the background. Above this energy up to about 1.0 MeV, the evaluated data were given by fitting the data measured by Le[60], Diven[61], and Stavisskij[62]. The capture cross section from 1 MeV to 3 MeV was obtained from model calculation normalized to data of ENDF / B–6 at 3 MeV energy point; above 3 MeV, we adopted ENDF / B–6 data. The evaluted data are consistent with experimental data 0.75 mb of Budnar[63] at 14.1 MeV. A plot of these experimental data and the evaluated cross sections is shown in Fig. 6.

2.11 (n,d) Cross Section

The experimental datum 10.0 mb of natural Cr measured by Grimes[64] at 14.8 MeV energy point was used to normalize the corresponding calculated results.

2.12 (n,t) and (n, ^{3}He) Cross Sections

Because there are no experimental data, they are taken from calculated results. Also the cross sections are very small.

3 SECONDARY NEUTRON ANGULAR DISTRIBUTIONS

An elastic scattering angular distributions are given by calculatios in terms of Legendre coefficients in c. m. system. An experimental data of 22 measured energy points by Kinney[16] ,Guenther[8] , Holmgvist[17] , Smith[18] and Stelson[19] were used in the optical model calculation. The calculated results are in agreement with the concerned experimental data (Fig. 10–1, 10–2) well.

The discrete inelastic angular distributions (MT = 51~ 71) also were taken from calculated results in terms of Legendre coefficients in c.m. system.

The angular distributions for (n,2n), (n,3n), (n,n′α), (n,n′p) and continuum inelastic scattering (MT = 16, 17, 22, 28 and 91) were assumed to be isotropic.

4 SECONDARY NEUTRON ENERGY DISTRIBUTIONS

For the inelastic continuum,(n,2n), (n,3n), (n,n′α) and (n,n′p) reactions (MT = 91, 16, 17, 22 and 28), they were also taken from calculated results.

5 THEORETICAL CALCULATIION

In the theoretical calculation, various parameters are required to input : optical model parameters, level density parameters[65] and information on nuclear level scheme[6]. These patameters were adjusted based on the experimental data.

The data were calculated in the energy range from1 keV to 20 MeV with programs AUJP[28] based on optical model and MUP–2[1] based on optical model, H–F statistical model with width fluctuation correction and the unified treatment of exciton model and evaporation model. The comparison between calculated and measured data is given in the Table 2.

Table 2 The comparison between calculated and measured data

(MeV)	tot			n,n			non		
	theo.	eval.	x %	theo.	eval.	x %	theo.	eval.	x %
1.0	3.080	3.080	0.00	3.030	3.037	0.23	0.050	0.043	16.3
2.0	3.090	2.990	3.24	2.459	2.411	1.99	0.631	0.549	14.9
3.0	3.291	3.220	2.20	2.473	2.221	1.13	0.818	0.999	18.1
4.0	3.736	3.673	1.72	2.493	2.405	3.66	1.243	1.268	1.97
6.0	3.586	3.595	0.25	2.205	2.155	2.32	1.381	1.443	4.30
8.0	3.274	3.287	0.40	1.892	1.885	0.37	1.382	1.402	1.43
10.0	2.921	2.880	1.42	1.538	1.530	0.52	1.383	1.350	2.44
12.0	2.675	2.635	1.52	1.290	1.299	0.77	1.385	1.336	3.67
14.0	2.462	2.452	0..41	1.108	1.137	2.55	1.354	1.315	2.96
16.0	2.301	2.262	1.72	1.000	0.972	2.88	1.301	1.290	0.85
18.0	2.215	2.195	0.90	0.962	0.925	4.00	1.253	1.270	1.34
20.0	2.161	2.120	1.93	0.923	0.862	7.08	1.238	1.258	1.59

$x = [|\text{theo.} - \text{eval.}| / \text{eval.}] \times 100$

The main parameters used are as follows:

(1) Optical potential parameters (MeV or fm)

$A_r = A_{so} = 0.6892$	$V_0 = 57.147$
$A_s = A_{vv} = 0.7$	$V_1^* = -0.136$
$X_r = X_{so} = 1.1516$	$V_2 = -0.0165$
$X_s = X_v = 1.1092$	$V_3 = -24.0$
$X_c = 1.17$	$V_4 = 0.0$
$U_0 = -2.116$	$W_0 = 6.537$
$U_1 = 0.362$	$W_1 = -0.1203$
$V_{so} = 6.2$	$W_2 = -12.0$

(2) Level density parameters, they are given in Table 3.

Table 3 Level density parameters*

P(z)	P(n)	S(z)	S(n)	P(z)	P(n)	S(z)	S(n)
^{50}Cr				^{52}Cr			
1.2	−0.2	−14.3	14.55	1.2	0.0	−14.3	13.7
−0.2	1.36	−12.2	13.7	−0.26	1.2	−12.2	12.5
1.53	−0.1	−12.8	14.93	1.53	−0.2	−12.8	14.55
0.0	1.4	−12.1	14.1	0.0	1.36	−12.1	13.70
1.75	−0.1	−12.0	14.5	1.75	−0.1	−12.0	14.93
P(z)	P(n)	S(z)	S(n)	P(z)	P(n)	S(z)	S(n)
^{53}Cr				^{54}Cr			
1.2	1.15	−14.30	13.45	1.2	−0.2	−14.3	15.45
−0.26	0.0	−12.2	13.7	−0.26	1.15	−12.2	13.45
1.53	1.2	−12.8	12.5	1.53	0.0	−12.8	13.7
0.0	−0.2	−12.1	14.55	0.0	1.2	−12.1	12.5
1.75	1.36	−12.0	13.7	1.75	−0.2	−12.0	14.55

* The level density formula of Ref. [65] were used.

(3) Pre–equilibrium parameter DK= 150.0

6 CONCLUDING REMARKS

Because the new experimental data are available in recent years, the evaluated data have been considerably improved, especially for cross sections of total, (n,p), (n,d), (n,γ), total inelastic reactions and inelastic scattering to some discrete levels and elastic scattering angular distributions.

ACKNOWLEDGMENTS

The authors wish to thank Profs. Cai Dunjiu, Liu Tingjin and Liang Qichang for their help in this work.

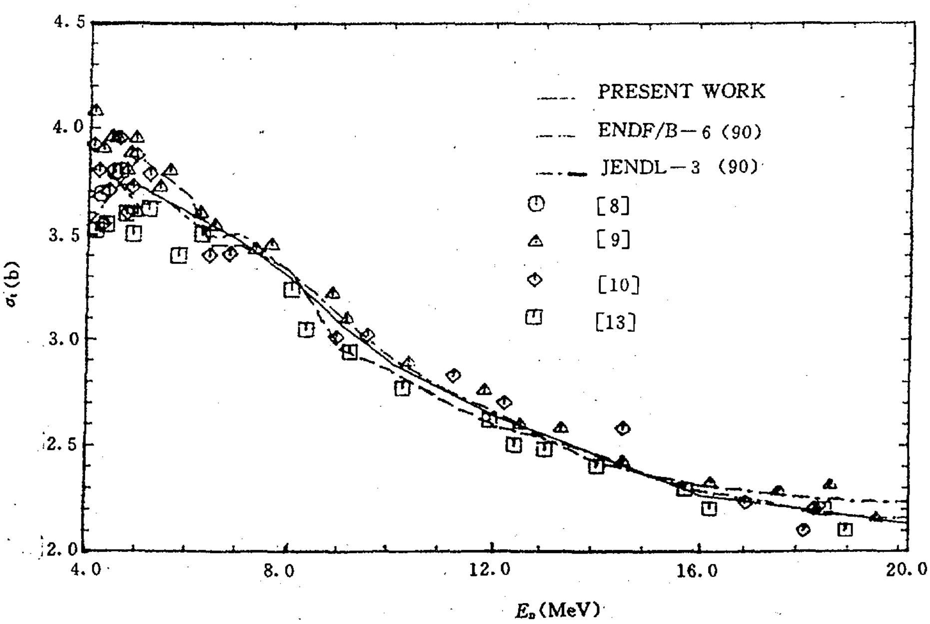

Fig. 1 Neutron total cross section of Cr

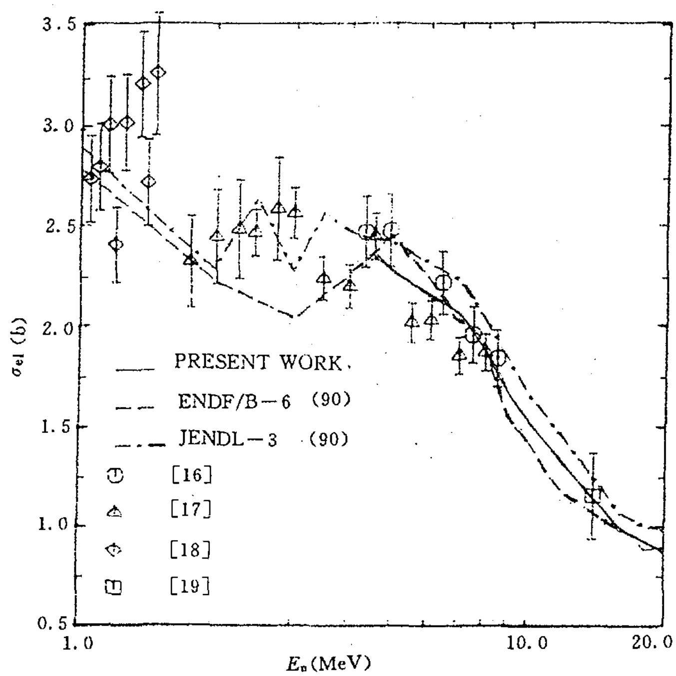

Fig. 2 Neutron elastic cross section of Cr

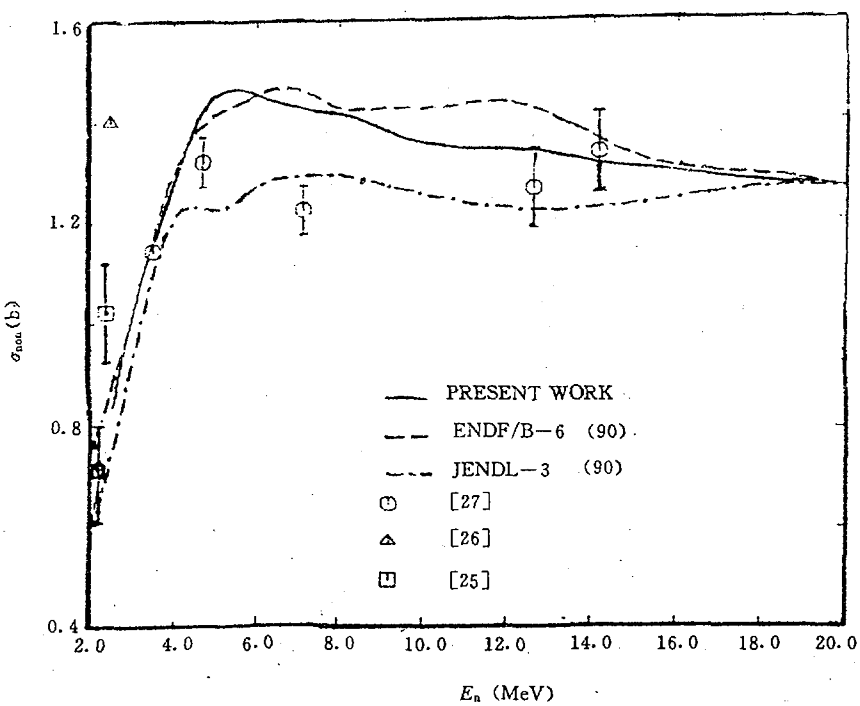

Fig. 3 (n,non) cross section of Cr

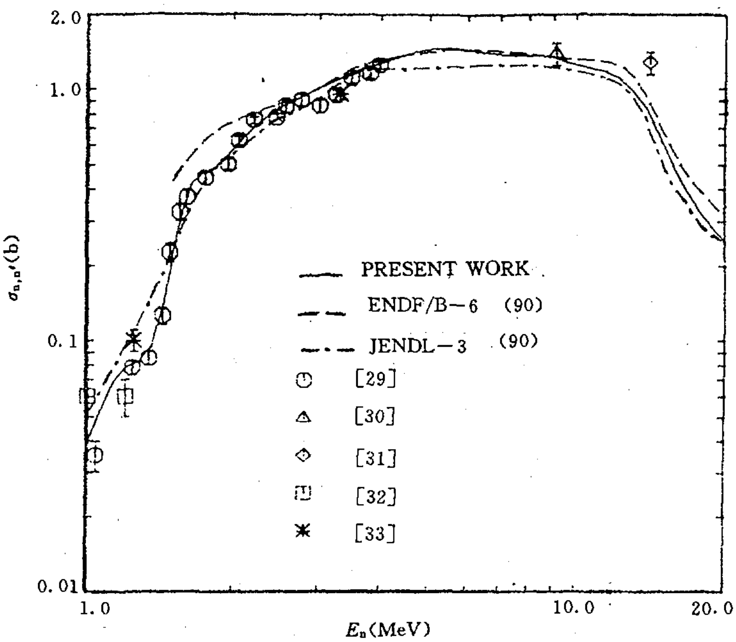

Fig. 4 (n,n′) cross section of Cr

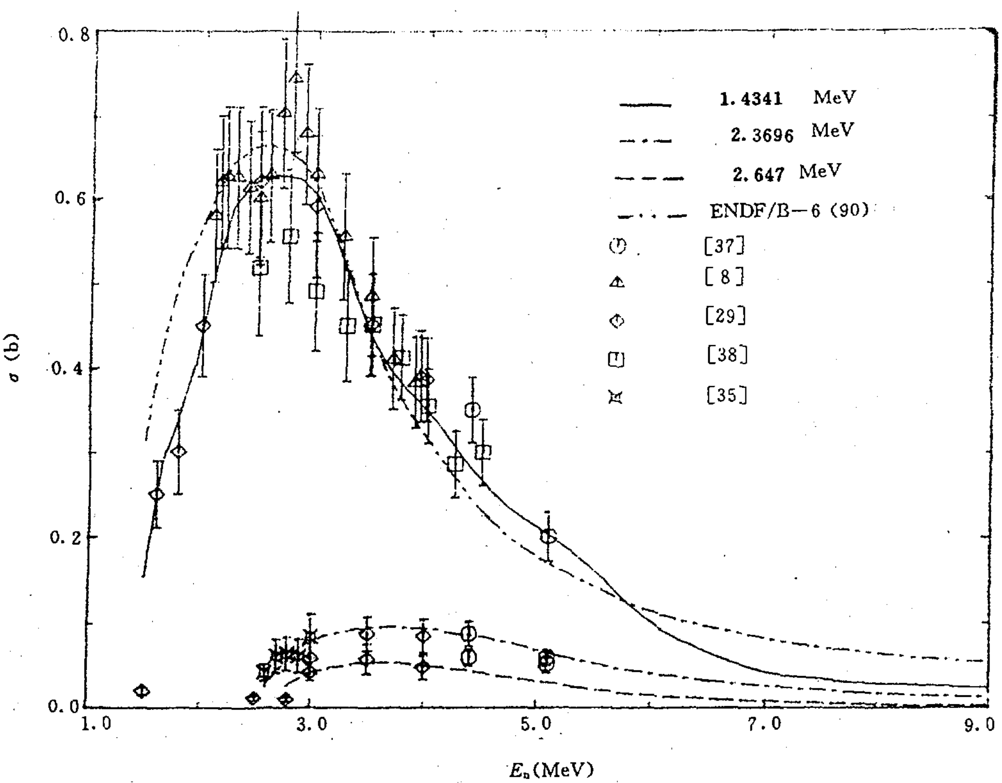

Fig. 5−1 Inelastic cross sections of Cr excited states

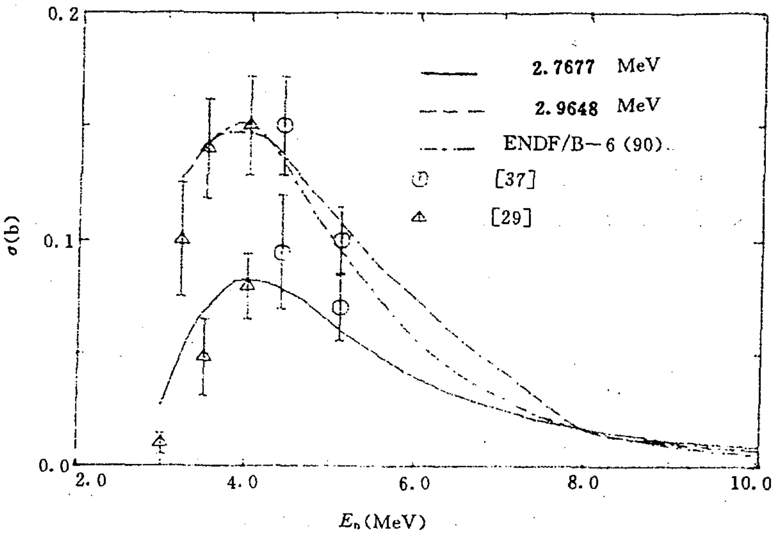

Fig. 5-2 Inelastic cross sections of Cr excited states

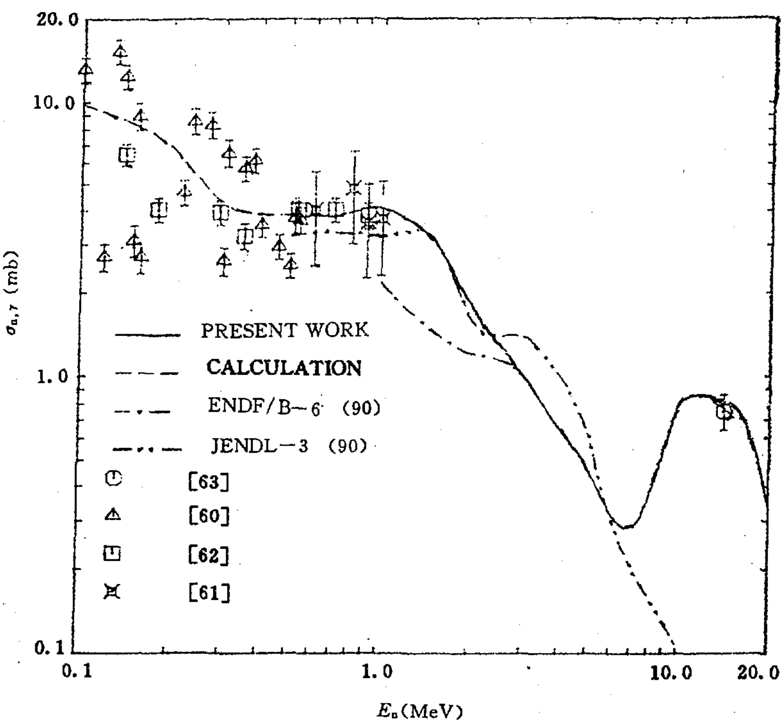

Fig. 6 (n,γ) cross section of Cr

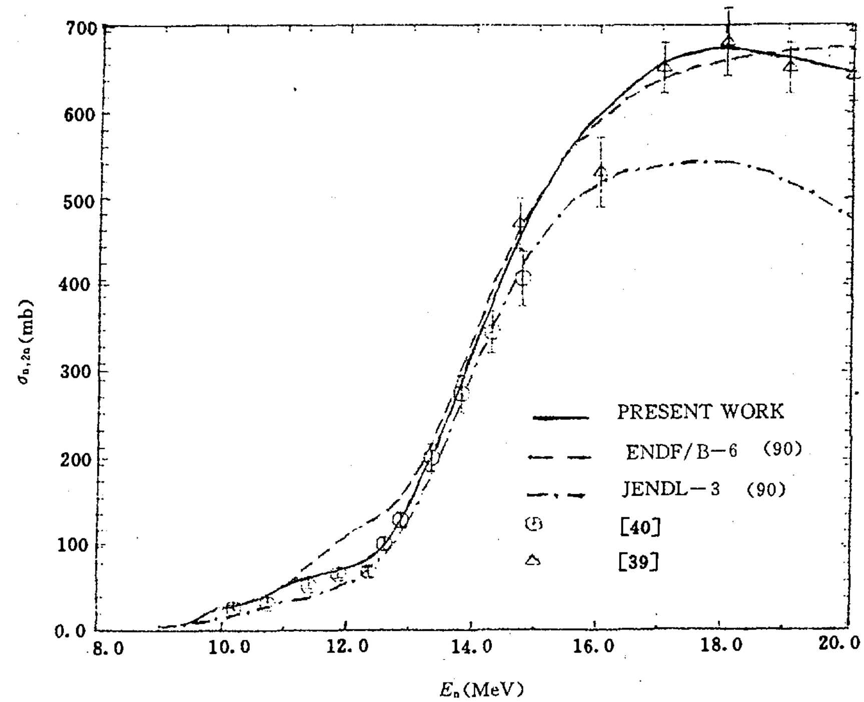

Fig. 7 (n,2n) cross section of Cr

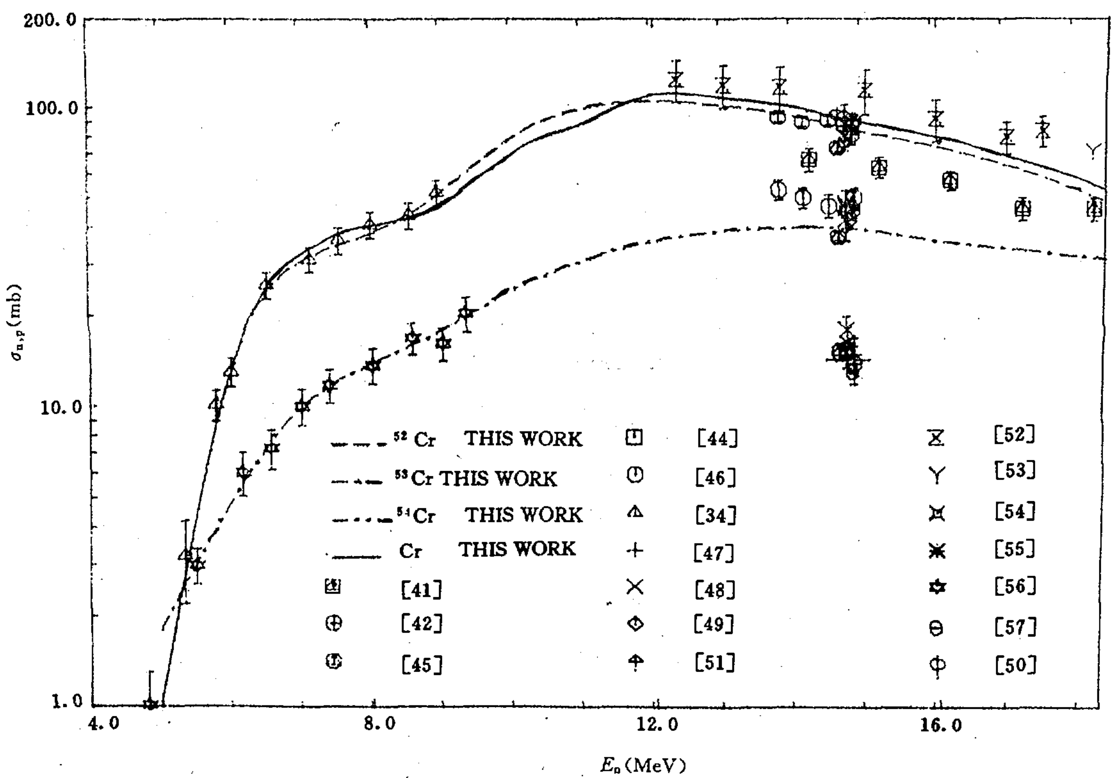

Fig. 8 (n,p) cross section of ^{52,53,54}Cr and Cr

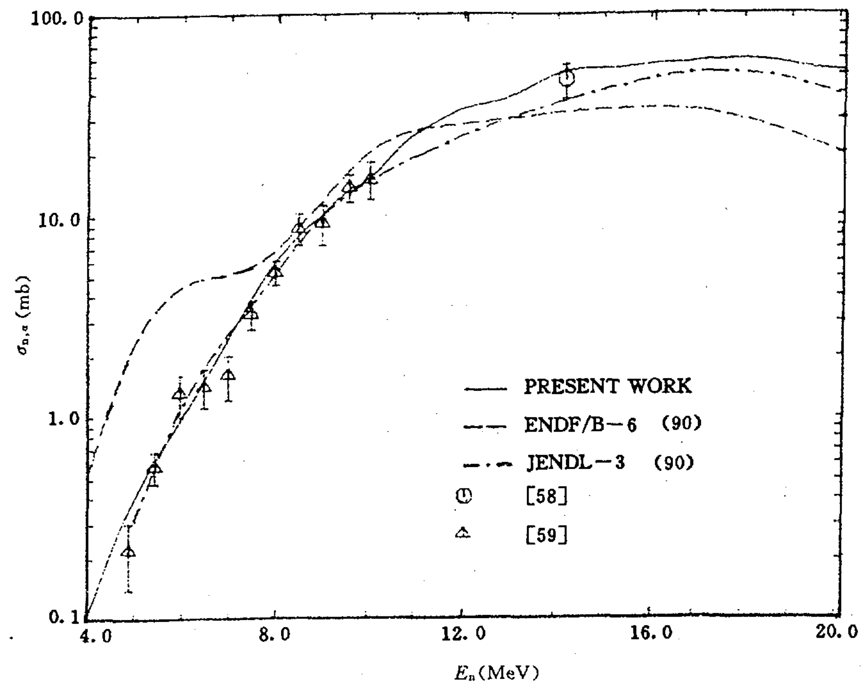

Fig. 9 (n,α) cross section of Cr

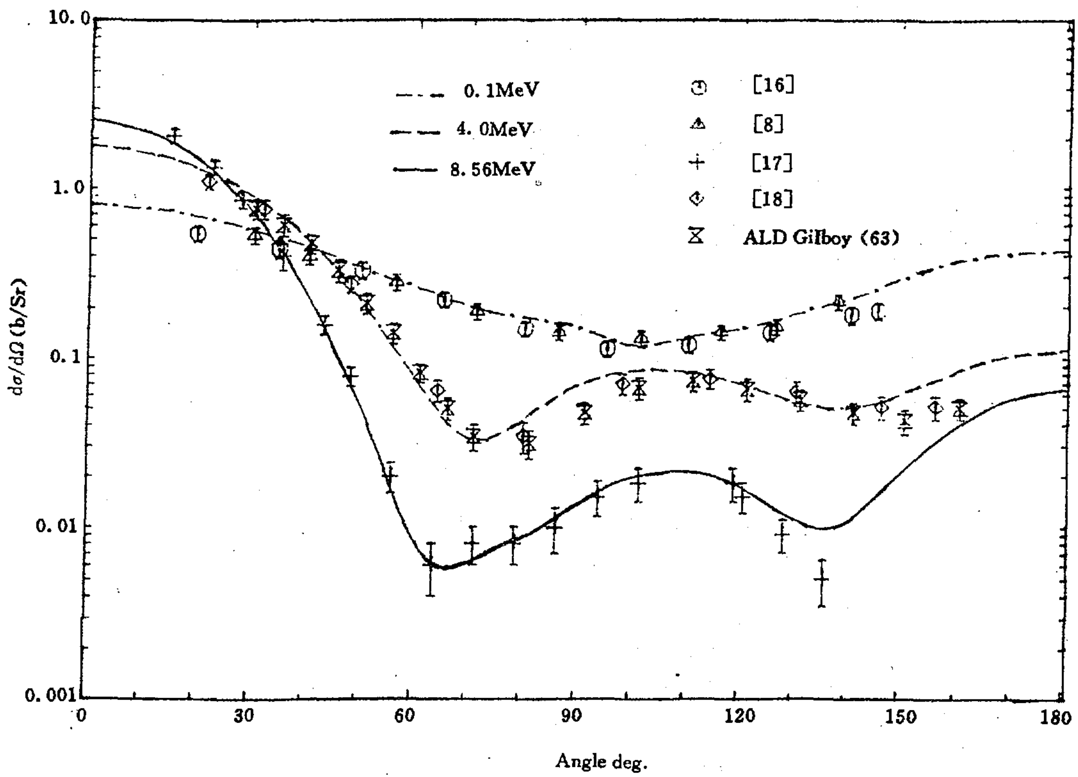

Fig. 10–1 Elastic scatter angular distributigns of Cr

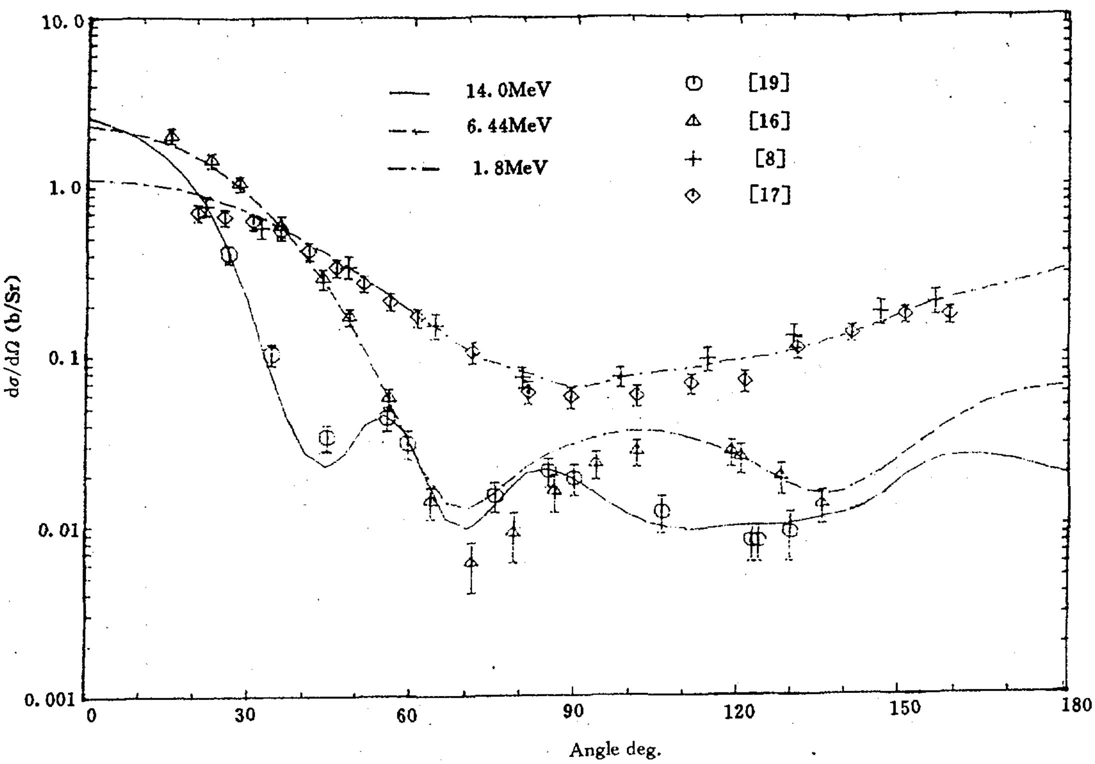

Fig. 10−2 Elastic scatter angular distributigns of Cr

REFERENCES

[1] Yu Ziqiang, Cai Chonghai et al., Thoretical calculation program MUP2 for middle and heavy nuclei,inter report(1986)

[2] Wang Chuenhao, CNDC−58010, 182(1983)

[3] S. F. Mughabghab, BNL−325 (4th Edition) (1986)

[4] D. C. Hetrick and N. M. Larson, ENDF / B−6 (1989)

[5] T. Asami et al., JENDL−3 (1987)

[6] P. Andersson et al., Nuclear Data Sheets 48, 251(1986); 42, 457(1984); 38, 463(1983); 28, 179(1979); 26, 5(1979)

[7] V. Filippov et al., 83KIEV 3, 107(1983)

[8] P. T. Guenther et al., Nucl. Sci. Eng., 82, 408(1982)

[9] D. C. Larson et al., ORNL−5787, 174(1981)

[10] F. G. Perey et al., CSISRS(1973)

[11] Green et al., WAPD−TM−1073(1973)

[12] Foster et al., Phys. Rev., C3, 576(1971)

[13] S. Cierjacks et al., KFK−1000(1968)

[14] J. F. Whalen et al., ANL−7210(1966)

[15] C. T. Hibdon et al., Phys. Rev., 108, 414(1957)

[16] W. E. Kinney et al., ORNL–4806(1974)
[17] B. Holmqvist et al., AE–385(1970); AE–430(71)
[18] A. B. Smith et al., Privite Comm., (1966)
[19] P. H. Stelson et al., Nucl. Phys., 68, 97(1965)
[20] Sokolov et al., U. F. Z., 18(2), 263(1973)
[21] Malmskog et al., AE–FN–25(1972)
[22] M. V. Pasechnik et al., Yadernaya Fizika 11, 958(1970)
[23] I. A. Korzh et al., U. F. Z., 12(9), 1571(67); 9(5), 577(64)
[24] L. Y. Kazakova et al., EANDC–50, 200(1965)
[25] A. I. Abramov et al., AE–12, 62(1962)
[26] V. I. Strizhak et al., Z. E. T., 31(5), 907(1956)
[27] H. L. Taylor et al., Phys. Rev., 100, 174(1955)
[28] Zhou Hongmo, Yu Ziqiang et al., Auto–parameter adjusting optical model calculation program AUJP, inter report (1986)
[29] P. T. Karatzas et al., Nucl. Sci. Eng., 67, 34(1978)
[30] Biryukov et al., 75 KIEV 4, 118(1975)
[31] I. Fujita et al., Nucl. Sci. Tech., 9, 301(1973)
[32] N. P. Glazkov et al., Sovt. Jour. At. Eng., 15, 416(1963)
[33] D. M. Van Patter et al., Phys. Rev., 128, 1246(1962)
[34] L. Smith et al., Nucl. Sci. Eng., 76, 43(1980)
[35] D. L. Broder et al., Sovt. Jour. At. Eng., 16(2), 103(1964)
[36] D. A. Salnikov et al., Helsinki Conf. (70); IAEA–CN26 / 79
[37] Shinjiro Itagaki et al., 88 Mito, 283–286(1988)
[38] E. Almen Ramstrom et al., Sovt. J. At. Energy, 503(1975)
[39] G. F. Auchampaugh et al., 77BNL, 231(1977)
[40] J. Frehaut et al., BNL–NCS–51245, 399(1980)
[41] Ghorai et al., BAP 31, 65(1986)
[42] Hoang Dac et al., HOANG DAC LUC(1986)
[43] Klochkova et al., 80 KIEV, 2, 58(1980)
[44] Gupta et al., PRM24, 637(1985)
[45] I. Ribansky et al., ANE 12(11), 577(1985)
[46] M. Viennot et al., MOH–5, 10(1982)
[47] Artemev et al., Sovt. At. Energy, 49(3), 195(1980)
[48] S. M. Qaim et al., Nucl. Phys., A283, 269(1977)
[49] Valkonen et al., JU–RR–1 / 76(1976)
[50] J. Dresler et al., INR–1464, 12(1973)
[51] B. Mitra et al., Nucl. Phys., 83, 157(1966)
[52] J. E. Strain et al., ORNL–3672(1965)
[53] Kern et al., Nucl. Phys., 10, 226(1959)

[54] R. Pepelnik et al., 85 SANTA, 1, 211(JA46)(1985)
[55] B. M. Bahal et al., GKSS–84–E–(1984)
[56] L. Smith et al., Nucl. Sci. Eng.; 78, 420(1981)
[57] H. A. Husain et al., J. Inorg. Nucl. Chem., 29, 2665(1967)
[58] E. Wattecamps et al., 82 ANTWER, 159(1983)
[59] A. Paulsen et al., Nucl. Sci. Eng., 78(4), 377(1981)
[60] Le Rigoleur et al., CEA–N–1661 (1973)
[61] B. C. Diven et al., Phys. Rev., 120, 556(1960)
[62] Yu. Ya. Stavisskij et al., Sovt. Jour. At. Eng., 12(6), 514(1962)
[63] M. Budnar et al., INDC(YUG)–6(1979)
[64] S. M. Grimes et al., Phys. Rev. C19, 2127(1979)
[65] Su Zongdi et al., A new set of level density parameters for Fermi Gas Model, inter report(1984)

THE EVALUATION OF NEUTRON NUCLEAR DATA FOR NATURAL IRON

Liu Tingjin Liu Wenqin

(CHINESE NUCLEAR DATA CENTER, IAE)

INTRODUCTION

Natural iron is an important structrure and shielding material for fission and fusion reactor, its neutron nuclear data is very important for reactor engeneering. So the data always have continously been measured and evaluated in the world, for example, for ENDF / B of USA, JENDL of Japan, BROND of USSR, so that they could be more reliable.

The possible reactions on natural iron and their Q values in the energy region up to 20 MeV are listed in Table 1.

The neutron data files 1~5 in the energy region from 10^{-5} eV to 20 MeV have been evaluated and recommended by this work, based on previous evaluation[1] , all measured data up to 1985 and new theoretical calculation[2].

1 THE EVALUATION OF EXPERIMENTAL DATA

1) Total Cross Section

There are more than 70 papers concerning the measurements of total cross section. Among them, there are 5 papers[3~7], which are more important and were measured after 1960 using white neutron sources.

In the energy region from 0.4 to 5 MeV, there are a lot of resonance structures, it's better to keep the measured resonances, so it is not suitable to average multi–sets of data. Therefore, two sets of better data[6,7] in the energy region 0.4 ~ 0.5 MeV and 0.5 ~ 5 MeV respectively were choosen, and the energy points were selected (Table 2). The two sets of data are linked with each other at 0.5 MeV point but there is a small shift (< 0.06 keV) for the resonance energies.

Above 5 MeV, it is a smooth region, 4 sets of data[3~6] were choosen and the data were averaged over 20 or 5 energy points (Table 2), and then the data were fitted with spline function[8].

After above processing, the data were taken as recommended ones (Fig. 1).

2) Nonelastic Scattering and (n,2n) Reaction Cross Section

There are more than 20 measurements of nonelastic scattering cross section. After the analysis, 13 sets of data[9~21] of them were used. It can be seen that, in present evaluation, no newly measured but more data were used than previous evaluation. The data were fitted with spline function and taken as recommended data (Fig. 2). It should be noticed that in the energy region of 4 ~ 12 MeV the recommended data go through the top limit of the measured data, this is the result of considering the consistence between total, elastic and nonelastic cross section.

(n,2n) cross sections are deficient in experimental measurements and only two sets of data[22,23] at 14 MeV can be used, among them the fission cross section of ^{238}U was taken as standard for Frehaut's measurement, the data were renormalized by using new data of ENDF / B–5.

3) (n,x) Reaction Cross Section

In the energy region below 20 MeV, there are (n,α), (n,p), (n,d), (n,t) reactions. For natural iron, the measured data are very few for all these reactions (although there are lots of data for ^{56}Fe (n,p) reaction). Only 2, 2, 1, 1 sets of data can be used respectively for (n,α)[24,25], (n,p)[26,27], (n,d)[28], (n,t)[29] reactions.

4) Inelastic and Capture Cross Section

For total inelastic cross section, 8 sets of data[30~37] can be used. It can be seen that the data were all measured in early years and are concentrated on 2 ~ 3 MeV region.

There are 5 sets of data[38~42] for inelastic scattering to the first、 second level of ^{56}Fe ($Q = -0.847$, -2.0851 MeV). The data were fitted with spline program[8] and taken as the recommended data in low energy region for the cross section of inelastic scattering to the third, fifth levels of natural iron (Fig. 3).

A few measured data are for other levels and there is a large discrepancy between them.

There are 4 sets of data[43~46] for (n,γ) reaction cross section, and they mainly concentrate on low energy region. The data were fitted with spline code[8].

5) Elastic Scattering Cross Section and Angular Distribution

16 sets of measured data[41~62] were used for elastic scattering cross section and angular distribution. Among them, Holmgvist's data (1969) were renormalized by ENDF / B–5 (n,p) scattering standard data. It can be seen that the data are mainly in the energy region below 8 MeV, it is not enough to get the excitation function in the whole energy region.

For the angular distribution, where there are measured data in the energy region 0.45~ 16.1 MeV, the differential cross sections at 10 energy points were selected and taken as the basis for adjusting optical model parameters in the theoretical calculation[2].

2 RECOMMENDATION AND COMPREHENSIVE ADJUSTING

1) Based on above evaluated experimental data as well as experimental data of iron isotopes[63], especially total, nonelastic and differential elastic scattering cross sections, the optical model and other parameters in the theoretical calculation were adjusted, so that the agreement between experimental and theoretical calculated data becomes as good as possible, and as a result, a complete data, including cross section, angular distributions and energy spectra, have been got in the whole energy region 0.4~20 MeV[2].

Considering the situation of experimental and theoretical data, the recommended data for each reaction channels are as follows :

Total, nonelastic cross sections : experimental data;

Cross sections of inelastic scattering to third, fifth level : experimental data for low energy region (threshold~ 5 MeV); theoretical calculation for high energy region (5~20 MeV) normalized to experimental data at 5 MeV;

(n,p), (n,2n) reaction cross sections : theoretical calculation normalized to experimental data at 14 MeV (Fig. 4,5).

Others (except mentioned below) : theoretical calculation.

2) To keep the consistent relation between total, elastic and nonelastic scat-

tering cross sections and also to conveniently treat the resonance structure in the total cross section, the elastic cross section (MT=2) were obtained by substracting the nonelastic cross section from total cross section :

$$\sigma_{nn} = \sigma_{tot} - \sigma_{non} \tag{1}$$

The calculated elastic cross sections are roughly agree with experimental data (Fig. 6).

3) In order to satisfy the consistence relation for nonelastic channels, the total inelastic scattering cross section (MT=4) were calculated as follows :

$$\sigma_{in} = \sigma_{non} - \sigma_{n2n} - \sigma_{n\gamma} - \sigma_{np} - \sigma_{nd} - \sigma_{n^3He} - \sigma_{nt} - \sigma_{n\alpha} - \sigma_{nn'p} - \sigma_{nn'\alpha} \tag{2}$$

4) To meet the consistent relation for inelastic scattering channels, the continuous inelastic scattering cross section (MT=91) were calculated as follows :

$$\begin{aligned} \sigma_{inc} &= \sigma_{int} - \sigma^{t}_{in1} - \sigma^{t}_{in2} - \sigma^{e}_{in3} - \sigma^{t}_{in4} - \sigma^{e}_{in5} - \sigma^{t}_{in6} - \cdots \sigma^{t}_{in40} \\ &= \sigma^{t}_{inc} - (\sigma^{t}_{int} - \sigma_{int}) - [(\sigma^{e}_{in3} + \sigma^{e}_{in5}) - (\sigma^{t}_{in3} + \sigma^{t}_{in5})] \end{aligned} \tag{3}$$

where, σ_{inl} ($l=1, 2, \cdots 40$) is the cross section of inelastic scattering to discrete level, σ_{int} is the total inelastic cross section calculated above, and the footnotes t, e refer to theoretical and experimental data respectively.

There are some small negative values in some paticular small energy region for σ_{inc} calculated in such way. Obviously it is not reasonable, so the negative values are all taken as zero, and correspondingly the total inelastic, nonelastic and elastic cross section are corrected, so that the consistent relations for inelastic, noelalstic and total reaction channels can be kept. The continuous inelastic scattering cross section got in this way is shown in Fig. 7.

For natural iron, the upper bound of the resolved resonance region is taken at 0.4 MeV, but the threshold of the inelastic scattering to the first and second levle are lower than 0.4 MeV. In present evaluation, the data of these inelastic scattering are still kept, and taken as background included in the total inelastic, nonelastic and total cross sections.

3 RESONANCE PARAMETERS

In the energy region 10^{-5} eV～400 keV, multi–level resonance parameters of 4 isotopes ($^{54,56,57,58}Fe$) are given, and in lower energy region, negative resonance is taken. The parameters were got from Ref. [65], but to improve the agreement with expreimental data, following adjusting and modifying were made :

1) Thermal Energy Region

Using original negative resonance parameters, the calculated scattering cross section (so total cross section) is smaller by about 2.5 b than experimental one. The neutron width was adjusted to make the calculated data agree with experimental ones at the thermal energy point and energy region nearby. The oringinal and adjusted parameters as well as the results calculated with them are given in Table 3.

2) The Energy Region near Resonance Upper Bound 400 keV

In the energy region 380~ 400 keV, the average values of scattering cross section (so total cross section) calculated with original parameters are two times larger than the average of experimental ones[7] in the energy region near 400 keV (Fig. 7) (there are still lots of resonance structures). Checking the parameters, background cross section and the cross section in smooth region, no problems have been found, and the parameters are basically the same as recommended in BNL–325[66]. There are also no much effects in adjusting the leading s wave resonances. Adding 4 important s wave resonances above 400 keV (Γ_n = 480~ 7700 eV), the calculated cross sections become much lower, and agree with experimental data, and linked with smooth region data at the bound 400 keV (Table 4, Fig. 8). It can be seen that the interference effect between the resonances is quite large and in some cases (e. g. for Fe, there are large s wave resonances above the upper bound) the important resonances above the upper bound must be added, otherwise the cross sections calculated with the parameters are much different from real ones.

4 ANGULAR DISTRIBUTIONS AND ENERGY SPECTRA

Although there are lots of experimental data for elastic scattering differential cross section in the energy region 0.4~ 16.1 MeV, the theoretical calculated data[2] are still taken as recommended ones in the whole energy region, for the agreement between calculated and experimental data is quite well (Fig. 9).

The angular distributions for inelastic scattering to discrete levels are deficient in experimental data, the calculated data are used.

For angular distributions of continuous neutrons, including inelastic scattering to continuous states, (n,2n),. (n,n′p), (n,n′α) etc. reactions, there are no experimental data and can′t be calculated, so they are assumed to be isotropic.

Theoretical calculated data for secondary neutron spectra are recommended.

5 CONCLUSION REMARKS

This evaluation was basically completed in 1986, at that time, the newest evaluations were ENDF / B–5[67]. and JENDL–2[68] (but could'nt get the data of ENDF / B–5).

Comparing with previous evaluation[1] and ENDF / B–5[67], for total cross section, in addition to the measured data of Cierjacks[6] (1966) and Carlson[3] (1970), which were commonly used by all authors, new data of Foster[4] (1971), Perey[5] (1972) and Pattenden[7] (1973) were used in this evaluation. The penetration calculation with total cross section and comparing with macroscopic measured data show that the results of this evaluation is improved in high energy region comparing with ENDF / B–4[70].

Comparing previous evaluation and ENDF / B–5, the cross section of (n,2n), (n,x) reactions have also been improved. For example, a new important data (Frehaut[23] (1980)) were added for (n,2n) reaction, and there are new measured data for (n,α) (Paulsen[24] (1981), Wattecamps[25] (1983)) and (n,d) reaction (Grimes[28] (1979)), while no experimental data were available in previous evaluation and ENDF / B–5.

In 1990, ENDF / B–6 and JENDL–3 data were available, so a comparision with JENDL–3 (the data of iron are given in its isotopes in ENDF / B–6) was done in 1991 and the results (shown in Figures) are also presented in this report. It can be seen that there are some differences for total and elastic cross sections in high energy range, and also quite large differences for noelastic、(n,2n), (n,p) cross sections, and for cross sections of inelastic scattering to first, second levels of ^{56}Fe.

Table 1 n+^{0}Fe Reactions and their Q values (E_n ‹20 MeV)

Reaction	Q Values (MeV)	Thres. Energy Eth (MeV)	MT Number
tot	0		1
(n,n)	0		2
non	0		3
(n,n′)	−0.846	0.8611	4
(n,2n)	−11.204	11.406	16
(n,n′α)	−7.6194	7.757	22
(n,n′p)	−10.19	10.374	28
(n,γ)	7.803		102
(n,p)	0.089		103
(n,d)	−7.9651	8.109	104
(n,t)	−11.932	12.148	105
(n, ^{3}He)	−10.535	10.725	106
(n,α)	0.8484		107

Table 2 The processing of measured data for total cross sections

Energy region (MeV)	Author	Processing	The number of points after processing
0.4∼0.5	Pattenden [7]	Select 1 each 2 Keep peak points	125
0.5∼5.0	Cierjacks [6]	Select 1 each 2 Keep peak points	1655
5∼20	Ciejacks [6]	Average over each 20 points	47
5∼20	Foster [4]	Average over each 5 points	23
5∼20	Perey [5]	Average over each 5 points	77
5∼20	Carlson [3]	Average over each 5 points	76

Table 3 The adjusting of negative resonance parameters and calculated thermal cross section

	Resonance parameters			
	E_n (keV)	Γ_n (eV)	Γ_γ (eV)	Γ_t (eV)
Oringinal	−2.0	180	0.64	180.64
Adjusted	−2.0	230	0.50	230.5

	Calculated thermal cross section					
	σ_{nn} (b)		$\sigma_{n\gamma}$ (b)		σ_t (b)	
	1)	2)	1)	2)	1)	2)
Oringinal	8.75	8.74	2.66	2.66	11.41	11.40
Adjusted	11.27	11.27	2.66	2.66	13.94	13.94
Experimental data[66]	11.35 ± 0.03		2.56 ± 0.03		13.91 ± 0.04	

1) Calculated with check program "PSYCHE"

2) Calculated with code MSBW2[69]

Table 4 The average of total cross section near upper bound 400 keV of resonance region

	The average over 380~400 keV		
	σ_{nn} (b)	$\sigma_{n\gamma}$ (mb)	σ_t (b)
Oringinal	10.778	6.773	10.78
Adjusted	5.958	7.088	5.965
Experimental			5.36
ENDF / B−4			6.25
JENDL−2			3.14 (300~400 keV)
			3.61 (400~500 keV)

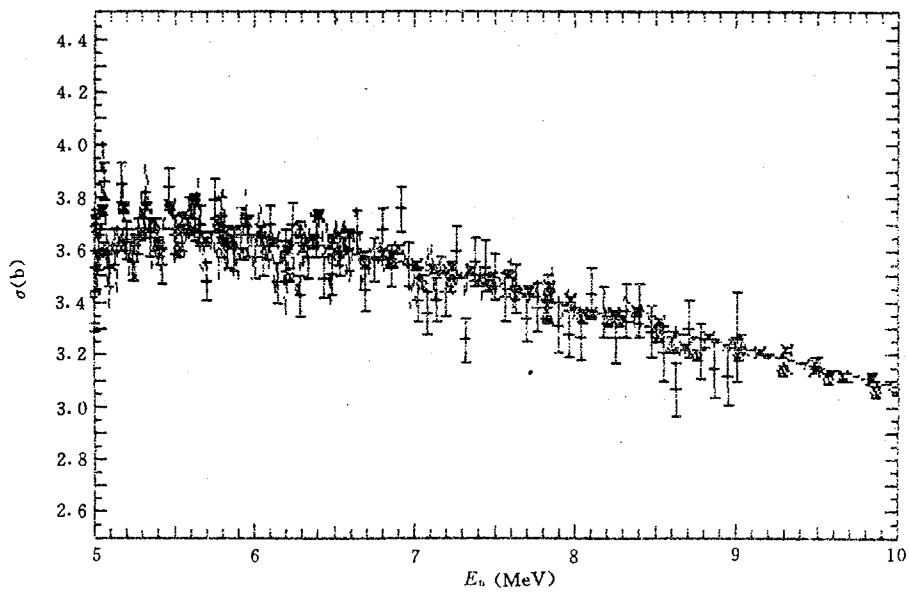

Fig. 1−1a Total cross section (5～10 MeV)

I Exp. data —— Present work - - - JENDL−3

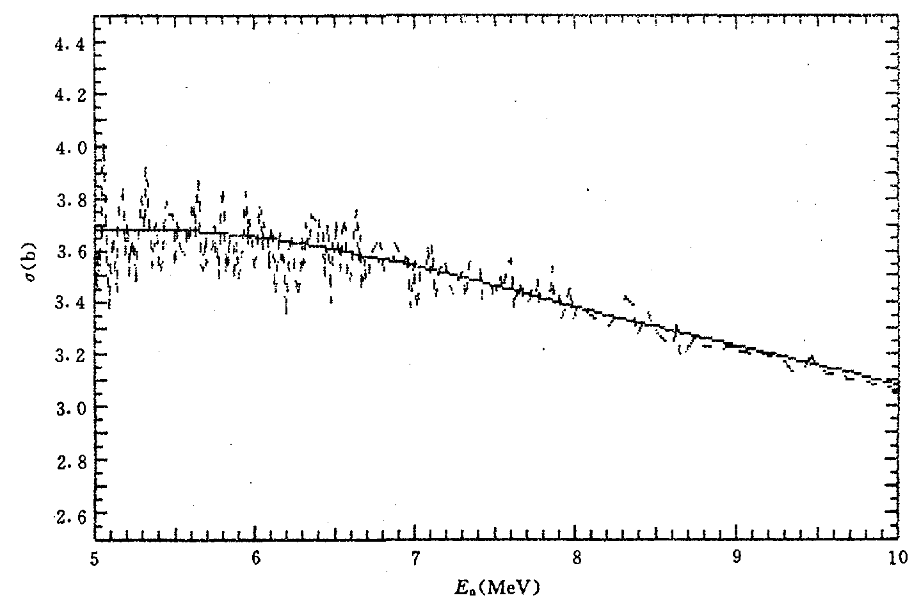

Fig. 1−1b Total cross section (5～10 MeV)

—— Present work - - - JENDL−3

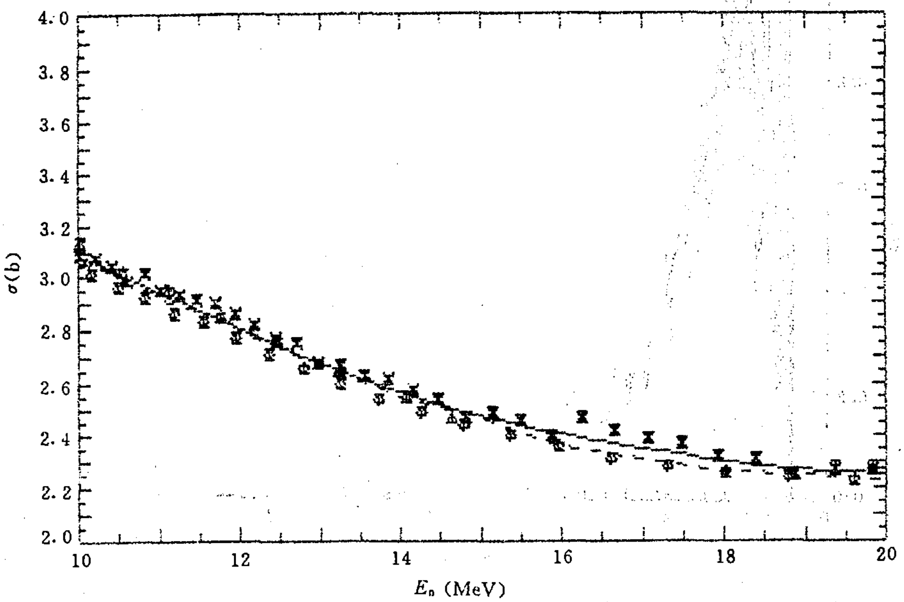

Fig. 1–2 Total cross section (10～20 MeV)

□ × △ Exp. data

—— Present work

– – – JENDL–3

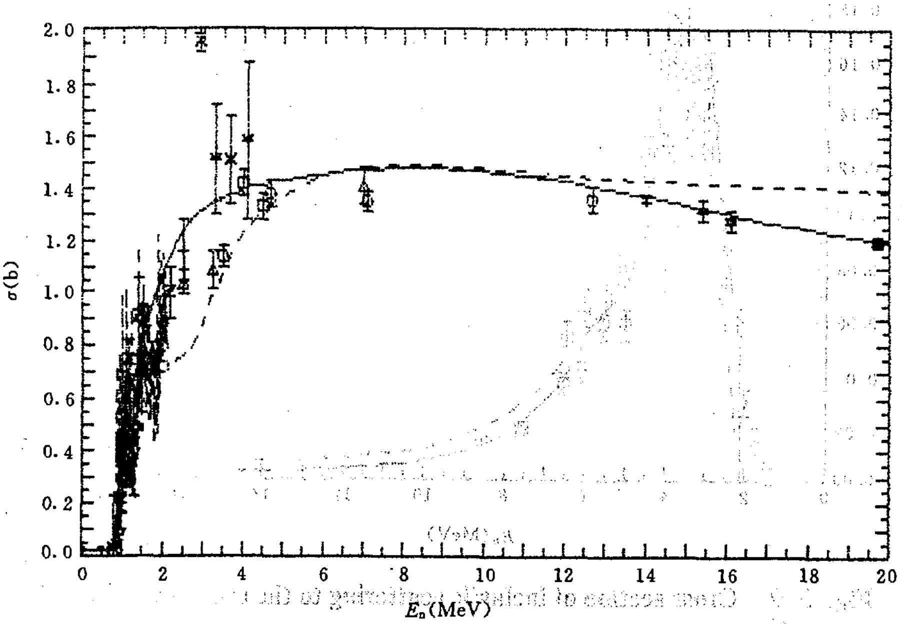

Fig. 2 Nonelastic scattering cross section

• × △ Exp. data —— Present work – – – JENDL–3

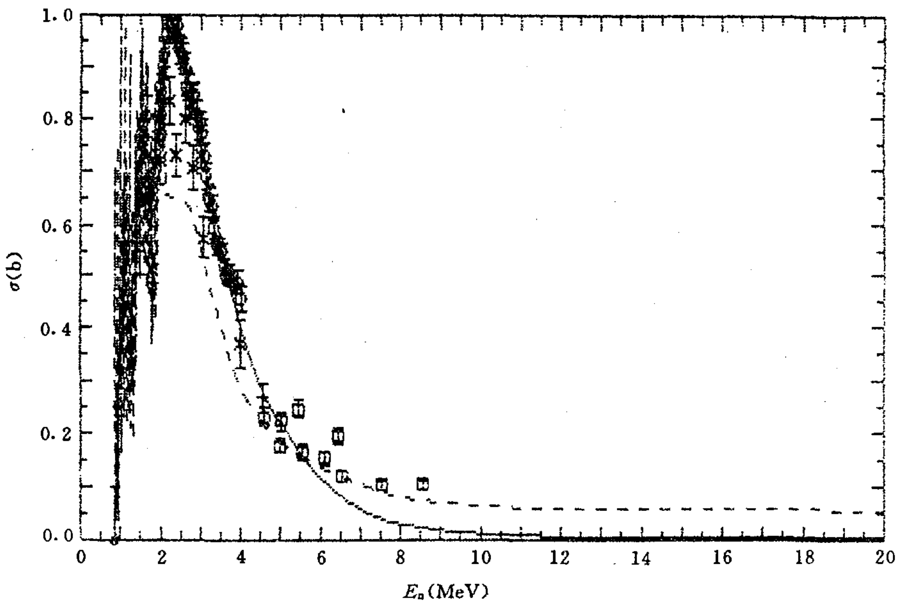

Fig. 3–1 Cross section of inelastic scattering to the first level of ^{56}Fe

□ × Exp. data

—— Present work

– – – JENDL–3

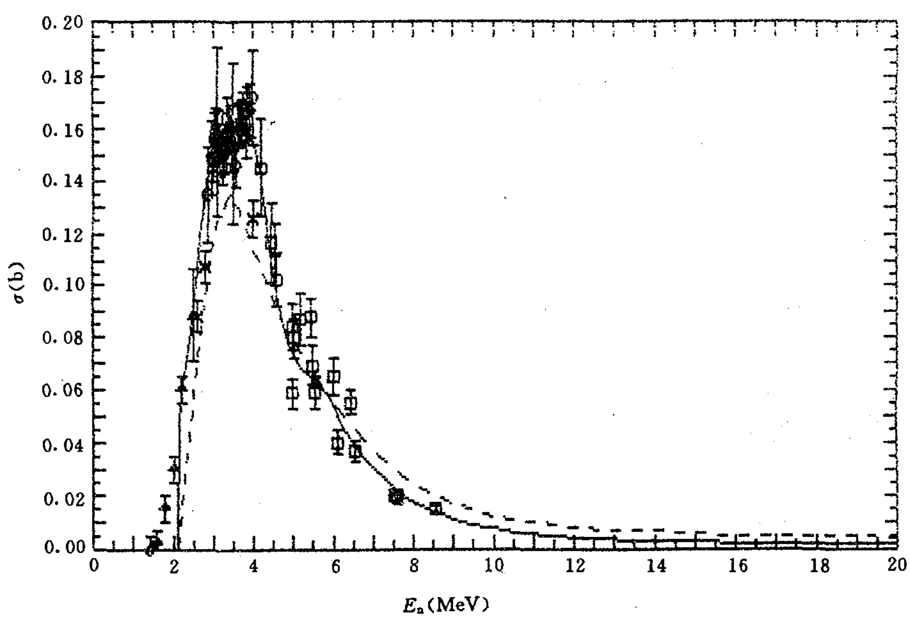

Fig. 3–2 Cross section of inelastic scattering to the second level of ^{56}Fe

□ △ Exp. data

—— Present work

– – – JENDL–3

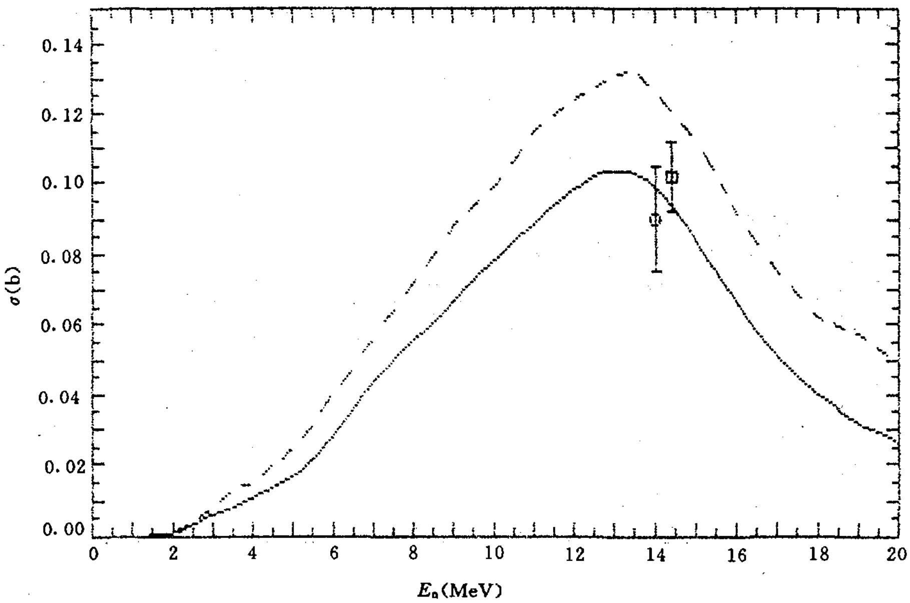

Fig. 4 (n,p) cross section

○ □ Exp. data

—— Present work

– – – JENDL–3

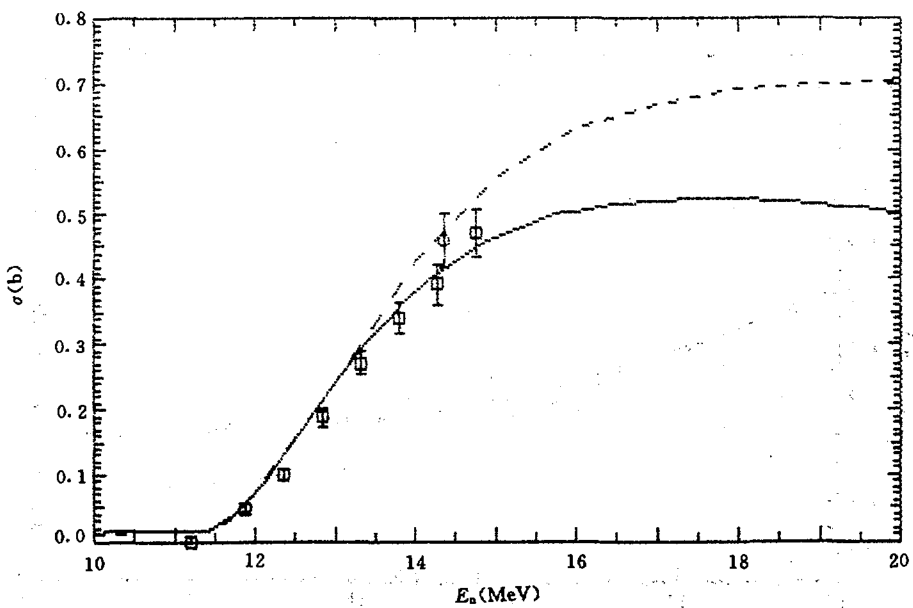

Fig. 5 (n,2n) cross section

□ Exp. data

—— Present work

– – – JENDL–3

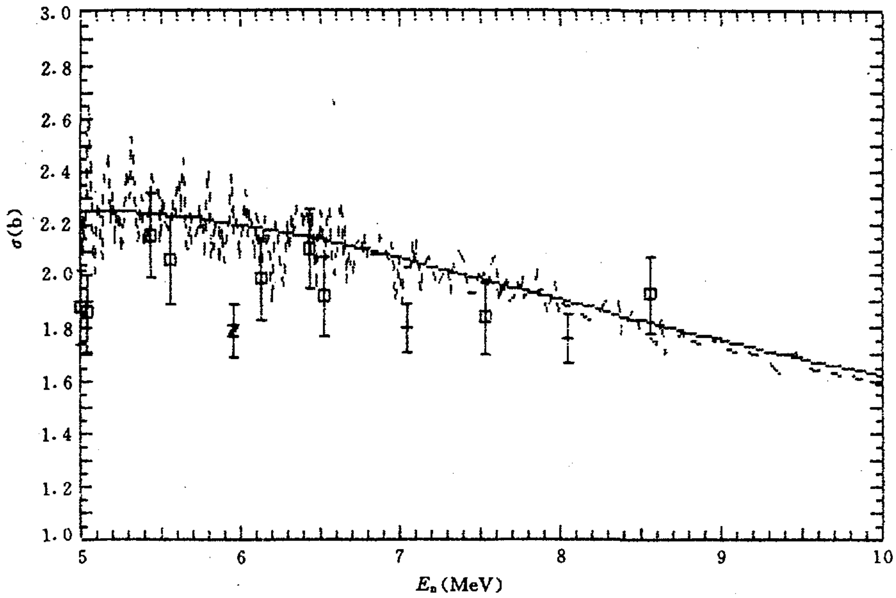

Fig. 6–1 Elastic scattering cross section (5～10 MeV)

□ × Exp. data

—— Present work

– – – JENDL–3

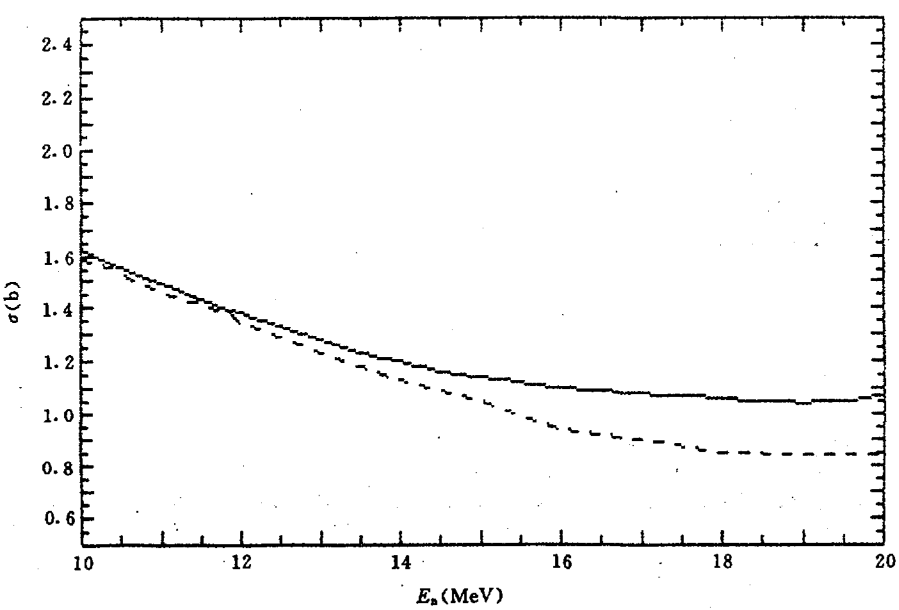

Fig. 6–2 Elastic scattering cross section (10～20 MeV)

—— Present work

– – – JENDL–3

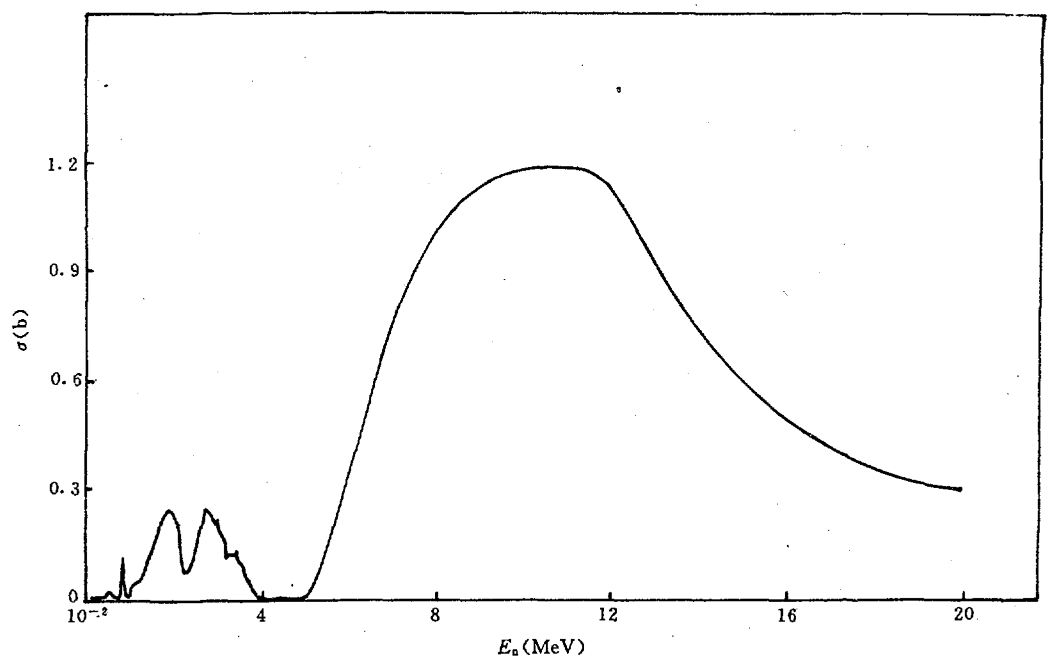

Fig. 7 Recommended cross section of inelastic scattering to continuous states

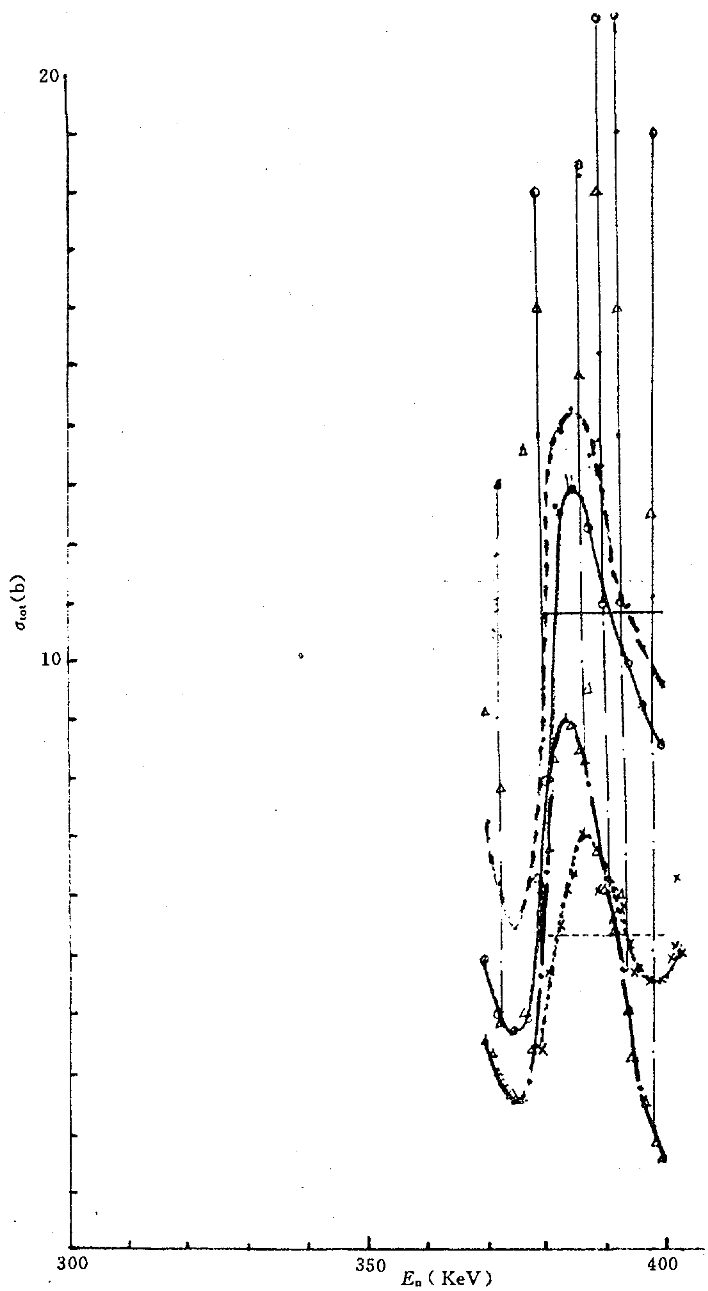

Fig. 8 Total cross section near upper bound 400 keV of resonance region

• • × • • × • • Exp. data

– – – Doppler broad T = 280°K calculated with MSBW2 code[69]

——— No broad 〃

△ • △ No broad, adding 4 resonances above 400 keV 〃

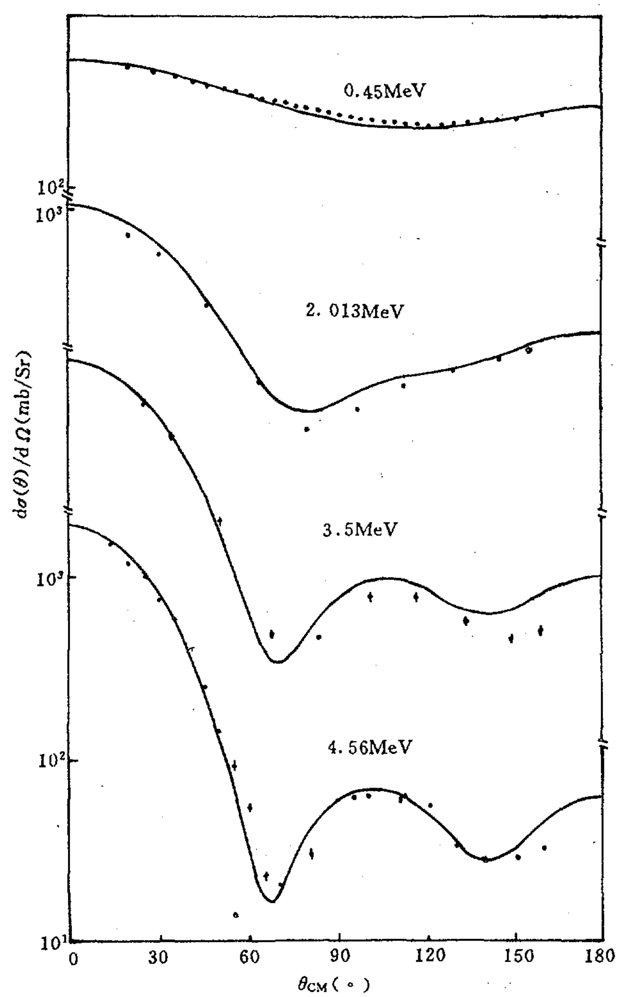

Fig. 9–1 Elastic scattering differential cross section (0.45~5 MeV)

I Exp. data

—— Present work, calcuated with optical model[2]

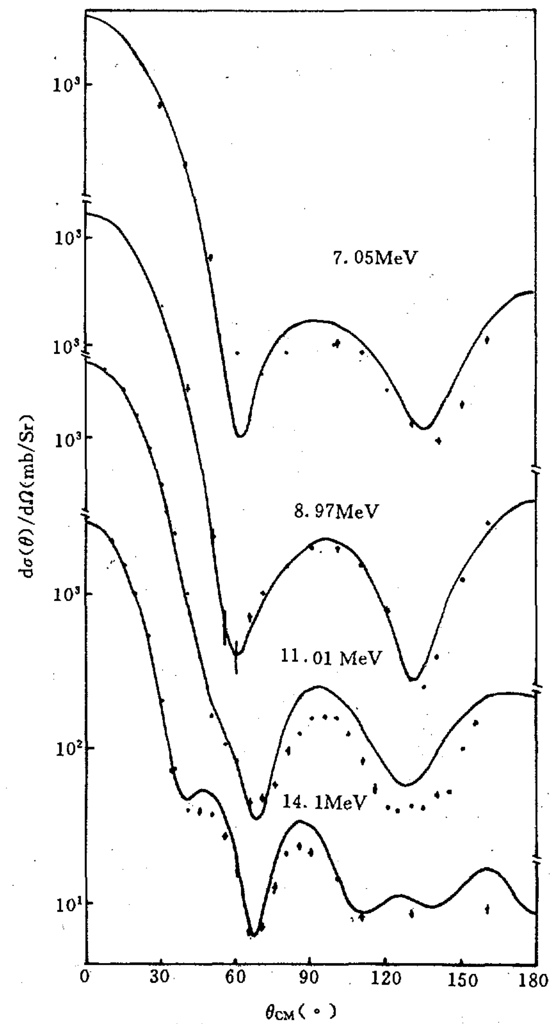

Fig. 9–2 Elastic scattering differential cross section (7 ~ 15 MeV)

Exp. data

—— **Present work, calculated with optical model**

REFERENCES

[1] CNDC, "Chinese Evaluated Nuclear Data Library, Version 1", p173 (1986)

[2] Han Yinlu et al., The Calculation of Neutron Nuclear Data for Natural Fe, Internal Report (1986)

[3] A. D. Carlson, Nucl. Sci. Eng., 42, 28 (1970)

[4] D. G. Foster, Phys. Rev., C3, 376 (1971)

[5] F. G. Perey, CRNL–4823 (1972)

[6] S. Cierjacks, KFK–1000 (1968)

[7] N. J. Pattenden, AERE–R–7425 (1973)

[8] Liu Tingjin et al., Chinese Jou. of Nuclear Sci. & Eng., 8, 1, 79 (1988); Zhou Hongmo et al., Atomic Energy Sci. & Tech., 4, 389 (1987)

[9] J. R. Beyster, Phys. Rev., 98, 1216 (1955)

[10] H. L. Taylor, Phys. Rev., 100, 174 (1955)

[11] J. R. Beyster, Phys. Rev., 104, 1319 (1956)

[12] M. K. Machwe, Phys. Rev., 114, 1563 (1959)

[13] H. Walt, Phys. Rev., 93, 1062 (1954)

[14] R. C. Allen, EXFOR 11693002 (1955)

[15] L. C. Beghian, Nucl. Sci. Eng., 17, 82 (1963)

[16] M. V. Pasechnik, 55 GENEVA (1955)

[17] V. I. Kukhtevich Atom. Ener., 5, 565 (1958)

[18] Flerov, Atom. Ener. 1, 4, 115 (1956)

[19] Yu. G. Dejtyarev, Atom. Ener. 11, 397 (1961)

[20] A. I. Abramov, Atom. Ener., 12, 62 (1962)

[21] V. I. Strizhak., Jou. of Exp. & Theo., 31, 907 (1956)

[22] C. A. Calnikov, Yad. Fiz., 12, 6, 1135 (1972)

[23] J. Frehaut, CEA–R–4627 (1980)

[24] Paulsen, Nucl. Sci. Eng., 78, 4, 377 (1981)

[25] Wattecamps, 82 ANTWEP, 159 (1983)

[26] F. L. Hassler, Phys. Rev., 125, 1011 (1962)

[27] V. V. Verbinski, Phys. Rev., 108, 779 (1957)

[28] S. M. Grimes, Phys. Rev., C19, 2127 (1979)

[29] T. Biro, Jou. Inorg. Nucl. Chem., 37, 1583 (1972)

[30] D. B. Thomson, Phys. Rev., 129, 1649 (1963)

[31] H. H. Landon, Phys. Rev., 117, 1192 (1958)

[32] A. Jacquot, Nucl. Phys., 84, 239 (1966)

[33] A. Salmikov, YK–7, 102 (1972)

[34] G. A. Prokopesk, Ukrainsij Fizi. Zhur. 14, 330 (1969)

[35] V. I. Popov, Atom. Ener., 30, 12, 498 (1957)

[36] N. P. Glazkov, Atom. Ener., 14, 400 (1963)
[37] R. W. Benjamin, Nucl. Phys., 79, 241 (1966)
[38] W. E. Wekinney, ORNL–4515,–7006 (1970)
[39] A. Smith, Nucl. Sci. Eng., 73, 186 (1980)
[40] B. Antolkovic, EANDC (OR)–51 (1966)
[41] W. B. Gilboy, Nucl. Phys., 64, 130 (1965)
[42] R. W. Behjam, Nucl. Phys., 79, 241 (1966)
[43] B. C. Diven, Phys. Rev., 120, 556 (1960)
[44] L. E. Rigolov, CEA–N–1661 (1973)
[45] Yu. Ya. Staviskii, Atom. Ener., 10, 264 (1961)
[46] A. V. Malyshen, Atom. Ener., 17, 508 (1964)
[47] A. Begum, Nucl. Phys., A332, 349 (1979)
[48] M. Hykutake, J. Phys. Soc. Japan, 38, 3, 606 (1975)
[49] A. Smith, Nucl. Sci. Eng., 73, 186 (1960)
[50] J. C. Ferrer, Nucl. Phys., A275, 325 (1977)
[51] D. E. Velkley, Phys. Rev., C9, 2181 (1974)
[52] W. E. Kinney, ORNL–4515 (1970)
[53] B. Holmgist, AE–430 (1971)
[54] B. Holmgist, AE–366 (1969)
[55] J. H. Coon, Phys. Rev., 111, 250 (1958)
[56] A. B. Smith, 66 PARIS (1966)
[57] W. B. Gilooy, Nucl. Phys., 64, 130 (1965)
[58] I. A. Korzh, Ukrainskij Fiz. Zhur., 12, 9, 1571 (1967)
[59] W. E. Kinney, 76 LOWELL, 1319 (1976)
[60] W. Malmskog, AE–FN–25 (1972)
[61] A. Jacquot, Nucl. Phys., 84, 239 (1966)
[62] E. Barnard, Nucl. Phsy., A118, 321 (1968)
[64] Yuan Hanrong et al., Internal Comm. (1986)
[64] CNDC, "Selected Papers of Fourth Nucl. Data Conf.", p43 (1986)
[65] CNDC, "Neutron Resonance Theo. & Param.", p342 (1981)
[66] S. F. Mughabghab, BNL–325, 4th Edi. (1984)
[67] R. Kinsey, ENDF–201 (1979)
[68] T. Nakagawa, JAERI–M 84–103 (1984)
[69] Lu Guoxiong et al., Internal Comm. (1988)
[70] Yu Peihua, Internal Comm. (1987).

THE EVALUATION OF NEUTRON DATA FOR NATURAL NICKEL

Ma Gonggui Zou Yiming Wang Shiming

(INSTITUTE OF NUCLEAR SCIENCE AND TECHNOLOGY, SICHUAN UNIVERSITY, CHENGDU)

ABSTRACT

The present work was done for CENDL–2 and supersedes the CENDL–1 (MAT = 1280, evaluated by Ma Gonggui[1]).

Complete neutron nuclear data for natural nickel were evaluated based on both data measured up to 1989 and calculated with program MUP2[2] and AUJP[3]. The cross sections were mainly refered to BNL–325 (4th–86)[4], that also compared with ENDF / B–6 (89)[5] and JENDL–3 (87)[6].

The following neutron data are given for Ni in the energy range 10^{-5} eV to 20 MeV in ENDF / B–5 format (MAT = 2280). The cross sections include total, elastic, nonelastic, total inelastic, inelastic cross sections to 21 discrete levels and continuum state, (n,2n),(n,3n),(n,n′α) + (n,αn′), (n,n′p) + (n,pn′), (n,p), (n,d), (n,α) and capture cross sections. Derived data (MT = 251, 252 and 253) are also included.

Angular distributions and energy spectrum of secondary neutron are also given.

INTRODUCTION

This is almost a completely new evaluation, the neutron cross sections and angular distributions as well as the secondary neutron energy spectrum have been updated.

The resolved resonance parameters for $^{58, 60, 61, 62, 64}$Ni and the background were given from 10^{-5} eV to 0.6 MeV based on ENDF / B–6 data[5].

The levels for inelastic scattering were almost taken from new data (see Table 1)[7].

Table 1 Discrete levels of Ni (Abundance %)

^{58}Ni (68.27)		^{60}Ni (26.1)		^{61}Ni (1.13)		^{62}Ni (3.59)		^{64}Ni (0.91)	
0.0	0^+	0.0	0^+	0.0	$3/2^-$	0.0	0^+	0.0	0^+
1.4545	2^+	1.3325	2^+	0.0674	$5/2^-$	1.1729	2^+	1.3458	2^+
2.4591	4^+	2.1586	2^+	0.2830	$1/2^-$	2.0486	0^+		
2.7755	2^+	2.2849	0^+			2.3018	2^+		
2.9018	1^+	2.5058	4^+			2.3364	4^+		
2.9424	0^+	2.6262	3^+			2.8912	0^+		
3.0376	2^+	3.1197	4^+						
3.2634	2^+								

1 NEUTRON CROSS SECTIONS

1.1 Total Cross Section

Above the resolved resonance region,there are still some small structure in some energy range. The experimental data were taken from Larson[8], Perey[9], Smith[10] and Koester[11]. In the energy range from 0.6 MeV to 5.0 MeV, the data were mainly taken from Larson's corresponding experimental data. In the smooth energy from 5.0 MeV to 20 MeV, they were obtained from a spline fit to the experimental data of Larson and Perey, shown in Fig. 1.

1.2 Elastic Scattering Cross Section

Above the resolved resonance from 600 keV to 20.0 MeV, the evaluated data were obtained by subtracting the sum of cross sections of all non–elastic processes from the total cross section. In general, the agreement between the evaluated cross section and the experimental data of Li, Smith, Kinney et al. [10, 12~21] is good. This is shown in Fig. 2.

1.3 Non–Elastic Scattering Cross Section

Below 14.2 MeV, the cross section is based on the experimental data of Beyster et al.[22~32], most of the results were measured using sphere transmission method. Above 14.2 MeV, experimental data 1.44 b at 14 MeV were used to normalize the corresponding model calculated results. A plot of these data and the evaluated data is shown in Fig. 3.

1.4 Total Inelastic Cross Section

Below 9.1 MeV, the experimental data were taken from Smith, Biryukov, Border and Towel[33~40]; nearby 14 MeV, they were taken from Fujita and

Salnikov[38~39], including contribution of (n,nx) reactions. Above 7.0 MeV, the calculated results using MUP–2 code were normalized to experimental data 0.93 b at 9.1 MeV energy point. From threshold to 9.1 MeV, the spline function fitting are performed for a number of experimental results. A plot of these experimental data and the evaluated ones are shown in Fig. 4.

1.5 Inelastic Cross Section to Discrete Levels and Continuum

The inelastic scattering cross section to 21 discrete levels were calculated by using MUP–2 code. For 1.3325 and 1.4545 MeV levels, the data were obtained by fitting experimental data measured by Itagaki, Traiforos, Guss, Budtz, Smith, Almen,Kinney, Boschung, Rodgers, Border and Towle; For 1.1729, 2.1586, 2.2849, 2.3018, 2.4591, 2.5058, 2.6261 and 2.7755 MeV levels, the calculated results were normalized to the corresponding experimental data[40~51] (Fig. 5).

The Continuum part was obtained by subtracting the cross section of inelastic scatteringe to 21 discrete levels from the total inelastic.

1.6 (n,2n) and (n,3n) Cross Section

For (n,2n) reaction, the experimental data were measured by Veeser[52] and Ashby[53] in the energy range from 14.7 to 21 MeV. The evaluation data were obtained by spline function fitting experimental data, also compared with the evaluation of Zhou[99]. There are extensive data only for ^{58}Ni. Below 14.7 MeV, the calculated results were normalized to 14.7 MeV energy point. Based on experimental data, The evaluated data are greatly improved (Fig. 6).

Due to no experimental data, the (n,3n) cross section data were taken from theoretical calculated results.

1.7 (n,p) Cross Section

For (n,p) reaction, the experimental data of natural Ni were measured by Hassler[54] only at 14.4 MeV energy point, by means of detecting the outgoing protons, which were plagued with problems of (n,n′p) reaction contamination. On the other hand, the data of the most abundant isotopes ^{58}Ni and ^{60}Ni obtained by activation analysis are extensive, complete and consistent. Hence, it was decided to evaluate the (n,p) cross section for the element in terms of the cross sections of the individual isotopes. Evaluated smooth curves for ^{58,60}Ni, and ^{61}Ni are obtained by fitting experimental data measured by Greenwood et al.[56~88] and with reference to evaluated curve of Lu[55]. Below 14.5 MeV, the (n,p)cross section was obtained from a sum of these curves weighted by the isotopes abundance. Above 14.5 MeV, theoretical calculation was nomalized to the fitting measured value 255.5 mb at 14.5 MeV [57, 59, 66, 68] (Fig. 7).

1.8 (n,n′p) + (n,pn′) Cross Section

The ^{58}Ni experimental (n,n′p) + (n,d) cross section data were measured by

Pavlik[62] in the energy range from 12.76 to 19.57 MeV and Ribansky et al.[64, 66, 69, 77, 79, 87] around 14 MeV. Similar data around 14 MeV for the other isotopes were measured by Bahal et al.[63, 72, 74, 75, 87~89]. The fitting experimental value for natural Ni 384.8 mb at 14.5 MeV was used to normalize the corresponding calculated results.

1.9 (n,α), (n,n'α) + (n,αn') Cross Section

For (n,α) reaction of natural Ni, the experimental data were measured by Wattecamps[90], Kneff[91], Grimes[93] and Paulsen[92] at 14.8 MeV and in the energy range from 4.89 to 9.97 MeV, respectively. The α particles were measured at five angles with telescope detectors in a reaction chamber. Below 14.1 MeV, the evaluated data are given by fitting experimental data; Above 14.1 MeV, experimental value 95.7 mb at 14.1 MeV was used to normalize corresponding calculated results.A plot of these experimental data and the evaluated cross section are shown in Fig. 8. Based on these data, the evaluated data are greatly improved.

Because there are no experimental data for natural Ni, the (n,n'α) + (n,αn') cross section was taken from calculated results.

1.10 Capture Cross Section

The capture cross section from 10^{-5} eV to 600 keV is given by the resonance parameters and the background. Above this energy and up to about 3.0 MeV they were given from the report[94], in which the experimental data measured by Diven[95], Poenitz[96] and Stavisskii[97] were fitted. The capture Cross Section from 1.0 MeV to 20.0 MeV was obtained from model calculations normalized to experimental fitting data 8.01 mb at 1.0 MeV. The evaluated curve is located between ENDF / B–6 and JENDL–3.

1.11 (n,d) Cross Section

The experimental data 13.0 mb of natural Ni from Grimes[93] at 14.8 MeV energy point was used to normalize the corresponding model calculated results.

2 SECONDARY NEUTRON ANGULAR DISTRIBUTIONS

The elastic scattering angular distributions were calclulated with MUP–2 code[2], given in terms of Legendre coefficients in the c. m. system. The experimental data of 22 energy points measured by Smith[11], Li Jingde[12], Kinney[13], Guenther[14], Holmgvist[15], Ferrer[16], Clarken[19] and Hansen[20] were used in the calculation with optical model. The calculated result is in good agreement with the concerned experimental values (Fig. 9).

The discrete inelastic angular distributions (MT = 51~71) were also calculated with MUP–2.

The angular distributions for (n,2n), (n,3n), (n,n′α), (n,n′p) and continuum inelastic (MT = 16, 17, 22, 28, 91) were assumed to be isotropic.

3 SECONDARY NEUTRON ENERGY DISTRIBUTIONS

For the inelastic continuum, (n,2n), (n,3n), (n,n′α) and (n,n′p) reactions (MT = 16, 17, 22, 28), the secondary neutron spectra were also taken from MUP–2 calculation results.

4 THEORETICAL CALCULATION

In the theoretical calculation, various parameters are required as input : optical model parameters, level density parameters[98] and nuclear level scheme[7]. These patameters were determined on the basis of experimental data.

The data for Ni were calculated with programs AUJP[3] based on optical model and MUP–2[2] based on optical model, H–F theory with width fluctuation correction and the unified treatment of exciton model and evaporation model in the energy range from 1 keV to 20 MeV. The comparison between calculated and measured data is given in the Table 2.

Table 2 The comparison between calculated and measured data

(MeV)	tot			n,n			non		
	theo.	exp.	x %	theo.	exp.	x %	theo.	exp.	x %
1.0	3.710	3.130	18.5	3.682	3.117	18.7	0.025	0.020	25.0
3.0	3.302	3.402	3.01	2.256	2.246	1.70	1.092	1.156	5.53
5.0	3.580	3.640	1.65	2.017	2.088	3.40	1.523	1.551	1.80
6.0	3.599	3.679	2.17	2.019	2.120	4.76	1.550	1.559	0.58
8.0	3.477	3.527	1.42	1.922	2.054	6.42	1.516	1.473	2.92
10.0	3.228	3.268	1.22	1.697	1.836	7.57	1.510	1.432	5.44
12.0	2.994	3.014	0.66	1.477	1.597	7.51	1.501	1.417	5.92
14.0	2.747	2.748	0.04	1.282	1.304	1.68	1.484	1.443	2.84
16.0	2.582	2.572	0.39	1.121	1.116	0.45	1.460	1.456	2.74
18.0	2.459	2.450	0.37	1.031	1.031	0.87	1.439	1.419	1.41
20.0	2.406	2.371	1.47	1.014	1.004	0.99	1.417	1.368	3.58

$x = [|\text{theo.} - \text{exp.}| / \text{exp.}] \times 100$

The main parameters used are as follows:

(1) Optical potential parameters (MeV or fm)

$A_r = A_{so} = 0.7284$ $V_0 = 54.103$

$A_s = A_{vv} = 0.41$ $V_1 = -0.1183$

$X_r = X_{so} = 1.1764$ $V_2 = -0.0141$

$X_s = X_v = 1.3191$ $V_3 = -17.5984$

$X_c = 1.0$ $V_4 = 0.0$

$U_0 = -1.7484$ $W_0 = 12.0$

$U_1 = 0.253$ $W_1 = -0.1545$

$V_{so} = 3.1$ $W_2 = -1.2687$

(2) Level density parameters, they given in Table 3.

Table 3 Level density parameters*

P(z)	P(n)	S(z)	S(n)	P(z)	P(n)	S(z)	S(n)	P(z)	P(n)
^{58}Ni				^{60}Ni				^{61}Ni	
1.2	−0.2	−16.57	15.45	1.2	−0.15	−16.57	15.8	1.2	1.30
−0.1	1.15	−14.75	13.45	−0.1	1.32	−14.75	14.98	−0.1	−0.15
1.3	−0.0	−14.4	13.7	1.3	−0.2	−14.4	15.45	1.3	1.32
0.0	1.2	−14.0	12.5	0.0	1.15	−14.0	13.45	0.0	−0.2
1.2	−0.2	−14.3	14.55	1.2	−0.0	−14.3	13.7	1.2	1.15
S(z)	S(n)	P(z)	P(n)	S(z)	S(n)	P(z)	P(n)	S(z)	S(n)
^{61}Ni				^{62}Ni				^{64}Ni	
−16.57	16.38	1.2	−0.18	−0.18	−16.57	17.25	1.2	−0.1	−16.57
−14.75	15.8	−0.1	1.3	1.3	14.75	16.38	−0.1	1.5	−14.75
−14.4	14.98	1.3	−0.15	−0.15	14.4	15.8	1.3	−0.18	−14.4
−14.0	15.45	0.0	1.32	1.32	14.0	14.98	0.0	1.3	−14.0
−14.3	13.45	1.2	−0.2	−0.2	−14.3	15.45	1.2	−0.15	−14.3

* The level density formula of Ref. [98] were used.

(3) Pre–equilibrium parameter $DK = 180.0$

5 CONCLUDING REMARKS

Because the new experimental data have been available in recent years,the evaluated data are considerably improved, especially for cross sections of total, (n,p), (n,n′p), (n,α), (n,d), total inelastic and inelastic scattering to some discrete levels and elastic scattering angular distributions.

ACKNOWLEDGMENTS

The authors wish to thank Profs. Cai Dunjiu, Liu Tingjin and Liang Qichang for their beneficial helps in tis work.

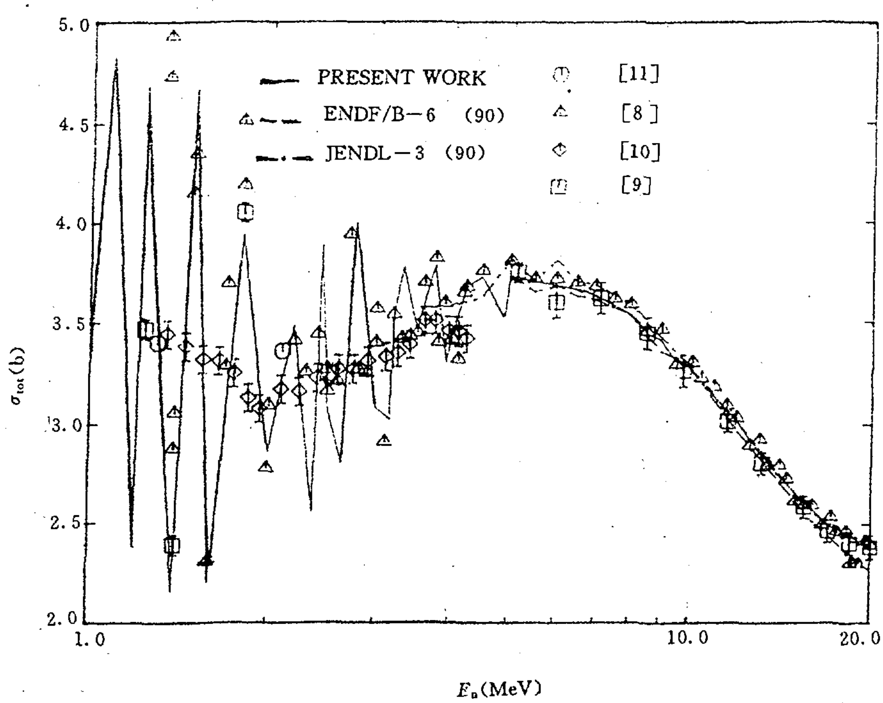

Fig. 1 Neutron total cross section of Ni

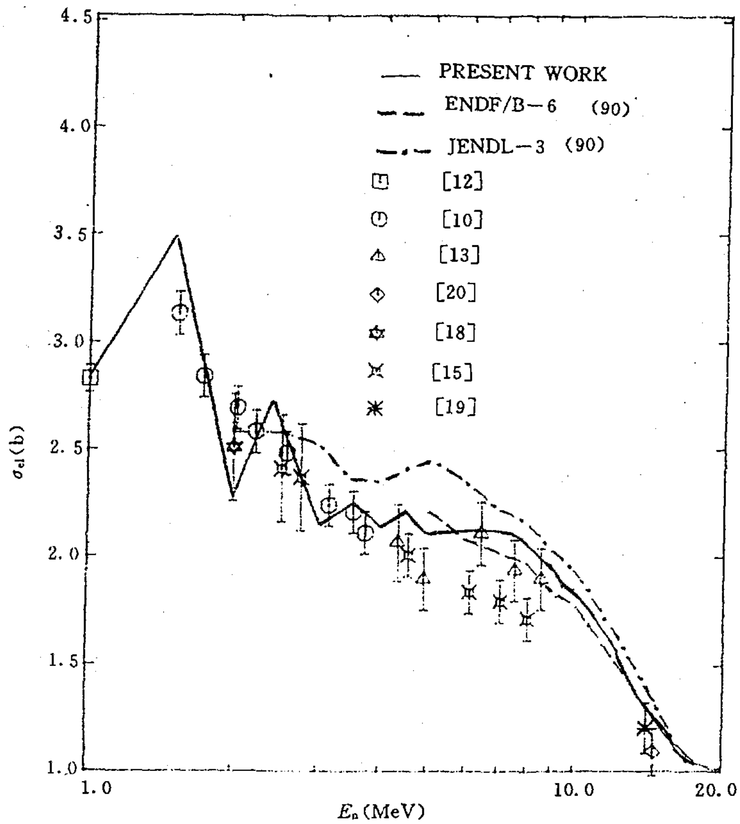

Fig. 2 Neutron elastic cross section of Ni

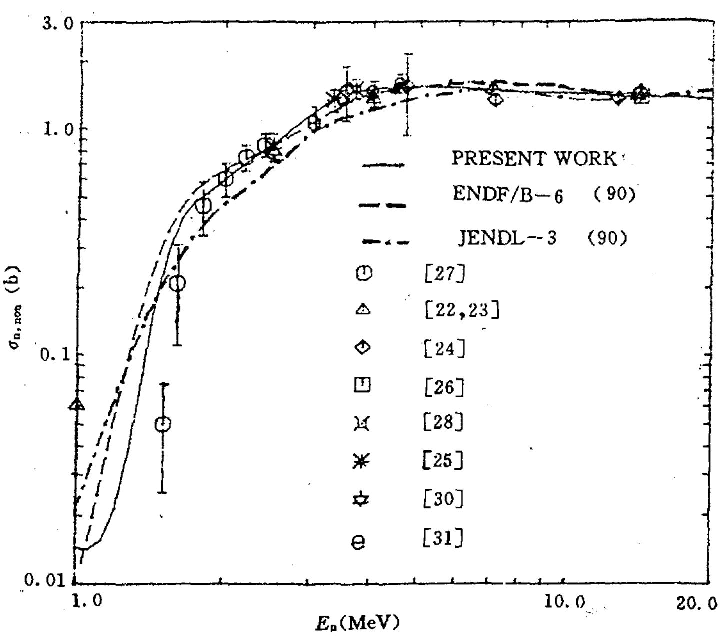

Fig. 3 (n,non) cross section of Ni

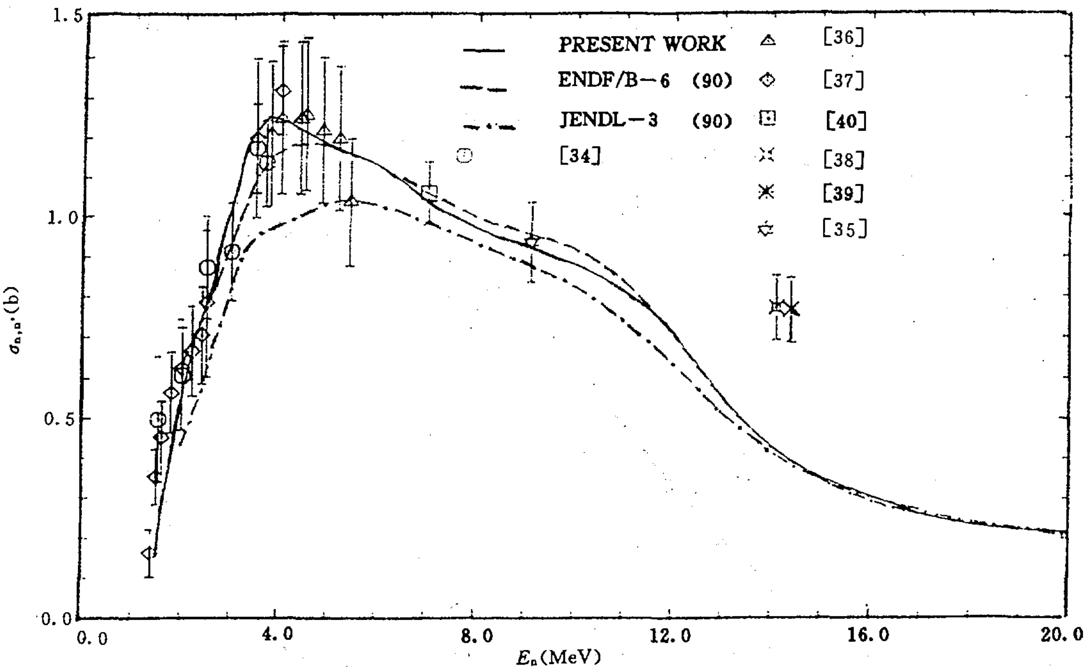

Fig. 4 (n,n′) cross section of Ni

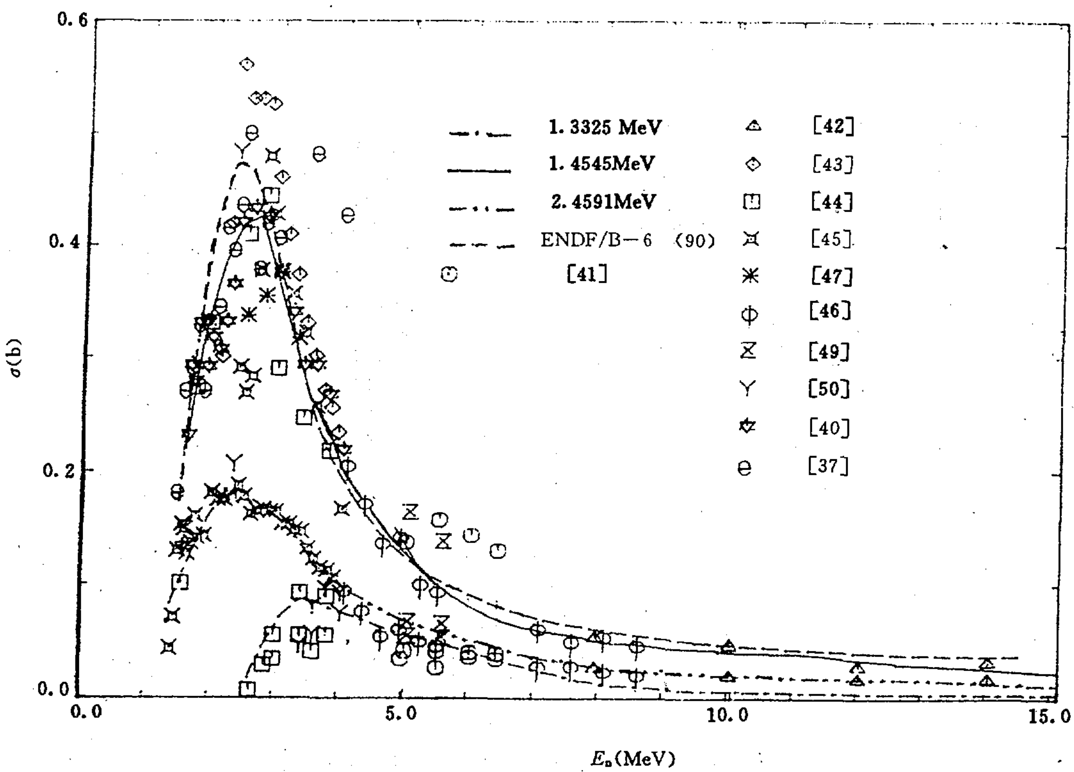

Fig. 5 Inelastic cross section of Ni excited states

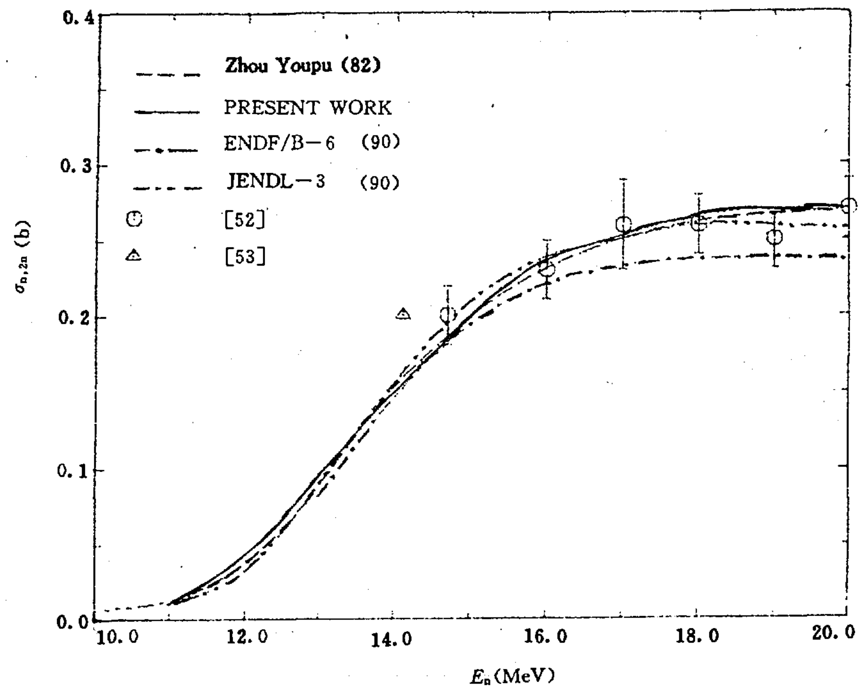

Fig. 6 (n,2n) cross section of Ni

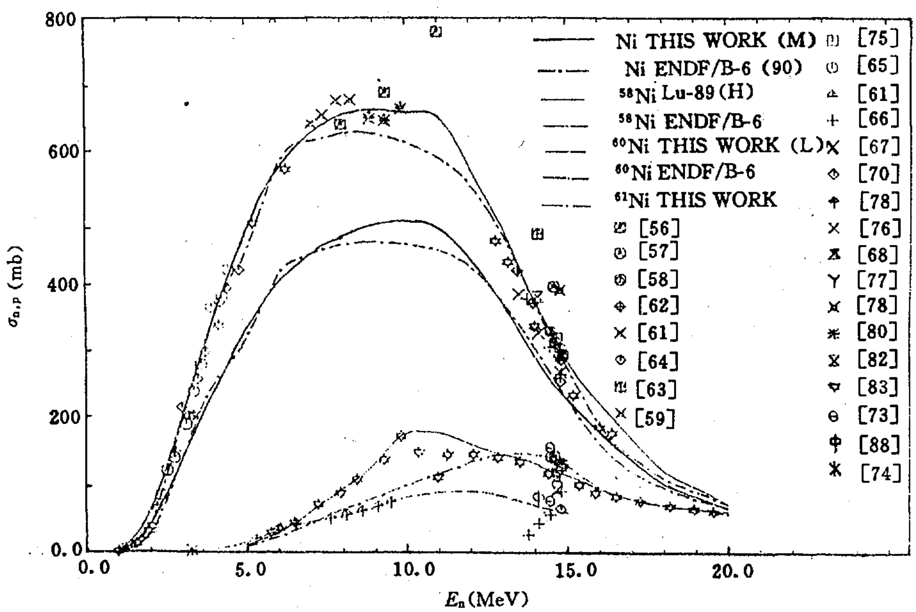

Fig. 7 (n,p) cross section of ^{58,60,61}Ni and Ni

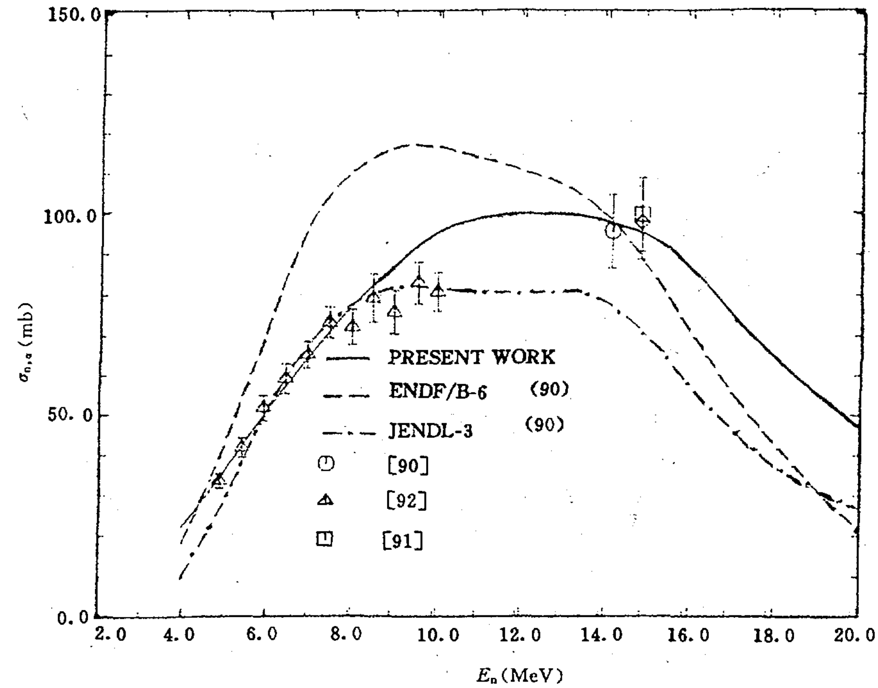

Fig. 8 (n,α) cross section of Ni

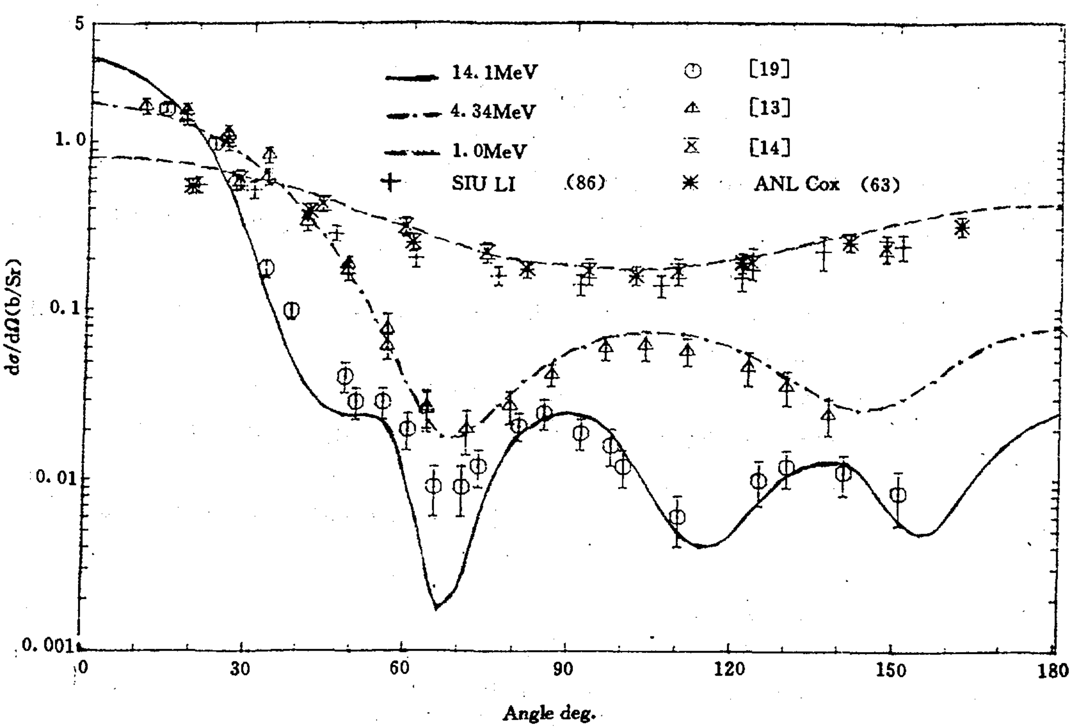

Fig. 9—1 Elastic scatter angular distributions of Ni

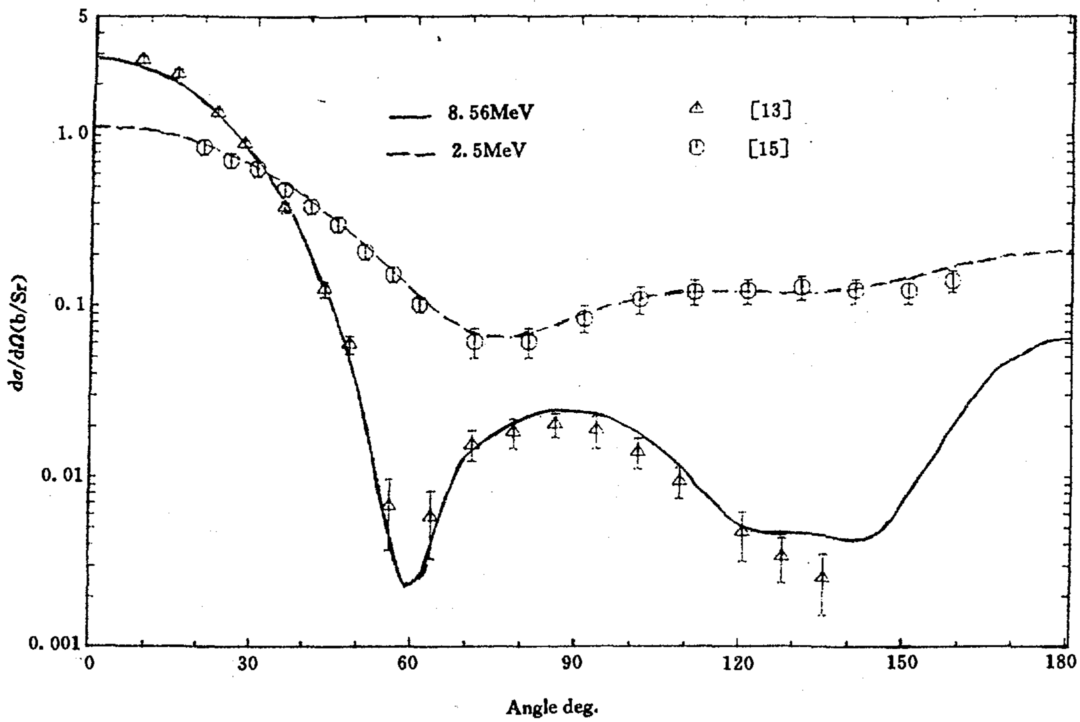

Fig. 9–2 Elastic scatter angular distributions of Ni

REFERENCES

[1] Ma Gonggui, CNDC–58010, 182(1986)

[2] Yu Ziqiang, Cai Chonghai et al., Thoretical calculation program MUP2 for middle and heavy nuclei, inter report(1986)

[3] Zhou Hongmo, Yu Ziqiang et al., parameter auto adjusting optical model calculation program AUJP, inter report (1986)

[4] S. F. Mughabghab, BNL–325 (4th Edition) (1984)

[5] Larson et al., ENDF / B–6 (MAT = 2825, 2831, 2834, 2837, 2843), (1989)

[6] S. Iijima et al., JENDL–3 (1987)

[7] P. Andersson et al., Nuclear Data Sheets, 48, 251(1986); 42, 457(1984); 38, 463(1983); 28, 179(1979); 26, 5(1979)

[8] D. C. Larson et al., 80BNL, 277(1980)

[9] F. G. Perey et al., EXFOR 10342002(1973)

[10] A. B. Smith et al., Nucl. Sci. Eng., 77, 110(1981)

[11] L. Koester et al., Z. Phys., 330 387(1988)

[12] Li Jingde et al., INDC–CPR–011 / GI(1988)

[13] W. Kinney and F. G. Perey, ORNL–4807(1974)
[14] P. T. Guenther et al., Nucl. Sei. Eng., 59, 106(1976)
[15] B. Holmqvist et al., AE–385(1970), AE–430(1971), AE–303(1967)
[16] J. C. Ferrer et al., Nucl. Phys., A275, 325(1977)
[17] R. W. Bauer et al., Nucl. Phys., 48, 152(1963)
[18] L. E. Kazakova et al., EANDC–50,200(1965)
[19] R. L. Clarke and W. G. Gross, Nucl. Phys., A95, 320(1967)
[20] L. F. Hansen et al., Proc. USNDC, 9, 84(1973)
[21] J. L. Kammerdiener et al., UCRL–51232(1972)
[22] J. R. Beyster et al., Phys. Rev., 104, 1319(1956)
[23] J. R. Beyster et al., Phys. Rev., 98, 1216(1955)
[24] H. L. Taylor et al., Phys. Rev., 100, 174(1955)
[25] M. V. Pasechnik, Proc. of the International Conf. on Peaceful Uses of Atomic Energy, Geneva, 2, 3(1955)
[26] M. T. MacGregor et al., Phys. Rev., 108, 726(1957)
[27] A. I. Abromov, Sovt. Jour. At. Eng., 12, 65(1962)
[28] M. K. Machwe et al., Phys. Rev., 114, 1563(1959)
[29] V. I. Strizhak, Sovt. Jour. At. Energy, 2, 68(1957)
[30] V. I. Strizhak, et al., Z. E. T., 31, 907(1956)
[31] B. Holmqvist et al., Sovt. Jour. At. Energy, 303(1967)
[32] H. R. Poze et al., Z. E. T., 30, 1017(1956)
[33] Xiang Zheng Yu, Inter. Report, (1980)
[34] A. B. Smith et.al., ANL–NDM–54 (1980)
[35] Biryukov et.al., 75Kiev, 4, 118(1975)
[36] D. L. Border et al., Second IAEA Conf. on Nucl. Data for Reactors, Helsinki, 2, 295(1970)
[37] D. L. Border et al., ANL–Trans–177(1964)
[38] I. Fujita et al., Jour. Nucl. Sci. Technology, 9, 301(1972)
[39] O. A. Salnikov et al., Second Inter. Conf. on Nucl. Data for Reactors, Helsinki; Vol.11, 359(1970)
[40] J. H. Towle et al., Nucl. Phys., A100, 257(1967)
[41] Shinjiro Itagaki et al., Nucl. Data For Sci. and Tech. (88Mito), 283(1988)
[42] P. P. Guss et al., Nucl. Phys., A438, 187(1985)
[43] C.Budtz et al., Z. Physik, A306, 265(1982)
[44] S. Traiforos et al., Nucl. Sci. Eng., 72, 191(1979)
[45] A. B. Smith et al., Nucl. Sci. Eng., 72, 293(79); 59, 106(76)
[46] W. E. Kinney and F. G. Perey, ORNL–4807(1974)
[47] E. Almen Ranstiom et al., Sovt. J. At. Energy, 503(1975)
[48] V. C. Rorers et al., Nucl. Sci. Eng., 45, 297(1971)

[49] P. Boschung et al., Nucl. Phys., A161, 593(1971)
[50] W. L. Rodgers et al., COO−1513−33 2. CSISRS AN / SN−50401 / 11 (1967)
[51] D. L. Border et al., Jour. of Nuc. Eng., 18, 645(1964)
[52] L. R. Veeser et al., 77BNL., 231, EXFOR 12936008 (1977)
[53] V. J. Ashby et al., 58GENEVA, 15, 3, 2494(1958)
[54] F. L. Hassler et al., Phys. Rev., 125, 1011(1962)
[55] Lu Hanlin, Inter. Report(1989)
[56] S. L. Graham et al., Nucl. Sci. Eng., 95, 60(1987)
[57] N. I. Molla et al., INDC(BAN)−3, EXFOR 30825009, (1986)
[58] L. R. Greenwood et al., DOE−ER−0046−21(1985)
[59] I. Garlea et al., INDC(GDR)−34, 57(1985)
[60] S. Darolzy et al., Sovt. At. Energy, 58(2), 128(1985)
[61] N. V. Kornilov et al., C. 83Kiev, 3, 191(1983)
[62] A. Pavlik et al., Nucl. Sci. Eng., 90, 186(1985)
[63] K. Kobayashi et al., NEANDC(j)−116(1985)
[64] I. Ribansky et al., INDC(CSR)−7(1985)
[65] H. A. Husain et al., ARI 34(4), 731(1983)
[66] M. Viennot et al., MOH−5, 10(1982)
[67] P. Raics et al., AK 23, 45(1981)
[68] Swinhoeet al., AERE−PR / NP−26, 39(1979)
[69] R. N. Glover et al., Nucl. Phys. 29, 309(1962)
[70] M. W. Wu et al., Nucl. Sci. Eng., 63, 268(1977)
[71] D. L. Smith et al., Nucl. Sci. Eng., 58, 314(1975)
[72] A. Paulsen et al., 71CANT, 129(1971)
[73] W. G. Cross et al., EANDC(CAN)−16, 1(1963)
[74] J. I. Van Loeff et al., Nucl. Phys., 24, 340(1961)
[75] B. M. Bahal et al., NEANDC(E)−252 / U, (5), 28(1984)
[76] E. W. Lees et al., R. AERE−R−9390(1979)
[77] K. Fukuda ey al., NEANDC(J)−56 / U, 44(1978)
[78] S. M. Qaim et al., Nucl. Phys., A283, 269(1977)
[79] H. Weigel et al., J. RCA, 22, 11(1975)
[80] J. D. Hemingway et al., Jour. Nucl. Energy, 27, 241(1973)
[81] G.N.Maslov et al., YK−9,50(1972)
[82] V. N. Levkovskii et al., YK−10(1), 44(1969)
[83] A. Paulsen et al., Nukleonik, 10, 91(1967)
[84] A. Paulsen et al., Z. Physik, 205, 226(1967)
[85] S. M. Qaim et al., Nucl. Sci. Eng., 88(2), 143(1984)
[86] M. Viennot et al., 82ANTWER, 406(1982)
[87] D. L. Allan et al., PPS / A, 70, 195(1957)

[88] A. K. Valter et al., IZV, 26(8), 1079(1962)
[89] I. L. Preiss et al., Nucl. Phys., 15, 326(1960)
[90] E. Wattecamps et al., 83ANTWER, 159(1983)
[91] D. Kneff et al., Nucl. Sci. Eng., 92 491(1986)
[92] A. Paulsen et al., Nucl. Sci. Eng., 78(4) 377(1981)
[93] S. M. Grimes et al., Phys. Rev. C19, 2127(1979)
[94] Shi Xia min C. Nucl. Phys., 4(2), 120(1982)
[95] B. C. Diven et al., Phys. Rev. 120, 556(1960)
[96] W. P. Poenitz et al., Nucl. Cross Section and Technology, Vol, 901 Proc. of a conf. at Washington(1975)
[97] Yu. Ya. Stavisskii., Sovt. Jour. At. Energy, 10, 255(1962)
[98] Su Zongdi et al., A new set of level density parameters for Fermi Gas model, inter report(1984)
[99] Zhou Youpu, Inter report hsj–81157(bp)(1982)

EVALUATED NEUTRON NUCLEAR DATA FILE FOR COPPER

Zou Yiming Ma Gonggui Wang Shiming

(INSTITUTE OF NUCLEAR SCIENCE AND TECHNOLOGY OF SICHUAN UNIVERSITY, CHENGDU)

ABSTRACT

A comprehensive evaluated neutron nuclear data file and theoretical calculation for copper are described.

This complete data contain neutron cross sections, angular distribution and energy distribution of secondary neutrons in the energy region from 10^{-5} eV to 20 MeV.

INTRODUCTION

Natural copper consists of two isotopes, ^{63}Cu and ^{65}Cu.

Below 20 MeV considered neutron induced reaction Q values of the isotopes are listed in Table 1.

Table 1 Reaction Q value (MeV) of $^{63,65}Cu$

Reactions	^{63}Cu (69.1%)	^{65}Cu(30.9%)
(n,n)	0.0	0.0
(n,n′)	−0.6697	−0.7710
(n,2n)	−10.841	−9.9045
(n,3n)	−19.200	−17.820
(n,α)	7.9159	7.0670
(n,p)	0.7165	−1.3488
(n,n′p)	−6.1245	−7.4446
(n,t)	−8.2389	−8.6219
(n,n′t)	−16.058	−15.463
(n, ^3He)	−9.5278	−12.262
(n,n′ ^3He)	−18.863	−20.661
(n,d)	−3.9000	−5.2200
(n,n′d)	−14.500	−14.879
(n,α)	1.7149	−8.2939
(n,n′α)	−5.7765	−6.7703

The present evaluation was based on experimental data available up to June 1989 and theoretical calculation with MUP−2[1] code. It contains neutron cross sections, angular distributions and energy spectra of secondary neutron for mentioned above mentioned reactions. Comparing with CENDL−1, the evaluated neutron cross sections have considerabely improved for charged particle emission reaction due to the theoretical calculation code had been improved. The present evaluated neutron cross sections are in essentially in agreement with ENDF / B−6[8] and JENDL−3[103].

1 THEORETICAL CALCULATION AND THE PARAMETERS

In this calculation, AUJP[3] and MUP−2[1] were used.

Original optical potential parameters were taken from the work of Xu Dingan[4], nuclear level informations of ^{63}Cu and ^{65}Cu were taken from Refs. [5, 6] respectively, and level density parameters were taken from Ref. [7].

The adjusted optical model parameters are given as following: (MeV or fm)

$$V = 55.563 - 0.457E + 0.0018E^2 - 27.039(N-Z)/A$$
$$r_0 = 1.19, \quad a_0 = 0.75$$

$$W_d = 16.08 - 0.353E - 35.47\,(N-Z)/A, \quad \text{or zero},$$
$$r_w = r_d = 1.41, \quad a_w = a_d = 0.26$$
$$V_{so} = 3.41, \quad r_{so} = 1.19, \quad a_{so} = 0.75$$

The level density parameters are :

^{63}Cu

PZ	0.0	1.20	−0.10	1.30	0.0
PN	−0.18	1.30	−0.15	1.32	−0.2
SZ	−17.10	−16.57	−14.75	−14.40	−14.00
SN	17.25	16.38	15.80	14.98	14.45

^{65}Cu

PZ	0.0	1.20	−0.10	1.30	0.0
PN	−0.10	1.50	−0.18	1.30	−0.15
SZ	−17.10	−16.57	−14.75	−14.40	−14.00
SN	18.05	17.55	17.25	16.38	15.80

The giant dipole resonance parameters are given in the following:

^{63}Cu

SAO 0.050 0.250 0.075 0.032 0.034 0.026 0.034 0.026 0.0 0.0 0.0 0.050 0.050 0.050 0.050 0.050

GM 6.89 6.89 6.89 2.44 2.44 2.56 2.44 2.56 6.89 6.89 6.89 6.37 6.37 7.61 6.37 7.61

EG 16.70 16.70 16.70 16.30 16.30 16.37 16.30 16.37 16.70 16.70 16.70 18.51 18.51 18.90 18.51 18.90

^{65}Cu

SAO 0.050 0.075 0.075 0.034 0.034 0.026 0.034 0.026 0.0 0.0 0.0 0.050 0.050 0.050 0.050 0.050

GM 6.89 6.89 6.89 2.44 2.44 2.56 2.44 2.56 6.89 6.89 6.89 6.37 6.37 7.61 6.37 7.61

EG 16.70 16.70 16.70 16.30 16.30 16.37 16.30 16.37 16.70 16.70 16.70 18.51 18.51 18.90 18.51 18.90

Preequilibrium parameters are :

DK = 380 (for ^{63}Cu), 130 (for ^{65}Cu).

The calculated total, elastic scattering and non–elastic scattering cross sections are in agreement with the evaluated experimental data, as illustracted in Table 2.

The calculated total inelastic scattering cross section, discrete level inelastic scattering cross section, (n,γ) and (n,2n) cross sections are essentially in agreement with the evaluated experimental data.

Table 2 The comparison between calculated and measured data

(MeV)	tot			n,n			non		
	eval.	cal.	err.	eval.	cal.	err.	eval.	cal.	err.
1.0	3.43	3.65	6.6	3.18	3.41	7.1	0.248	0.234	6.0
1.5	3.09	3.22	4.2	2.45	2.61	7.0	0.64	0.61	5.0
2.0	3.00	3.08	2.7	2.10	2.13	1.5	0.90	0.94	4.4
2.5	3.13	3.10	1.0	1.95	1.94	0.5	1.18	1.16	2.0
3.0	3.30	3.22	2.4	1.92	1.91	0.5	1.38	1.30	6.0
4.5	3.70	3.64	1.6	2.12	2.14	0.9	1.58	1.50	5.0
6.0	3.80	3.76	1.1	2.20	2.27	3.2	1.60	1.49	6.2
7.0	3.75	3.72	0.8	2.16	2.25	4.2	1.59	1.47	7.5
8.0	3.67	3.65	0.5	2.09	2.17	3.8	1.58	1.47	7.0
10.0	3.40	3.44	1.2	1.85	1.93	4.3	1.55	1.51	2.6
12.0	2.20	3.17	0.9	1.70	1.67	1.8	1.50	1.50	0.0
14.5	2.90	2.86	1.4	1.44	1.39	3.5	1.46	1.46	0.0
17.0	2.66	2.66	0.0	1.22	1.23	0.8	1.44	1.44	0.0
20.0	2.47	2.56	3.6	1.07	1.14	7.5	1.40	1.40	0.0

err. = [|cal. − eval.| / eval.] × 100

2 RECOMMENDED NEUTRON CROSS SECTIONS

2.1 Total Cross Sections

Below 99.5 keV, the resonance parameter of ^{63}Cu and ^{65}Cu were given. They were taken directly from Hetrick, Fu, Larson[8].

Below 1 MeV, there are considerable structure in the experimental data. So in this energy regions, the better resolution experimental data were recommended respectively. From 35 to 100 keV, the data of Garg[9] were used; from 100 keV to 1 MeV, the data of Whalen[10] were used. In this energy range, the new data of Poenitz[11], which are averaged cross section over 50 keV energy range and have higher precision (about 2.5%), are in good agreement with these data.[9, 10].

Above 1 MeV, the data become smooth. The normal polynomial fitting result of 13 groups[10~22]was used, including the data of Poenitz[11] above 1 MeV and the new measured average cross section of Guenther[12] over 200 keV intervals.

The data of Morales[23] measured in 1987, due to no detail information and seriously disagreement with others[17, 20, 21], were abandoned.

The present evaluated total cross sections are in agreement with that of CENDL–1 and JENDL–3[103]; and are also in agreement with ENDF / B–6[8], except somewhat higher in the energy region 0.2~ 2.0 MeV, as illustracted Fig. 1.

2.2 Elastic Scattering Cross Sections

The recommended elastic scattering cross sections were obtained by subtracting the non–elastic cross sections from the evaluated total cross sections. The calculated cross section was compared with the available experimental data. In the energy region between 0.2~ 14 MeV, the cross section is in agreement very well with the available measurements [25~29]. Between 4~ 8 MeV, the calculated curve was slighly higher than the measured data of Holmqvist[30].

2.3 Non–elastic Scattering Cross Sections

There are more experimental results from threshold to 20 MeV. The new data[31, 32] near 14 MeV, measured with spherical shell and anti–spherical method with higher precision (about 2.0%), are in very good agreement with the others[35, 38, 40, 42]. The normal polynomial fitting of the experimental data [31~42] was used as recommended data.

The evaluated data are in good agreement with ENDF / B–6 and JENDL–3, except ENDF / B–6 is higher above 15 MeV, as illustrated in Fig.2. Meanwhile ENDF / B–5[24] is about 6% higher than the others from 5 to 12 MeV.

2.4 Inelastic Scattering Cross Sections

(1) Discrete Inelastic Scattering Cross Sections

The discrete inelastic scattering cross sections include 7 leves of ^{63}Cu and 5 leves of ^{65}Cu. The excitation energy and spin parity of the levels are listed in Table 3, taken from Refs. [5, 6].

Table 3 (1) Energy levels of ^{63}Cu

Level	Energy (MeV)	Spin Parity	Level	Energy (MeV)	Spin Parity
1	0.0	1.5^-	5	1.4120	2.5^-
2	0.6697	0.5^-	6	1.5470	1.5^-
3	0.9621	2.5^-	7	1.8610	3.5^-
4	1.3270	3.5^-	8	2.0110	1.5^-

Table 3(2) Energy levels of ^{65}Cu

Level	Energy (MeV)	Spin Parity	Level	Energy (MeV)	Spin Parity
1	0.0	1.5^-	4	1.482	3.5^-
2	0.771	0.5^-	5	1.623	2.5^-
3	1.116	2.5^-	6	1.725	1.5^-

There are more experimental data for lower 4 levels (0.6697, 0.7710, 0.9621 and 1.1160) and they are in agreement with the calculated results.

The calculated results were taken as the recommended discret level inelastic scattering cross sections. In order to keep up the total inelastic scattering cross section, the discrete inelastic scattering cross sections were somewhat adjusting in the energy region below the threshold of the continuum inelastic scattering cross sections.

The recommended discrete inelastic cross sections were in agreement with measured data [43~47], ENDF / B–6 andJENDL–3, as illustrated in Fig. 7.

The recommended total inelastic cross section was obtained by subtracting sum of the cross sections of the other reactions from the evaluated non–elastic cross section, and are in very good agreement with ENDF / B–5, ENDF / B–6 and JENDL–3. The comparasion between the evaluations and measured data [12, 45, 48, 49] is shown in Fig. 4.

(2) Continuum Inelastic Scattering Cross Section

Continuum inelastic scattering cross section was obtained by subtracting the sum of the discrete inelastic scattering cross sections from the total inelastic scattering cross section.

2.5 (n,2n) Cross Sections

From threshold to 13.5 MeV, the only experimental data of Frehaut[50] was used. From 13.5 to 20 MeV, the (n,2n) cross section was taken from the evaluation[51] of (n,2n) cross sections for isotopes.

Both ^{63}Cu (n,2n) and ^{65}Cu (n,2n) cross sections have been used as standards, therefore many sets of experimental data are available. The evaluation[51] was based on measurements[52~60] for ^{63}Cu, and measurements [52, 56, 62~67] for ^{65}Cu. The newer experimental data of ^{63}Cu[61] and ^{65}Cu [68~71] is in very good agreement with the evaluation[51].

The recommented (n,2n) cross sections are in agreement with ENDF / B–5, ENDF / B–6 and JENDL–3. Between 12 MeV and 13.5 MeV the three evaluations are somewhat higher than the experimental data[50]. Above 17 MeV the data of JENDL–3 appear somewhat lower than the others and the data of Zhou[51], as illustrated in Fig 5.

2.6 (n,3n) Cross Section

The (n,3n) cross section was taken from the model calculation due to lack of experimental data.

2.7 Capture Cross Section

From 35 keV to 1 MeV, the normal polynomial fitting of the data of Stavisskij[72], Diven[73] and Voignier[74]was taken. Between 1 to 3 MeV, the data of Voignier[74] was used. From 3 to 20 MeV the linear interpolation and the extrapolation were made in log– log scales, through the measured data[75] near 14 MeV.

The evaluatedcrosssections are in very good agreement with ENDF / B–6 and JENDL–3, except the above 3 MeV, as illustrated in Fig.3.

2.8 (n,p) and (n,n′p) Cross Sections

(1) (n,p) cross sections

One set of experimental data[76] for ^{63}Cu and ^{65}Cu near 14 MeV was abandoned, because the data for ^{65}Cu is about 50% higher than the others [68, 77, 78].

The calculated (n,p) cross section for ^{65}Cu are in agreement with available experimental data[68,77~79].

The evaluated (n,p) cross section was teken from the calculation, and are in agreement with which obtained by subtracting the evaluated (n,d) cross section from the data of Colli[80] at 14.1 MeV.

(2) (n,n′p) cross sections

The recommented (n,n′p) cross section was taken from model calculation, and normalized to a new measured data[82] which is almost the average value of the two sets of discrepance data[80, 81] at 14.1 MeV.

2.9 (n,α) and (n,n′α) Cross Sections

(1) (n,α) cross sections

The cross sections for the natural element were obtained from evaluated cross sections for the isotopes.

The (n,α) cross section for ^{63}Cu was taken from the data of Winkler[83] below 8 MeV, above that the exciting curve of Paulsen[84] was normalized to the weighted average value of the data[85~88].

The (n,α) cross section for ^{65}Cu was taken from the model calculation.

(2) (n,n′α) cross sections

There are only a few experimental results for ^{65}Cu. The model calculation are in agreement with the experimental data[89, 90], and are somewhat higher than that of Santry[79]. The (n,n′α) cross section were obtained from the model calculation.

2.10 (n, ^{3}He) and (n,n′ ^{3}He) Cross Sections

There are no experimental data for these reactions, and the calculated results are very small. Therefore, these processes was ignored.

2.11 (n,t) and (n,n′t) Cross Sections

The (n,t) cross section was taken from the calculation, due to lack of experimental data.

The (n,n′t) cross sections was ignored, due to lack of experimental data and very small calculated values.

2.12 (n,d) and (n,n′d) Cross Sections

There are only one set of experimental data[91] at 14.8 MeV. It is in agreement with the calculation result. Therefore, the calculation results were used.

The (n,n′d) cross section was directly taken from the calculation results, due to lack of experimental data.

3 ANGULAR DISTRIBUTION OF SECONDARY NEUTRON

The angular distributions of secondary neutrons, from elastic scattering and inelastic scattering to discrete levels, were given by Legendre coefficients in the center–of–mass system. The angular distributions of secondary neutrons for (n,n′ continuum), (n,2n), (n,3n), (n,n′p) (n,n′d) and (n,n′α) process were assumed isotropic.

The experimental data of elastic scattering angular distributions scattered in the energy range from 0.05 to16 MeV. For adjusting optical potential parameters, the following data were used: from 0.05 to 1.5 MeV, Lane[92] and Smith[26]; from 1.7 to 10 MeV, Tsukada[93] Holmqvist[30], Galloway[94], Bucher[95], Galloway[96],Gorlov[97], Anikin[98, 99]. and Guenther[12]; from 11 to 16.1 MeV, Bucher[95] Coon[27], Anderson[100], Begum[101] and Li Jingde[102].

The angular distributions of elastic scattering neutrons were taken from the calculation. They are in agreement with the experimental data, as illustrated in Fig. 6.

4 THE ENERGY DISTRIBUTION OF SECONDARY NEU TRON

The energy distributions of secondary neutrons from (n,n′ continuum), (n,2n), (n,3n) (n,n′p) (n,n′d) and (n,n′α) process were taken from the calculations.

5 SUMMARY

The recommended total, non–elastic, (n,γ) and (n,2n) cross sections were completely based on the experimental data. The evaluated total inelastic cross section and charged particle emition cross section are in agreement with the available experimental data.

The present evaluation is considerably different from that of CENDL–1, due to new experimental data and improved MUP–2 code, as the following:

(1) Nonelastic scattering cross sections of the present evaluation is about 14% higher than CENDL–1 between 0.85 to 2 MeV due to use of new experimental data.
(2) Below 13.5 MeV, the present (n,2n) cross sections become about 25% less than that of CENDL–1 due to use of Frehaut's data.
(3) The present evaluated particle emition cross sections are comparable with experimental data, and considerably different from CENDL–1, due to using improved MUP–2 code.

The present evaluated cross section are essentially in agreement with ENDF / B–6 and JENDL–3, but there are following differences :

(1) The present total cross sections are slightly higher than ENDF / B–5 and ENDF / B–6 in the energy region from 0.2 to 2 MeV.
(2) The evaluated non–elastic cross section of ENDF / B–5 from 3 to 12 MeV and that of ENDF / B–6 above 17 MeV are somewhat higher.
(3) The recommended (n,2n) cross sections of ENDF / B–6 are somewhat lower above 17 MeV.
(4) The evaluated (n,γ) cross section of ENDF / B–6 appears somewhat higher, and that of JENDL–3 appears lower above 3 MeV.

In order to improve the present evaluation, new measured data are needed, these data include :

(1) measurements of the charged particle emition cross sections for natural element.

(2) measurements of precise differential elastic scattering from 4 to 8 MeV.

ACKNOWLEDGMENTS

The authors are very grateful to Profs. Liang Qichang, Liu Tingjin for their much help in this work, in the meantime, also the same to Prof. Cai Dunjiu et al. of CNDC.

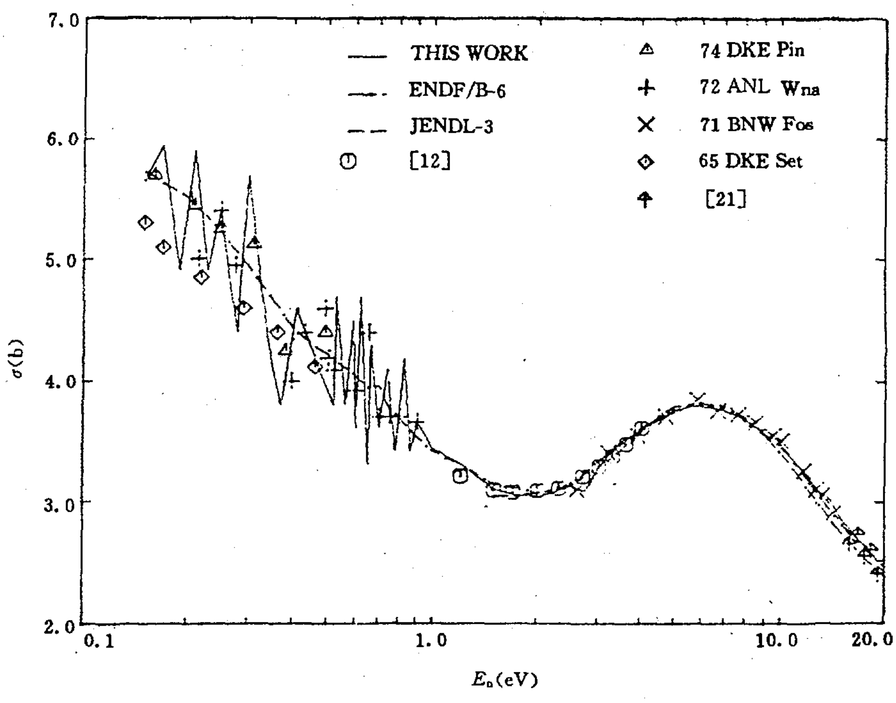

Fig. 1 Neutron total cross section of Cu

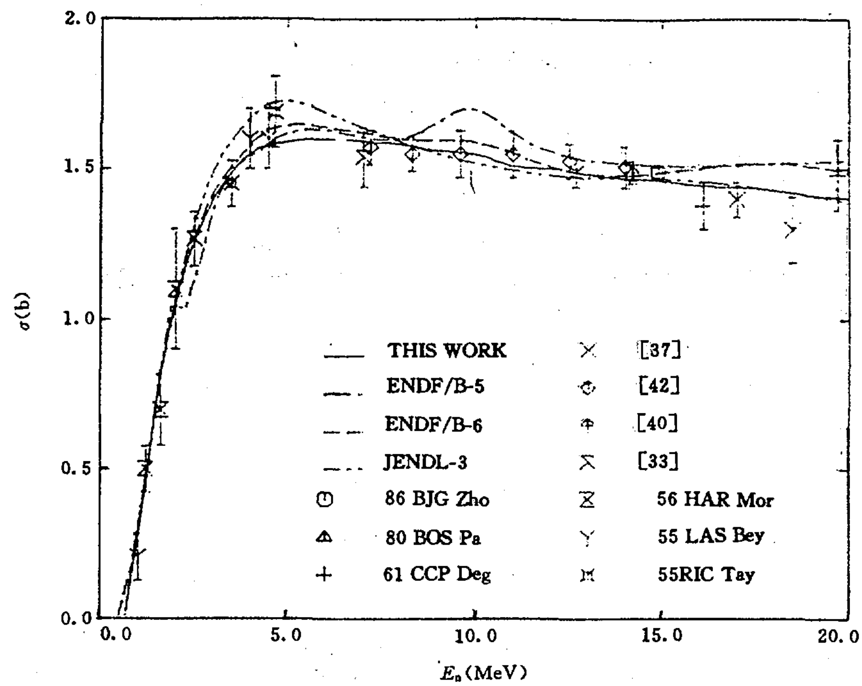

Fig. 2 Neutron nonelastic cross section of Cu

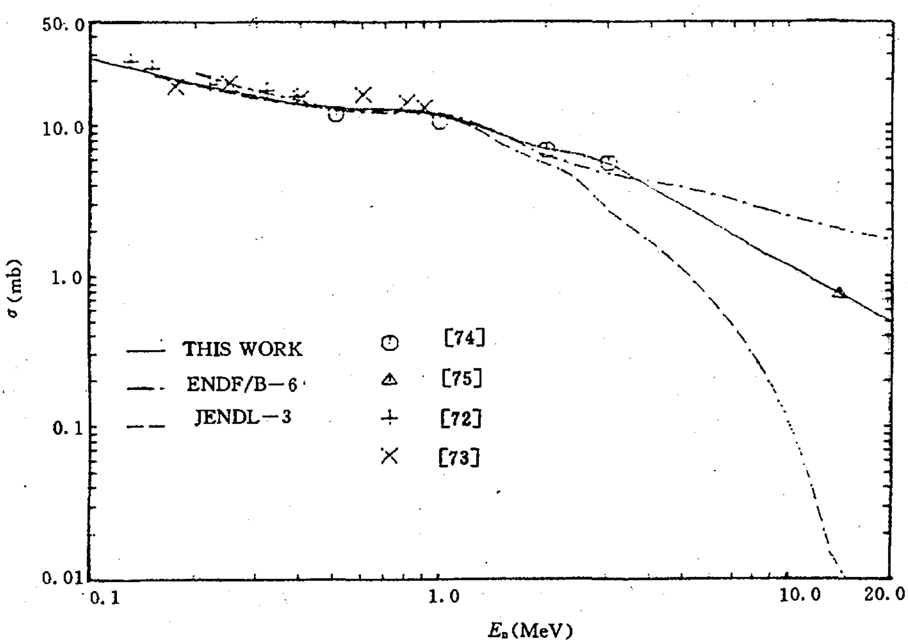

Fig. 3 Neutron capture cross section of Cu

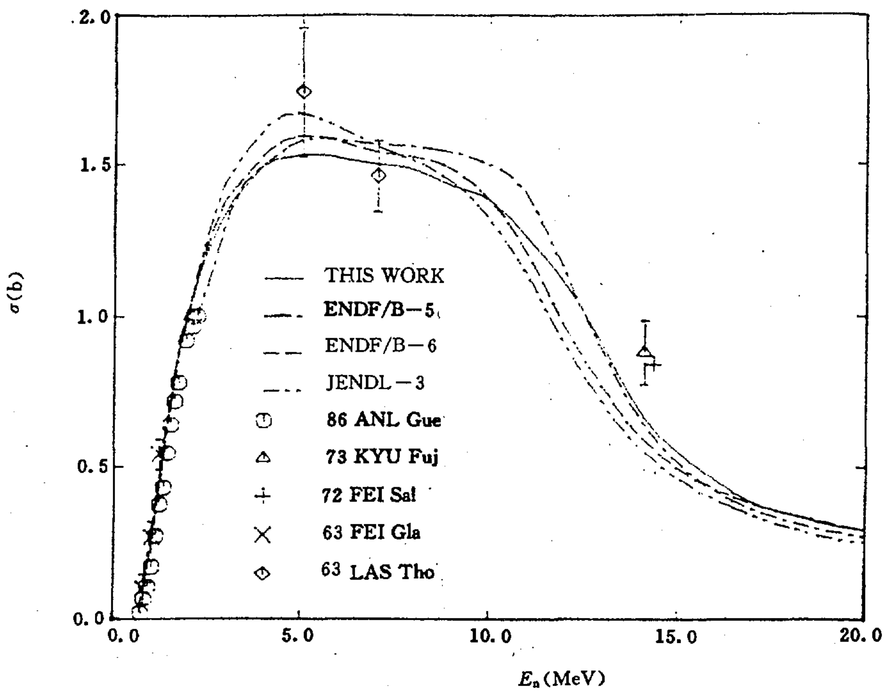

Fig. 4 Neutron total inelastic cross section of Cu

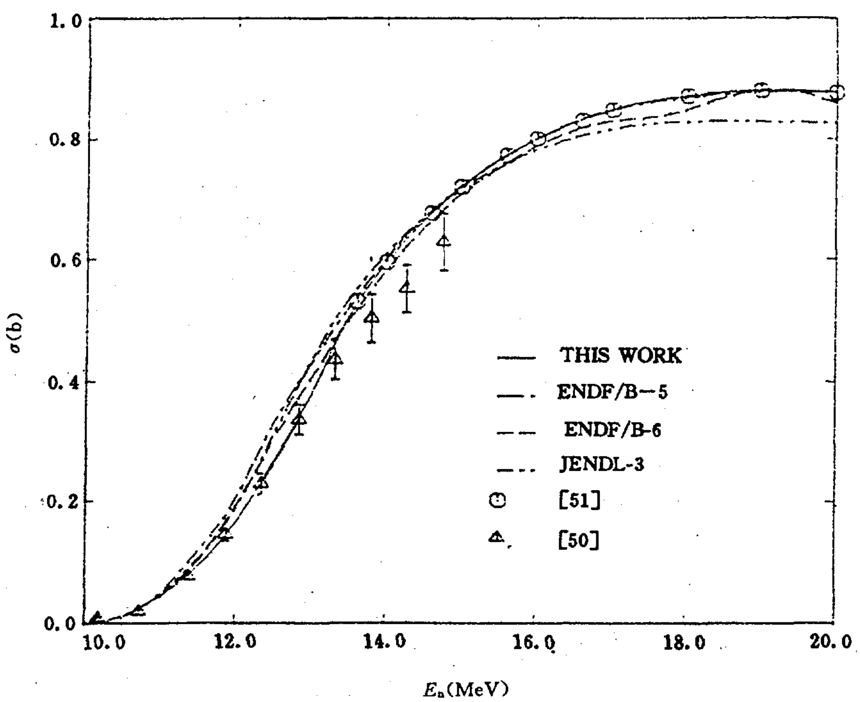

Fig. 5 (n,2n) cross section of Cu

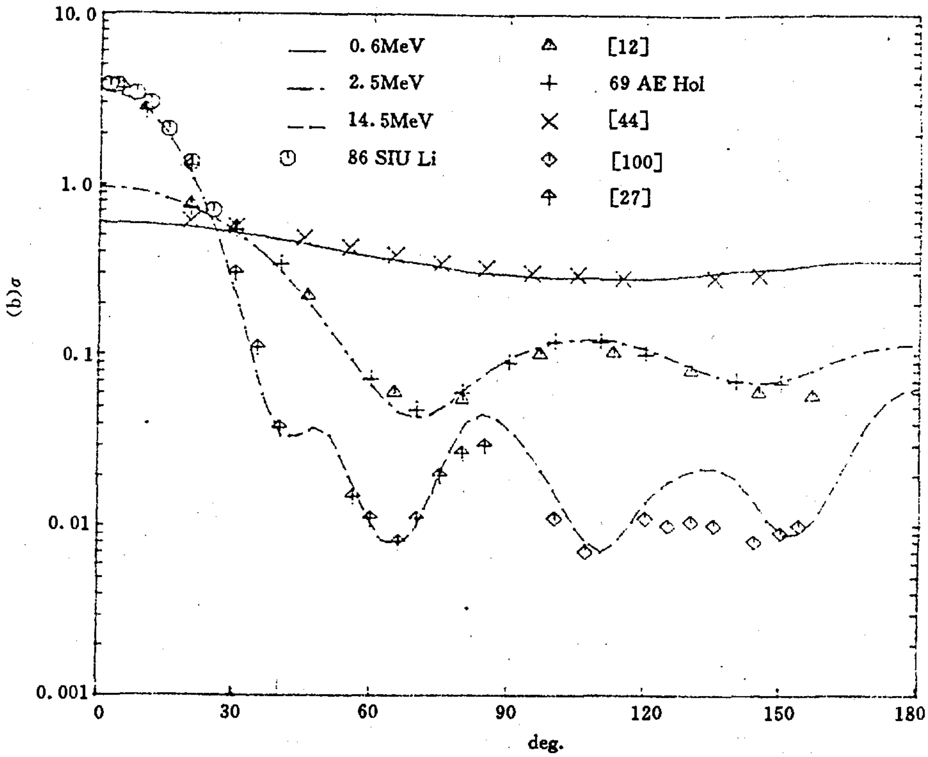

Fig. 6 Differential elastic scattering cross section of Cu

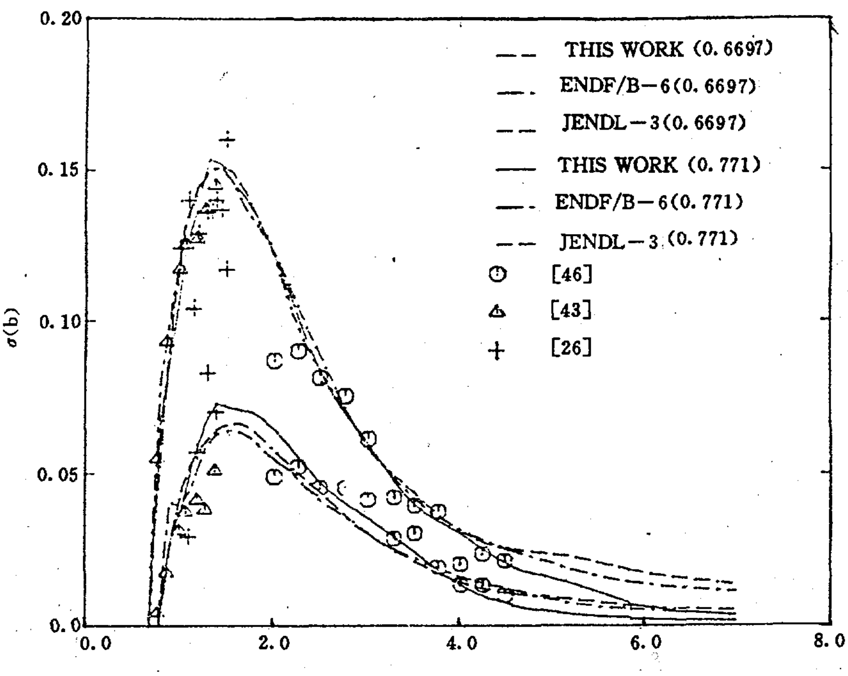

Fig. 7 Inelastic scattering to 0.6697 MeV, 0.7710 MeV levels cross sections

REFERENCES

[1] Yu Ziqiang, Cai Chonghai et al., Thoretical calculation program MUP–2 for medium and heavy nuclei, inter report (1986)

[2] Liu Shirui, Chinese Evaluated Nuclear Data Library, Version 1 (CENDL–1), CNDC–85010 p. 189(1986)

[3] Zhou Hongmo, Yu Ziqiang et al., Auto–parameter ajusting optical model calculation program AUJP, inter report (1978)

[4] Xu Dingan , Theoretical Calculation of the Neutron Reaction Data for Cu Induced by $E_n < 20$ MeV Neutron, CNDC–85011, p. 105(1986)

[5] R. L. Auble, Nuclear Data Sheets, 28, 559(1979)

[6] N. J. Ward et al., Nuclear Data Sheets, 47, 135(1986)

[7] Su Zongdi et al., Chinese Journal of Nuclear Physics Vol. 8, No. 3, 199(1986)

[8] Hetrick Fu Larson, ENDF / B–6 (1990)

[9] J. B. Garg et al., EANDC (US)–54, (1964)

[10] J. F. Whalen et al., ANL–7710, 12(1971)

[11] W. P. Poenitz et al., ANL–NDM–80(1983)

[12] P. Guenther et al., Nucl. Phys., A, 448, 280(1986)

[13] D. W. Miller et al., Phys. Rev., 88, 83(1952)

[14] J. H. Coon et al., Phys. Rev., 88, 562(1952)

[15] N. Nereson et al., Phys. Rev., 89, 775(1953)

[16] J. C. Albergotti et al., Nucl. Phys., 82, 652(1966)

[17] R. B. Day et al., Phys. Rev., 92, 358(1953)

[18] M. Mazari et al., Phys. Rev., 100, 972(1955)

[19] W. K. Robinson et al., J. Phys., 37, 482(1969)

[20] J. M. Peterson et al., Phys. Rev., 120, 521(1960)

[21] P. H. Bowen et al., Nucl. Phys., 22, 640(1961)

[22] D. G. Foster et al., Phys. Rev., C3, 576(1971)

[23] J. R. Morales et al., P. INDC (CHL)–002(1987)

[24] C. Y. Fu, ORNL–TM–8283 (ENDF / B–5 Description) (1982)

[25] A. Langsdorf jr et al., Phys. Rev., 107, 1077(1957)

[26] A. B. Smith et al., Phys. Rev., B, 135, 76(1964)

[27] J. H. Coon et al., Phys. Rev., 111, 250(1958)

[28] El–Kadi et al., Nucl. Phys., A390, 509(1982)

[29] Kinney et al., ORNL–4908 (1974)

[30] B. Holmqvist et al., AE–430 (1971)

[31] Pal Bharati, Nucl. Instru. Metherds, 171, 347(1980)

[32] Zhong Wenguang et al., Chinese Journal of Nucl. Phys., 8(3), 251(1986)

[33] J. R. Beyster et al., Phys. Rev., 104, 1319(1956)

[34] J. R. Beyster et al., Phys. Rev., 98, 600(1955)
[35] H. L. Taylor et al., Phys. Rev., 100, 174(1955)
[36] V. G. Degtyarev et al., Atomnaja Energija, 11, 397(1961)
[37] T. W. Bonner et al., Phys. Rev., 113, 1088(1959)
[38] Lu Zuyin, Chinese Journal of Atomic Energy, 6, 480(1964)
[39] A. Chatterjee et al., Phys. Rev., 161 (4), 1181(1967)
[40] M. H. Macgregor et al., Phys. Rev., 108, 726(1957)
[41] M. H. Macgregor et al., Phys. Rev., 111, 1155(1958)
[42] W. P. Ball et al., Phys. Rev., 110, 1392(1958)
[43] B. Holmqvist et al., AE−150 (1964)
[44] A. S. Smith et al., Phys. Rev., B135, 76(1964)
[45] H. Glazkov et al., Atomnaja Energija, 15, 416(1963)
[46] E. Almen−Ramstrom AE−503 (1975)
[47] W. E. Kinney et al., ORNL−4908 (1974)
[48] D. Thomson, Phys. Rev., 129, 1649(1963)
[49] I. Fujita et al., Journal of Nuclear science and Technology, 9, 301(1973)
[50] J. Frehaut et al., Symposium on neutron cross section from 10∼ 15 MeV, BNL, Upton, N. Y. 399(1980)
[51] Zhou youpu, Evaluation of reacted cross sections, Inter repot hsj−81157 (bp) (1982)
[52] R. N. Glover et al., Nucl. Phys., 29, 309(1962)
[53] H. Liskien et al., J. Nucl. Energ., Section A / B, 19, 73(1965)
[54] M. Bormann et al., Z. Physik, 166, 477(1962)
[55] J. M. Ferguson et al., Phys. Rev., 118, 228(1960)
[56] M. Bormann et al., Nucl. Phys., A130, 195(1969)
[57] R. A. Jargis, J. Phys., G4, 445(1978)
[58] D. R. Koehler et al., AOMC−RR−62−1(1962)
[59] J. L. Fowler et al., Phys. Rev., 77, 787(1950)
[60] L. A. Rayburn, Phys. Rev., 130, 731(1963)
[61] F. GHanbari et al., Annals of Nucl. Energy, 13, 301(1986)
[62] H. K. Vonach et al., 2nd Conf. on Neutron Cross Section and Techn., Washington V2, D. CH−7 Mark, P. 885(1968)
[63] W. Mannkart et al., Z. Physik, Sect., A272, 279(1975)
[64] R. J. Prestwood et al., Phys. Rev., 121, 1438(1961)
[65] D. C. Santry et al., Can. J. Phys., 44, 1183(1966)
[66] A. Paulson et al., Nukleonik, 7, 117(1965)
[67] M. Bormann et al., Z. Physik, 174, 1(1963)
[68] J. W. Meadows et al., Inter. Conf. on Nucl. Data for Basic and Applied Science, Santa Fe, New Mexico, 1, 123(AD01) (1985)
[69] G. Winker, Annals of Nucl. Energy., 10 (11), 601(1983)

[70] J. Cstkai, Int. Conf. on Nucl. Data for Science and Technology, Antwerp, 414 Sep.(1982)
[71] P. N. Ngoc et al., 5th All Union conference on neutron Physcis, Kiev, 1,259, Sep. (1980)
[72] U. Ya. Stavisskij et al., Atomnaja Energija, 15 (4), 323(1963)
[73] B. C. Diven et al., Phys. Rev., 120, 556(1960)
[74] J. Voignoer et al., Nncl. Scie. and Eng., 93, 43(1986)
[75] Budnar et al., INDC(YUG)–6 (1979)
[76] S. M. Qaim et al., Nucl. Phys., A283, 269(1977)
[77] P. Pepelnik et al., NEANDC(E)–262U (5), 32(1985)
[78] Gupta et al., Pramana, (India) 24, 637(1985)
[79] D. C. Santry et al., Can. J. Phys., 44, 1183(1965)
[80] L. Colli et al., Nuovo Cimento, (Italy) 13, 730(1959)
[81] D. L. Allan et al., Nucl. Phys., 10, 348(1959)
[82] Joensson et al., Arkiv for Fysik, 39, 295(1969)
[83] G. Winkler et al., Nucl. Scie. and Eng., 76, 30(1980)
[84] A. Paulsen et al., Nukleonik, 10, 91(1967)
[85] L. R. Greenwood, DOE–ER–0046–21, 15(1985)
[86] O. Y. Artemev et al., Atomnaja Energija, 49 (3), 195(1980)
[87] Garuska et al., INR–1871 / I / PL / A, 15(1980)
[88] G. Winkler et al., Nucl. Scie. and Eng., 67 (2), 260(1978)
[89] Ryves et al., Metrologia, 14 (3), 127(1978)
[90] Qaim et al., EUR–5182E, 939(1974)
[91] S. M. Grimes et al., Phys. Rev., C19, 2127(1979)
[92] R. O. Lane et al., Ann. Phys., 12, 135(1961)
[93] K. Tsukada et al., 2nd IAEA Conf. on Nucl. Data for Reactors, Helsiki, Finland, 2, 305 June (1970)
[94] R. B. Galloway et al., Nucl. Phys., A318, 173(1979)
[95] W. Bucher et al., Phys. Lett., B58, 277(1975)
[96] R. B. Galloway et al., Nucl. Phys., A212, 182(1973)
[97] G. V. Gorlov et al., Jadernaja Fizika, 8(6), 1086(1968)
[98] G. V. Anikin et al., Jadernaja Fizika, 12 (6), 1121(1970)
[99] Anikin et al., Atomnaja Energija, 60, 54(1986)
[100] J. D. Anderson et al., Phys. Rev., 115, 1010(1959)
[101] A. Begum et al., Nucl. Phys., A332, 349(1979)
[102] Li Jingde et al., Chinese J. Nucl. Phys., 10, 46(1988)
[103] N. Yamamuro, T. Kawakita, JENDL–3 (1990)

EVALUATION OF NEUTRON NUCLEAR DATA OF NATURAL ZIRCONIUM

Zou Yiming Ma Gonggui Wang Shiming

(INSTITUTE OF NUCLEAR SCIENCE AND TECHNOLOGY OF SICHUAN UNIVERSITY, CHENGDU)

ABSTRACT

In this paper, the neutron nuclear data evaluation and theoretical calculation for zirconium are described.

This complete evaluation contains neutron cross sections, angular distribution and energy distribution of secondary neutrons in the energy range from 10^{-5} eV to 20 MeV.

INTRODUCTION

Natural zirconium consists of five isotopes: $^{90, 91, 92, 94, 96}Zr$. Their abundances are given in Table 1.

Blow 20 MeV, neutron–induced reaction and their Q value are indicated in Table 1.

The present evaluation was based on experimental data available up to June 1989 and theoretical calculation with MUP–2[1] code. It contains neutron–induced major cross sections : total elastic scattering, nonelastic scattering, inelastic, (n,2n), (n,3n),(n,γ), (n,p), (n,n$'$p), (n,α), (n,n$'\alpha$) and (n,d) cross sections. This evaluation was adopted by CENDL–2 in ENDF / B–5 format.

Tab. 1 Reaction Q value (MeV) and abundance of the isotopes of zirconium

Reactions	^{90}Zr	^{91}Zr	^{92}Zr	^{94}Zr	^{96}Zr
	51.46%	11.23%	17.11%	17.40%	2.80%
(n,γ)	7.20	8.635	6.758	6.475	5.580
(n,n′)	−1.761	−1.205	−0.9345	−0.9188	−1.594
(n,p)	−1.506	−0.762	−2.840	−4.219	−6.016
(n,n′p)	−8.366	−8.709	−9.398	−10.299	−11.48
(n,d)	−6.141	−6.484	−7.173	−8.074	−9.254
(n,n′d)	−17.610	−13.344	−15.119	−15.565	−16.30
(n, ^{3}He)	−7.715	−8.558	−9.388	−11.200	−13.55
(n,n′ ^{3}He)	−18.828	−14.917	−17.193	−18.511	−20.41
(n,t)	−11.352	−7.087	8.861	−9.308	−10.04
(n,n′t)	−20.729	−18.555	−15.722	−15.865	−16.12
(n,α)	1.750	5.661	3.386	2.067	0.171
(n,n′α)	−6.678	−5.452	−2.972	−3.760	−4.929
(n,2n)	−11.983	−7.202	−8.635	−8.191	−7.831
(n,3n)	−21.294	−19.195	−15.833	−14.950	−14.31

1 THEORETICAL CALCULATION AND PARAMETERS

AUJP[3] and MUP−2[1] codes were used in the theoretical calculation.

AUJP is automatical−adjusting−parameter optical model code. MUP−2 code includs optical model, H−F statistical model and pre−equilibrium evaporation model.

In the theoretical calculation, original optical potential parameters were taken from Shi Xiangjun[4], nuclear level informations were taken from Ref. [5] for ^{90}Zr, Ref. [6] for ^{91}Zr, Ref. [7] for ^{92}Zr, Ref. [8] for ^{94}Zr, and Ref. [9] for ^{96}Zr respectively. The double giant resonance parameters of photonuclear reaction were taken from Ref. [10], level density parameters were taken from Ref. [11].

Level density formula are defined by

$$a = \{ 0.00880 \,[\, S(z) + S(n) + QB \,] \} A$$

$$V = 1.4 + 263 / A$$

where $QB = 0.142$ (for all isotopes)

$S(z) + S(n)$ are shell correct.

The adjusted optical model parameters are given in the following: (MeV or fm)

Real part: $V = 52.289 - 0.700E + 0.0180 \times 10^2 - 24.00\,(N-Z)/A$

$$r_0 = 1.26, \quad a_0 = 0.65$$

Imaginary volume absorption well depth

$W = 0.283E - 2.002$, or zero (the greater one is taken)

Imaginary surface absorption well depth

$W_d = 7.650 - 0.104E - 12.00\,(N-Z)/A$, or zero (the greater one is taken)

$$r_w = r_d = 1.27, \quad a_w = a_d = 0.54$$
$$V_{so} = 6.20, \quad r_{so} = 1.24, \quad a_{so} = 0.65$$

The level density parameters used in this work are given in the following :

Level density parameter for $P(Z)$ and $S(Z)$

Z	40	39	38	37	36
$P(Z)$	1.35	0.29	1.24	0.20	1.1
$S(Z)$	−16.75	−17.05	−16.41	−16.20	−15.20

Level density parameter for $P(N)$ and $S(N)$

N	$P(N)$	$S(N)$	N	$P(N)$	$S(N)$
47	0.00	16.72	53	−0.30	14.80
48	1.60	14.25	54	1.12	15.20
49	−0.28	14.88	55	0.00	15.59
50	1.2	12.88	56	1.15	17.15
51	0.10	12.95	57	0.00	17.00
52	0.75	13.65			

The adjusted pre–equilibrium parameters *DK* are as follows :

Isotopes	^{90}Zr	^{91}Zr	^{92}Zr	^{94}Zr	^{96}Zr
DK	690	55	55	55	190

The calculated total cross section, elastic scattering cross section and nonelastic scattering cross section by AUJP code are in agreement with the evaluated experimental data, as illustrated in Table 2.

Table 2 The comparison between calculated and evaluated experimental data

(MeV)	tot			n,n			non		
	eval.	cal.	err.	eval.	cal.	err.	eval.	cal.	err.
1.00	6.33	6.75	6.2	6.019	6.60	6.0	0.139	0.141	1.4
1.45	5.49	5.68	3.3	5.14	5.32	3.4	0.35	0.36	3.0
2.05	4.70	4.75	1.0	3.93	4.03	2.5	0.77	0.73	5.2
2.55	4.25	4.34	2.0	3.05	3.10	1.6	1.20	1.19	0.8
3.0	4.00	4.02	0.5	2.60	2.57	1.1	1.40	1.44	2.9
3.6	3.83	3.80	0.8	2.28	2.19	3.9	1.55	1.60	3.2
4.0	3.80	3.75	1.3	2.25	2.11	6.2	1.55	1.63	5.2
5.0	3.85	3.81	1.6	2.20	2.11	4.1	1.63	1.69	3.7
7.0	4.10	4.32	5.4	2.41	2.54	5.4	1.69	1.71	1.2
8.0	4.30	4.42	2.8	2.60	2.70	3.8	1.70	1.72	1.2
10.0	4.30	4.41	2.6	2.58	2.68	3.9	1.72	1.73	0.6
14.0	3.95	3.89	1.5	2.22	2.16	2.7	1.73	1.74	0.0
17.0	3.56	3.62	1.7	1.85	1.83	1.1	1.71	1.80	5.3
20.0	3.30	3.37	2.1	1.62	1.60	1.2	1.68	1.77	5.4

err. = [|cal. − eval.| / eval.] × 100%

The calculated (n,γ), (n,2n) and discrete inelastic scattering cross section by MUP–2 code are in agreement with the evaluated experimental data.

2 RECOMMENDED NEUTRON CROSS SECTIONS

2.1 Total Cross Sections

Below 90 keV, the resonance parameters were taken directly from the recommended values of M.Drake et al.[12].

Between 90 keV and 1 MeV, There are considerable structure in the experimental data. In this energy regions, the better resolution experimental results were recommended respectively, that is the data of Seth[15] from 90 keV to 0.5 MeV, and the data of Green[16] Between 0.5 and 1 MeV.

Above 1 MeV, the total cross section get smoother. Therefore, from 1 to 20

MeV, the orthogonal polynomial fit result of 7 sets of data[14, 16~21] was used, including the data of Poenitz[14].

The present evaluated total cross sections are in agreement with that of CENDL-1 and ENDF / B-6[12].

From 90 keV to 0.5 MeV, there is no structure for the evaluated total cross sections of JENDL-3[22], and they are almost a constant, and somewhat lower than ENDF / B-6 and our work below 0.2 MeV.

The present evaluated total cross section was compared with ENDF / B-6 and JENDL-3, and is shown in Fig. 1.

2.2 Elastic Scattering Cross Sections

The recommended elastic scattering cross sections were obtained by subtracting the nonelastic cross sections from the evaluated total cross sections in the entire energy range. The evaluated cross section agrees very well with the available measurements[23~27], but between 0.2~ 1 MeV, the evaluated curve is slightly lower than the measured data of Reitmann[24].

The evaluated cross sections are in agreement with ENDF / B-6 below 14 MeV, above that ENDF / B-6 is somewhat higher. JENDL-3 appears somewhat lower below 14 MeV, above that gets lower and lower with energy increasing.

2.3 Nonelastic Scattering Cross Sections

There are many experimental results from threshold to 20 MeV. The calculated non-elastic cross sections are in agreement with the experimental results, except the calculated cross section appear somewhat higher at high energy region.

The present evaluated nonelastic cross sections are taken from the orthogonal polynomal fit result of the experimental data[28~33].

The evaluated cross sections are in agreement with that of ENDF / B-6 below 14 MeV, above that ENDF / B-6 is somewhat lower, as illustrated in Fig. 2. Meantime JENDL-3 appears higher above 15 MeV.

2.4 Inelastic Scattering Cross Sections

(1) Discrete inelastic scattering cross sections

For the discrete inelastic scattering cross sections 6 levels of ^{90}Zr, 7 levels of ^{91}Zr, 5 levels of ^{92}Zr, 6 levels of ^{94}Zr, and 2 levels of ^{96}Zr are included. These excitation energies and spin parities taken from Ref. [5~ 9] are summarized in Table 3.

Table 3(1) Energy levels of ^{90}Zr

Level	Energy (MeV)	Spin Parity	Level	Energy (MeV)	Spin Parity
1	0.0	0.0^+	10	3.5890	8.0^+
2	1.7610	0.0^+	11	3.8430	2.0^+
3	2.1863	2.0^+	12	3.9700	5.0^-
4	2.3187	5.0^-	13	4.1200	2.0^+
5	2.7388	4.0^-	14	4.1300	0.0^+
6	2.7479	3.0^-	15	4.2380	2.0^+
7	3.0773	4.0^+	16	4.3300	4.0^+
8	3.3090	2.0^+	17	4.4300	0.0^+
9	3.4483	6.0^+			

Table 3(2) Energy levels of ^{91}Zr

Level	Energy (MeV)	Spin Parity	Level	Energy (MeV)	Spin Parity
1	0.0	2.5^+	5	2.0420	1.5^+
2	1.2050	0.5^+	6	2.1310	4.5^+
3	1.4670	2.5^+	7	2.1700	5.5^-
4	1.8820	3.5^+	8	2.1890	2.5^-

Table 3(3) Energy levels of ^{92}Zr

Level	Energy (MeV)	Spin Parity	Level	Energy (MeV)	Spin Parity
1	0.0	0.0^+	6	2.0660	2.0^+
2	0.9345	2.0^+	7	2.3390	3.0^-
3	1.3820	0.0^+	8	2.3900	4.0^+
4	1.4955	4.0^+	9	2.4860	5.0^-
5	1.8470	2.0^+			

Table 3(4) Energy levels of ^{94}Zr

Level	Energy (MeV)	Spin Parity	Level	Energy (MeV)	Spin Parity
1	0.0	0.0^+	5	1.6715	2.0^+
2	0.9188	2.0^+	6	2.0577	3.0^-
3	1.3004	0.0^+	7	2.1515	2.0^+
4	1.4697	4.0^+			

Table 3(5) Energy levels of ^{96}Zr

Level	Energy (MeV)	Spin Parity	Level	Energy (MeV)	Spin Parity
1	0.0	0.0^+	3	1.7510	2.0^+
2	1.5940	0.0^+			

There are a few experimental data[34~37] which are essentially in agreement with the calculated results.

The recommended discrete level inelastic cross section are taken from the calculated results, except 1.761, 2.186 levels of ^{90}Zr and 0.9345, 1.382, 1.4955 levels of ^{92}Zr, which were slightly adjusted to Genther's data.

The recommended discrete inelastic cross sections are in agreement with measured data, as illustrated in Fig. 6.

(2) Continuous inelastic scattering cross sections

Continuous inelastic scattering cross sections were obtained by subtracting the sum of the discrete inelastic scattering cross sections from the total inelastic scattering cross sections.

(3) Total inelastic scattering cross sections

The recommended total inelastic cross section was obtained by subtracting sum of the cross sections of all the other reactions from the evaluated non–elastic cross sections.

2.5 (n,2n) Cross Sections

There is only one experimental data of Frehaut[39] from threshold to 14.8 MeV, and it is in agreement with the calculated results.

The present evaluated (n,2n) cross sections adopted the data of Frehaut[39] below 14.8 MeV, above that the calculated results was used.

The present evaluation is in agreement with ENDF / B–6 below 16 MeV, except ENDF / B–6 is some what higher from 9.5 to 12 MeV. Above 16 MeV ENDF / B–6 appears lower. Meantime the difference between ours and

JENDL−3 becomes larger with incresing energy, as illustrated in Fig. 4.

2.6 (n,3n) Cross Sections

The (n,3n) cross section was taken from the model calculation due to lack of experimental data.

2.7 Capture Cross Sections

The two newer data sets[39, 40] agree with each other, and the energy range extended to 3.5 MeV. The evaluated capture cross section, from 90 keV to 3.5 MeV, are taken from the orthogonal polynomial fit result of the data[40~43] was used.

From 3.5 to 20 MeV the evaluation result of Drake[12] was adopted and normalized to the measured data[44] near 14 MeV.

The present evaluation is in agreement with that of ENDF / B−6. The evaluation of JENDL−3 appears lower than the experimental data, as illustrated in Fig 3.

2.8 (n,p) and (n,n′p) Cross Sections

(1) (n,p) cross sections

The (n,p) cross sections were obtained from its isotopes. The (n,p) cross section for ^{90}Zr was based on measurement by Qaim[45], Levkovskij[46], Bryhurst[47] and Carroll[48].

For the other isotopes, the theoretical calculation values were used, and normalized to the following measurement near 15 MeV : for ^{91}Zr, Qaim[45], Levkovskij[46]; for ^{92}Zr and ^{94}Zr, Pepelnik[49] and Fujino[50]; for ^{96}Zr, Vallis[51].

(2) (n,n′p) cross sections

The (n,n′p) cross sections were taken from the calculation result, due to lack of experimental data.

2.9 (n,α) and (n,n′α) Cross Sections

(1) (n,α) cross sections

Only a few experimental data can be obtained for three low abundance isotopes (^{92,94,96}Zr). Sum of the abundance is about 37 %. Therefore, this evaluation adopted the model calculation result.

(2) (n,n′α) cross sections

The (n,n′α) cross sections were taken from the calculation results, due to lack of experimental data.

2.10 (n,d) and (n,n′d) Cross Sections

(1) (n,d) cross sections

The (n,d) cross sections were taken from the calculation results, due to lack of experimental data.

(2) (n,n′d) cross sections

The process was ignored, due to no experimental data and small cross section of calculated results.

2.11 (n,t) and (n, ^{3}He) Cross Sections

The processes were ignored, due to no experimental data and small cross section of calculated results.

3 ANGULAR DISTRIBUTION OF SECONDARY NEUTRONS

The angular distributions of secondary neutrons, from elastic scattering and inelastic scattering to discrete levels, were represented by Legendre coefficients in the center–of–mass system. The angular distributions of secondary neutrons for (n,n′ continuum), (n,2n), (n,3n), (n,n′p) and (n,n′α) processes were assumed isotropic.

The experimental data of elastic scattering angular distributions scattered in the energy range from 0.06 MeV to 7 MeV and 14.5 MeV. For adjusting optical potential parameters, the following data were used : from 0.06 MeV to 0.22 MeV, Langsdof[23]; from 0.3 MeV to 1.5 MeV, Reitman[24]; from 1.55 MeV to 4.1 MeV, Smith[38], Beyster[52], Strizhak[53], Becker[54], Kent[25] and Walt[26]; from 5 MeV to 7 MeV, Beyster[52] and Buccino[55]; at 14.5 MeV, Clark[56], Bostrom[57] and Anderson[58].

The present evaluated angular distributions of elastic scattering neutrons were taken from the calculation results. They are in agreement with the experimental data, as illustrated in Fig.5.

4 THE ENERGY DISTRIBUTIONS OF SECONDARY NEUTRONS

The energy distributions of secondary neutrons from (n,n′continuous), (n,2n), (n,3n), (n,n′p) and (n,n′α) processes were taken from the calculation results.

5 SUMMARY

The recommended total, nonelastic, (n,γ) and (n,2n) cross sections below 14.8 MeV were completely based on the experimental data. The recommended elastic scattering angular distribution and inelastic scattering cross section of discrete levels are in agreement with the available experimental data.

For the present charged particle emitting cross sections, there is considerable difference from that of CENDL–1, due to using of MUP–2 code.

The present evaluated cross section is essentially agreement with ENDF / B–6, but there are some differences, as the following :

(1) Non–elastic scattering cross sections of ENDF / B–6 become smaller above 14 MeV.

(2) Above 17 MeV, the evaluated (n,2n) cross sections of ENDF / B–6 become lower. From 10 MeV to 12 MeV, ENDF / B–6 appears somewhat higher.

The present evaluated cross section is different from JENDL–3 in the following :

(1) Below 0.5 MeV, the evaluated total cross section of JENDL–3 is almost a constant, and appears somewhat lower below 0.2 MeV.

(2) The evaluated (n,γ) cross section of JENDL–3 is somewhat lower from 0.1 MeV to 3 MeV, and much lower above 3 MeV.

(3) Nonelastic scattering cross section of JENDL–3 is somewhat higher below 14 MeV, and becomes much larger above that.

(4) Above 15 MeV, the evaluated (n,2n) cross sections of JENDL–3 become larger with increasing energy.

ACKNOWLEDGMENTS

The authors are very grateful to Profs. Liang Qichang, Liu Tingjin for much help in this work, in the meantime, also the same to Prof. Cai Dunjiu et al. of CNDC.

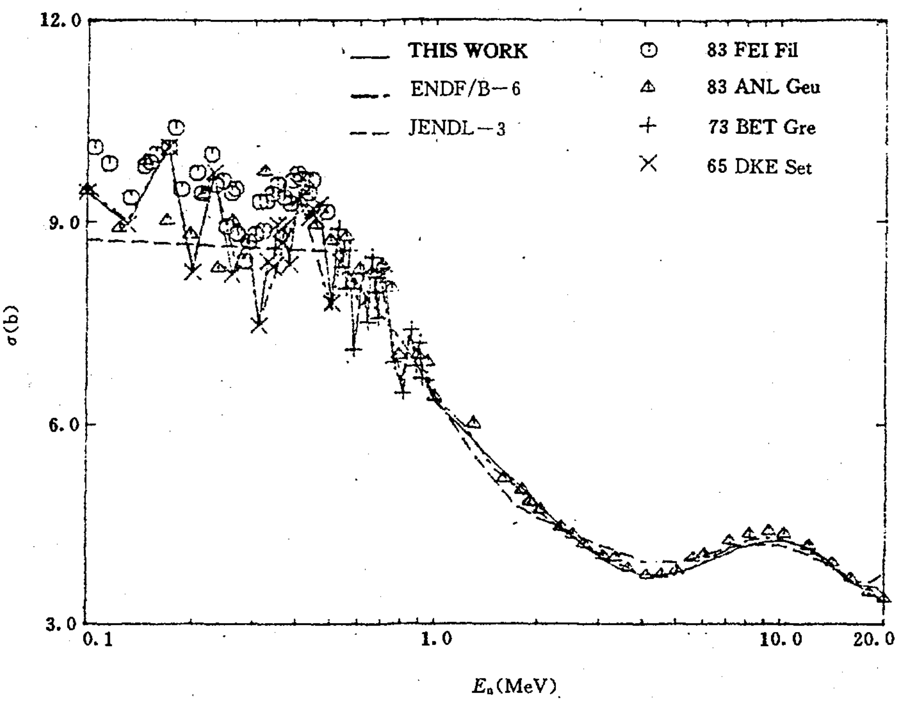

Fig. 1 Neutron total cross section of Zr

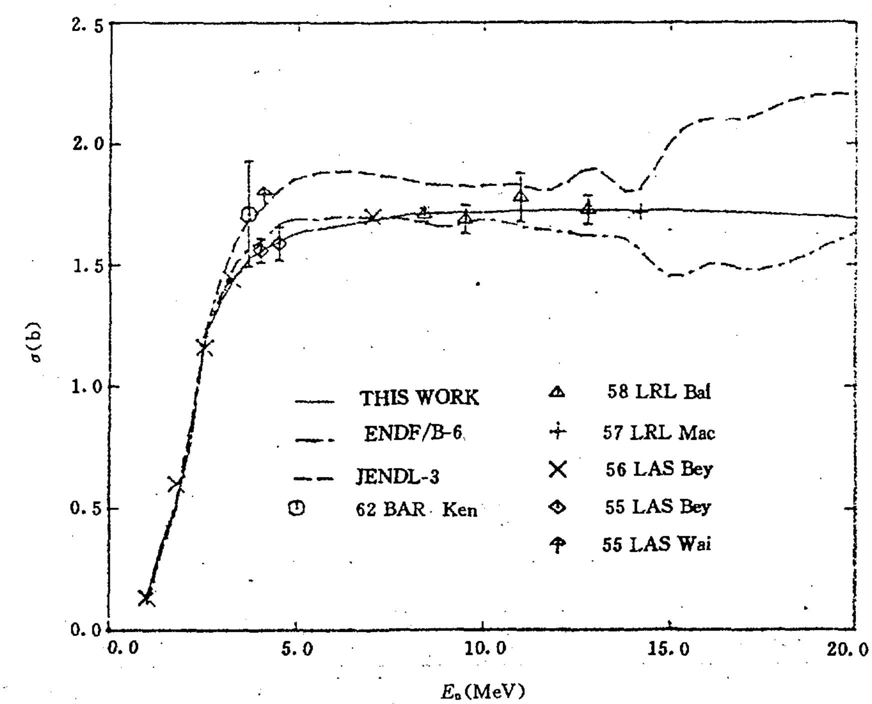

Fig. 2 Neutron nonelastic cross section of Zr

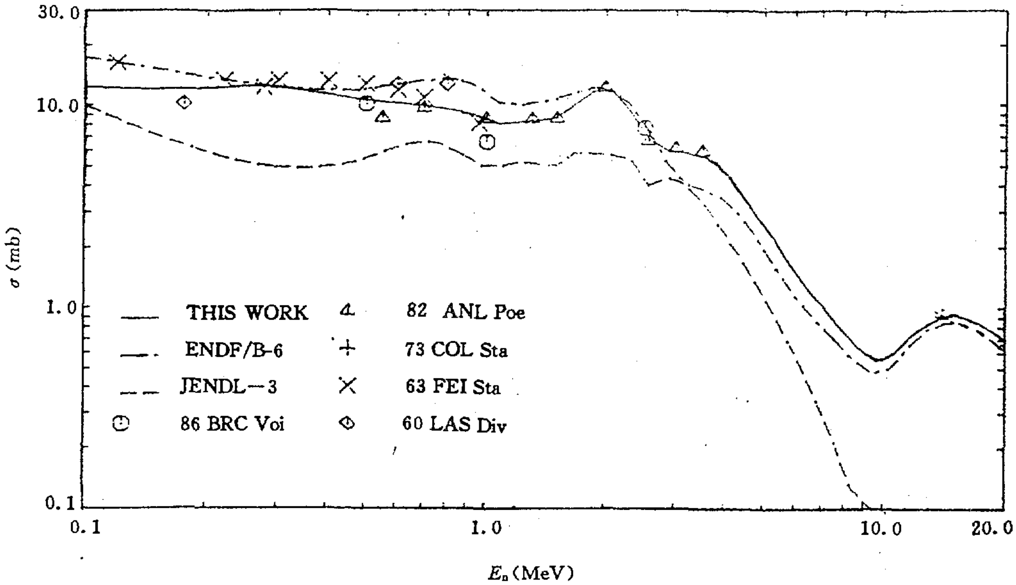

Fig. 3 Neutron capture cross section of Zr

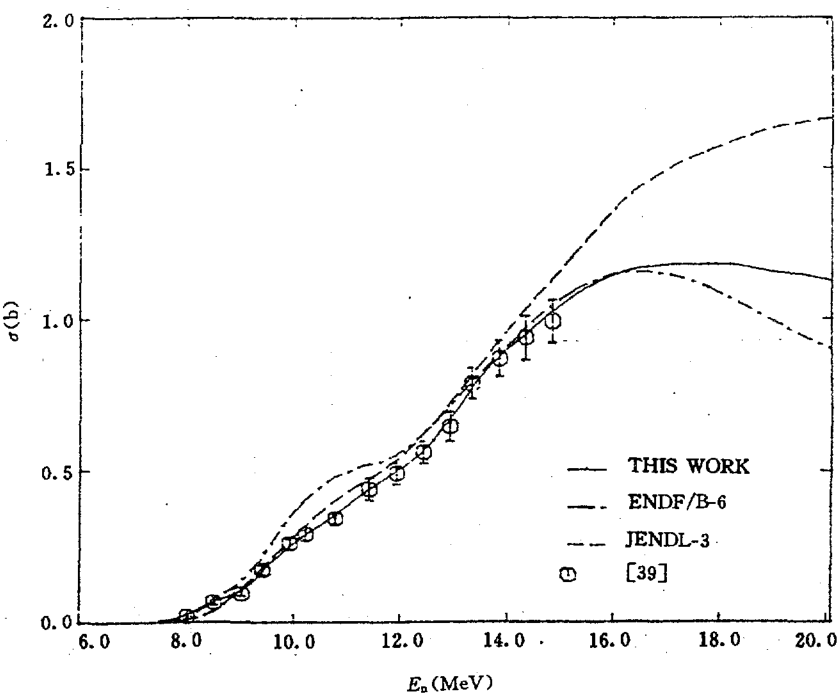

Fig. 4 (n,2n) cross section of Zr

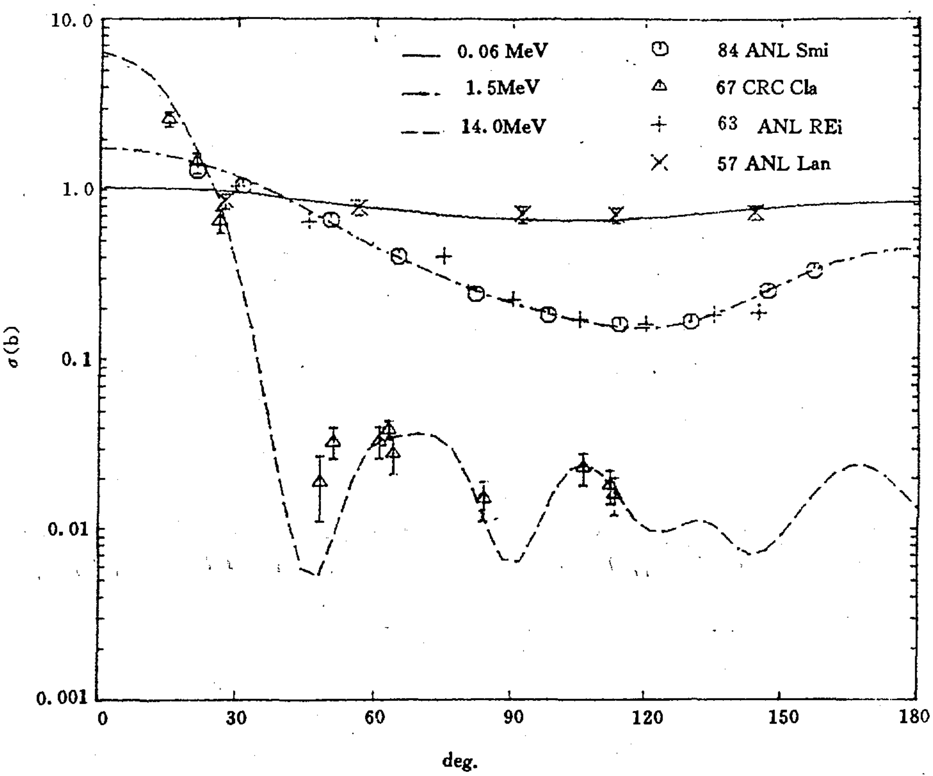

Fig. 5 Differential elastic scattering cross section of Zr

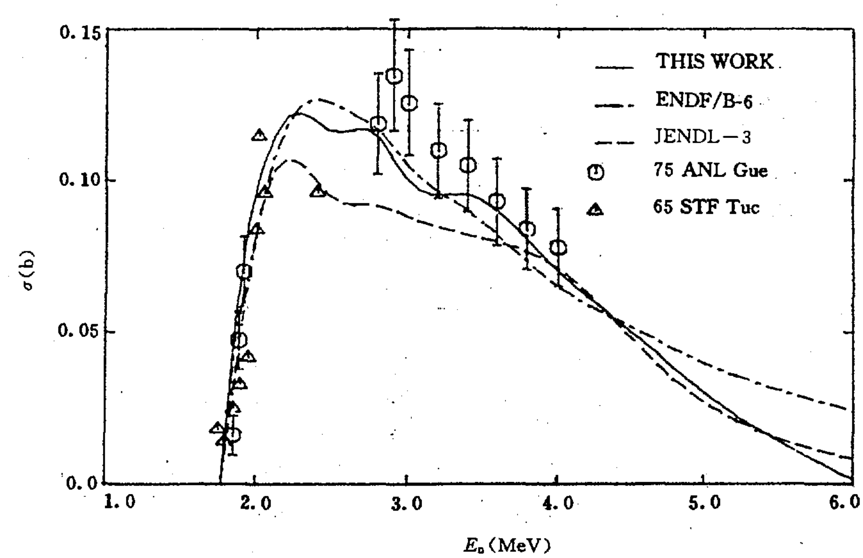

Fig. 6 1.761 MeV level inelastic scattering cross section of Zr

REFERENCES

[1] Yu Ziqiang, Cai Chonghai et al., Theoretical calculated program MUP–2 for medium and heavy nuclear, internal report (1986)

[2] Zhou Yiming, Cao Jianhua, Chinese Evaluated Nuclear Data Library, Version 1. CNDC–85010 p. 201(1986)

[3] Zhou Hongmo, Yu Ziqiang et al., Auto–adjusting parameter optical model calculated program AUJP, internal report (1978)

[4] Shi Xiangjun et al., Theoretical Calculation of the Neutron Reactions of Natural Zirconium Nuclide. CNDC–85011 p. 113 (1986)

[5] D. C. Kocher, Nuclear Data Sheets 16, 55(1975)

[6] H. W. Muller, Nuclear Data Sheets 31, 181(1980)

[7] P. Luksch, Nuclear Data Sheets 30, 573(1980)

[8] H. W. Muller, Nuclear Data Sheets 44, 277(1985)

[9] H. W. Muller, Nuclear Data Sheets 35, 281(1982)

[10] Su Zongdi et al., private communication (1983)

[11] Su Zongdi et al., Chinese Journal of Nuclear Physics Vol. 8, No. 3, 199(1986)

[12] M. K. Drake et al., ENDF / B–6 (1990)

[13] V. V. Filippov et al., 6th All Union Conference on Neutron Physics, Kiev, 3,107(1983)

[14] W. P. Poenitz et al., ANL–NDM–80 (1983)

[15] K. K. Seth et al., Phys. Lett., 16, 306(1965)

[16] L. Green et al., 3rd Conference on Neutron Cross Sections and Technology, University of Tennessee, Knoxville, Vol. 1, p.325 (1971) orWAPD–TM–1073(1973)

[17] D. G. Foster et al., Phys. Rev., C3, 576(1971)

[18] A. D. Carlson et al., Phys. Rev., 158, 1142(1967)

[19] R. B. Day et al., Phys. Rev., 92, 358(1953)

[20] J. M. Peterson et al., Phys. Rev., 120, 521(1960)

[21] M. Mazair et al., 2nd International Conference on the Peaceful Uses of Atomic Energy,Geneva, Vol. 15, p. 28(1958)

[22] M. Sasaki, JENDL–3 (1990)

[23] A. Langsdorf, Phys. Rev., 107, 1077(1957)

[24] D. Reitman et al., Nucl. Phys., 48, 593(1963)

[25] D. W. Kent et al., Phys. Rev., 125, 331(1962)

[26] M. Walt et al., Phys. Rev., 98, 677(1955)

[27] Korzh et al., Izv. Akad. Nauk SSSR, Ser. Fiz / BAS / 35 (4) 823(1971)

[28] J. R. Beyster et al., Phys. Rev., 98, 1216(1955)

[29] J. R. Beyster et al., Phys. Rev., 104, 1319(1956)

[30] M. H. MacGregor et al., Phys. Rev., 108, 726(1957)

[31] W. P. Ball et al., Phys. Rev., 110, 1392(1958)

[32] D. W. Kent et al., Phys. Rev., 125, 331(1962)
[33] M. Walt et al., Phys. Rev., 98, 677(1955)
[34] P. Guenther et al., Phys. Rev., C12, 1797(1975)
[35] A. B. Tucker et al., Phys. Rev., B137, 5, 1181(1964)
[36] G. P. Glasgow et al., Phys. Rev., C18, 2520(1978)
[37] Mc Daniel et al., Phys. Rev., C10, 1087(1974)
[38] A. B. Smith et al., Nucl. Phys. A415, 1(1984)
[39] J. Frehaut et al., Symposium on Neutron cross sections from 10~ 50 MeV, BNL Upton, N. Y., 399(1980)
[40] W. P. Poenitz ANL−83−4, 239(1982)
[41] J. Voignier et al., Nucl. Sci. and Eng., 93, 43(1986)
[42] U. Ya. Stavisskii et al., Atomnaya Energiya, 15(4), 323(1963)
[43] B. C. Diven et al., Phys. Rev., 120, 556(1960)
[44] M. Stamototetos et al., Nucl. Sci. Eng., 51, 113(1973)
[45] Qaim et al., EUR−5182E, 939(1974)
[46] Levkovskij Jadernaja Fizika, 10(1), 44(1969)
[47] B. P. Bryhurst et al., J. Inorg. Nncl. Chem., 23, 173(1961)
[48] Edward E. Carroll et al., Nucl. Sci. Eng., 25, 285(1966)
[49] R. Pepelnik et al., Internat. Conf. on Nucl. Data for Basic and Applied Science, Santa Fe, New Mexico 1, 211(JA46) (1985)
[50] Fujino et al., NEANDC (J)−51, 60(1977)
[51] D. G. Vallis et al., J. Inorg. Nncl. Chem., 22, 1(1961)
[52] R. Beyster et al., Phys. Rev., 104, 1319(1956)
[53] V. I. Strizhak et al., Ukrainskij Fijichnij Zhurnal, 5, 704(1960)
[54] R. L. Becker et al., Nucl. Phys., 89, 154(1966)
[55] S. C. Buccino et al., Z. Physik, 196, 103(1966)
[56] R. L. Clark et al., Nucl. Phys., A95, 320(1967)
[57] N. A. Bostrom et al., WADC−TN−59−107(1959)
[58] J. D. Anderson et al., Phys. Rev., 115, 1010(1959)
[59] S. H. Ahn et al., Phys. Rev., 119, 1667(1960)

NEUTRON DATA EVALUATION
FOR NATURAL NIOBIUM

Ma Gonggui Zou Yiming Wang Shiming

(INSTITUTE OF NUCLEAR SCIENCE AND TECHNOLOGY,
SICHUAN UNIVERSITY, CHENGDU)

ABSTRACT

The complete neutron nuclear data for natural niobium were evaluated based on both experimental data measured upto 1989 and calculated data with program MUP2[1] andAUJP[2].

The present work was done for CENDL−2 and supersedes the CENDL−1 (MAT = 1411) evaluation[3].

The following neutron data are given for Nb in the energy range 10^{-5} eV to 20 MeV (MAT= 2411) : total, elastic, nonelastic, total inelastic, inelastic cross sections to 13 discrete levels, inelastic continuum, (n,2n), (n,3n), (n,n′α) + (n,αn′), (n,n′p) + (n,pn′), (n,n′d) + (n,dn′), (n,p), (n,d), (n,t), (n,α) and capture cross sections. Derived data for MT = 251, 252 and 253 are also included.

Angular distributions and energy spectra of secondary neutron are also given.

INTRODUCTION

This is almost a completely new evaluation, the neutron cross sections and angular distributions as well as the secondary neutron energy distribution have been updated. The cross sections mainly refered to BNL−325 (4th−86)[4], that also compared with ENDF / B−6 (90)[5] and JENDL−3 (88)[6].

The resolved resonance parameters and the background used in the energy range from 10^{-5} eV to 7.35 keV are the same as ENDF / B−6[5].

We also able to see from Ref. [7] that the new data for the inelastic levels were updated (see Table 1).

Table 1 Discrete levels of Nb

0.0	9/2+	0.8104	3/2−	1.2900	1/2−
0.0308	1/2−	0.9498	13/2+	1.2972	9/2+
0.6870	3/2−	0.9789	11/2+	1.3153	5/2−
0.7439	7/2+	1.0827	9/2+	1.3200	5/2−
0.8086	5/2+	1.2537	5/2+		

1 NEUTRON CROSS SECTIONS

1.1 Total Cross Section

From the upper bound of the resonance region 7.35 keV to 20 MeV, it was assumed that the cross section is smooth and the experimental evidence supports this assumption. Therefore, in order to reduce the number of the data, the results of each reference were averaged over some energy region.

The experimental data were taken from Poenitz[9], Filippov[10], Smith[11~12], Green[13], Foster[14], Carlson[15], Uttley[16], Saplakoglu[17], Newson[18], Coon[19] and Miller[20].

The evaluated data were obtained from a spline fit to the experimental data (Fig. 1).

The present evaluation is also compared with that of ENDF / B–6 and JENDL–3 (Fig. 1).

1.2 Elastic Scattering Cross Section

Above the resolved resonance from 7.35 keV to 20 MeV, the elastic scattering cross section was calculated with AUJP code[8] based on experimental data at 20 measured energy points.

The experimental data were measured by Li[21], Pedroni[22], Adel–Fawzy[23], Cox[24], Korzh[25],Reitmann[26], Coles[27], Gorlov[28], Etemad[29], Holmqvist[30], Western[31],Kazakova[32], Longsdorf[33], Walt[34].

The present evaluated data are compared with those of ENDF / B–6, JENDL–3 and available experimental data in Fig. 2. In general, the agreement between the evaluated cross section and available experimental data is good.

1.3 Nonelastic Scattering Cross Section

For this cross section only Abramovs[35] measured data are available. It was obtained by subtracting the elastic scattering cross section from the total cross section.

1.4 Total Inelastic Cross Section

The total inelastic cross sections are the sum of all the discrete level excitation cross sections and the continuum cross section. The experimental data were taken from Simakov[36], Vanheerden[37], Coles[27], Goebel[38], Broder[39], Glazkov[40], and Thomson[41].

From threshold to 8.0 MeV, the spline function fitting were performed based on a number of experimental results. Above 8 MeV, the calculated results were normalized to experimental data 1.9 b at 8 MeV energy point. A plot of these experimental data and the evaluated cross section is shown in Fig. 3. The present evaluation is also compared with that of ENDF / B–6 and JENDL–3.

1.5 Inelastic Cross Section to the Discrete Levels and the Continuous States

The calculated data for 13 excited levels, up to excitation energy approximately 1.32 MeV, were taken from Ref. [6]. Generally, in the evaluation a compound nucleus reaction mechanism was assumed, thus the inelastic scattering cross sections for high energy discrete levels are very small.

The experimental data were measured by Smith[11], Almen–Ramstrom[42], Etemad[29], Smith[12], Coles[27], Reitmann[26], Vanheerden[37], Rogers[43] and Nemilov[44]. The excitation of the 30.8 keV level was entirely based on calculation. The cross sections are very small.

The plots of these experimental data and the evaluated cross sections are shown in Figs. 4–1, 4–2. In general, the agreement is reasonably good.

The Continuous part was obtained by subtracting the cross section of inelastic scatteringe to 13 excited levels from the total inelastic, scattering cross sections.

1.6 Capture Cross Section

The capture cross section from 10^{-5} eV to 7.35 keV is given by the resonance parameters and the background.Above this energy up to about 3 MeV, capture cross section was obtained by fitting the experimental data measured by Mu[45], Xi[46], Voignier[47], Yamamuro[48], Macklin[49], and Poenitz[50]. At 14 MeV, there are experimental data measured by Rigand[51]. The recent and selected earlier data sets were used in the evaluation. From 3 MeV to 20 MeV, the cross section was obtained from JENDL–3 (6.21 mb at 3 MeV).

The present evaluation is a description of the experimental data, as illustrated in Fig. 5. It is also good agreement with ENDF / B–6 and JENDL–3.

1.7 (n,2n) and (n,3n) Cross Sections

For (n,2n) reaction, the experimental data were measured by Veeser[52] and Frehaut[53] in the energy range from 14.7 to 20 MeV and 9.44to14.76 MeV; and Lychagin[54], Holub[55], Haering[56], Paulsen[57], Hermsdorf[58] above 15 MeV. The evaluated data were got from spline function fitting these measured data. The comparison of present evaluation with ENDF / B–6 and JENDL–3 is shown in Fig. 6.

For (n,3n) reaction has there is high energy threshold (approximately 16.9

MeV) and a small cross section, so the application interest is less. There is only one experimental data set (Veeser[52]). The recommended data are eyes–guide curve through these few experimental values(see Fig. 6).

1.8 (n,p) and (n,n'p) + (n,pn') Cross Sections

The (n,p) cross sections at 14.1 and 15 MeV were measured by Traxler[59], Koori[60] and Grimes[61] . The corresponding model calculated result was nomalized to experimental data 45 mb at 14.5 MeV.

(n,n′p) + (n,pn′) cross section data were taken from the calculated results.

1.9 (n,α) and (n,n′α) + (n,αn′) Cross Sections

For (n,α) reaction, the experimental data were measured by Mannann[62], Wolfle[63] , Fischer[64] ,Bormann[65] , Kulisic[66] , Bramlitt[67] ,Tewes[68] , Blosser[69] and Bayhurst[70] in the energy range 4~ 18 MeV. The present evaluation was based upon the relatively good experimental data and evaluation by Mannan[62]. The evaluated data are shown in Fig. 7. The cross section is 9.5 mb at 14.5 MeV. Based on these experimental data, the evaluated data are greatly improved.

It is experimentally known that (n,n′α) + (n,αn′) cross sections are very small. The above–mentioned (n,α) cross section and the measured total helium production imply that the (n,n′α) cross section is approximately 5.5 mb at 15 MeV. This value was used to normalize the calculated results.

1.10 (n,d) and (n,n'd) + (n,dn') Cross Sections

Experimental knowledge of these two processes appears confine to a single gas production measurement the (n,d) cross section was measured by Grimes at 15 MeV[61], to be 8.1 mb. The experimental data was used to normalize the corresponding calculated results.

Due to the high threshold, the (n,n′d) process must make a small contribution to this value. The evaluated data were taken from calculated.

1.11 (n,t) Cross Section

Experimental data of this reaction (included n,n′t + n,tn′) was measureds by Sudar at 14.6 MeV[71] and Qaim at 16.3~ 19.0 MeV[72]. The evaluation is based upon calculations with MUP2, normalized to the experimental data 0.37 mb at 14.6 MeV, and refered to evaluation of Zhao[73].

The present evaluated data is compared with those of ENDF / B–6 and available experimental data shown in Fig. 8.

2 SECONDARY NEUTRON ANGULAR DISTRIBUTIONS

Elastic scattering angular distributions were calculated with MUP–2 code and are given in terms of Legendre coefficients in the c. m. system. The experimental data at 20 energy points from Smith[12], Li[21], Simakov[36], Pedroni[22], Adel–Fawzy[23], Cox[24], Reitmann[26], Coles[27], Gorlov[28], Etemad[29], Hol–mqvist[30], Kazakova[32], Walt[34], Simakov[36], Ferrer[74] and Kammerdiener[75] were used in the optical model calculation. The calculated result was in good agreement with the concerned experimental value. All the evaluated differential elastic scattering cross sections are consistent with the values of Wick's Limit[76] implied by the above total cross section(see Figs. 9–1; 9–2).

The discrete inelastic angular distributions (MT = 51 ~ 63) also were taken from calculated results and given in terms of Legendre coefficients in the c.m. system.

The angular distributions for (n,2n), (n,3n), (n,n′α), (n,n′p), (n,n′d) and continuous inelastic (MT = 16, 17, 22, 28, 32, 91) were assumed to be isotropic.

3 SECONDARY NEUTRON ENERGY DISTRIBUTIONS

For the inelastic continuous, (n,2n), (n,3n), (n,n′α) and (n,n′p) (n,n′d) reactions(MT = 16, 17, 22, 28, 32), they were all taken from calculated results.

4 THEORETICAL CALCULATION

In the theoretical calculation, various parameters are required to input : optical model parameters, level density parameters[8] and information on nuclear level scheme[7]. These patameters were adjusted on the basis of experimental data.

The main parameters used are as follows :

(1) Optical potential parameters (MeV or Fermi)

$A_r = A_{so} = 0.7065$	$V_0 = 48.22$
$A_s = A_{vv} = 0.2684$	$V_1 = -0.326$
$X_r = X_{so} = 1.3322$	$V_2 = 0.00012$
$X_s = X_v = 1.349$	$V_3 = -24.0$
$X_c = 1.0$	$V_4 = 0.0$
$U_0 = -2.102$	$W_0 = 18.7$
$U_1 = 0.055$	$W_1 = 0.24$
$V_{so} = 2.502$	$W_2 = -12.0$

(2) Level density parameters, they are given in Table 2.

Table 2 Level density parameters for ^{93}Nb*

$P(Z)$	0.0	1.35	0.29	1.24	0.2
$P(N)$	−0.3	0.75	0.1	1.2	−0.28
$S(Z)$	−15.4	−16.75	−17.05	−16.41	−16.2
$S(N)$	14.8	13.65	12.95	12.88	14.88

* The level density formula of Ref. [8] were used.

(3) Pre–equilibrium parameter $DK = 160.0$

The data for Nb were calculated with programs AUJP[2] based on optical model and MUP–2[1] based on optical model, H–F theory with width fluctuation correction and the unified treatment of exciton model and evaporation model in the energy range from 1 keV to 20 MeV. The comparison between calculated and experimental data is given in the Table 3.

Table 3 The comparison between calculated and experimental data

(MeV)	tot			n,n			non		
	theo.	eval.	* x %	theo.	eval.	* x %	theo.	eval.	* x %
1.0	6.629	6.629	0.00	6.023	6.047	0.40	0.606	0.583	4.12
2.0	4.833	4.880	0.96	2.973	3.020	1.56	1.860	1.862	0.11
4.0	3.660	3.750	2.40	1.610	1.644	2.07	2.050	2.106	2.66
6.0	3.933	3.930	0.08	1.900	1.906	0.03	2.033	2.026	0.35
8.0	4.234	4.230	0.01	2.300	2.320	0.86	1.934	1.918	0.34
10.0	4.306	4.310	0.01	2.455	2.430	1.03	1.851	1.876	1.33
12.0	4.210	4.210	0.00	2.386	2.356	1.27	1.824	1.854	1.62
14.0	4.019	4.020	0.01	2.236	2.190	2.10	1.783	1.830	2.57
16.0	3.796	3.800	0.11	2.015	2.000	0.75	1.781	1.795	0.78
18.0	3.567	3.570	0.08	1.792	1.780	0.67	1.775	1.785	0.56
20.0	3.359	3.360	0.03	1.599	1.600	0.06	1.760	1.760	0.00

* $x = [|\text{theo.} - \text{eval.}| / \text{eval.}] \times 100$

5 CONCLUDING REMARKS

Because the new experimental data are available in recent years, we also adopted a new calculation program, the evaluated data have been considerably improved, especially for cross sections of total, (n,p), (n,n′p), (n,d), (n,t), (n,γ), total inelastic reactions and inelastic scattering to some discrete levels and elastic scattering angular distributions.

ACKNOWLEDGMENTS

The authors wish to thank Profs. Cai Dunjiu, Liu Tingjin and Liang Qichang for their help in this work.

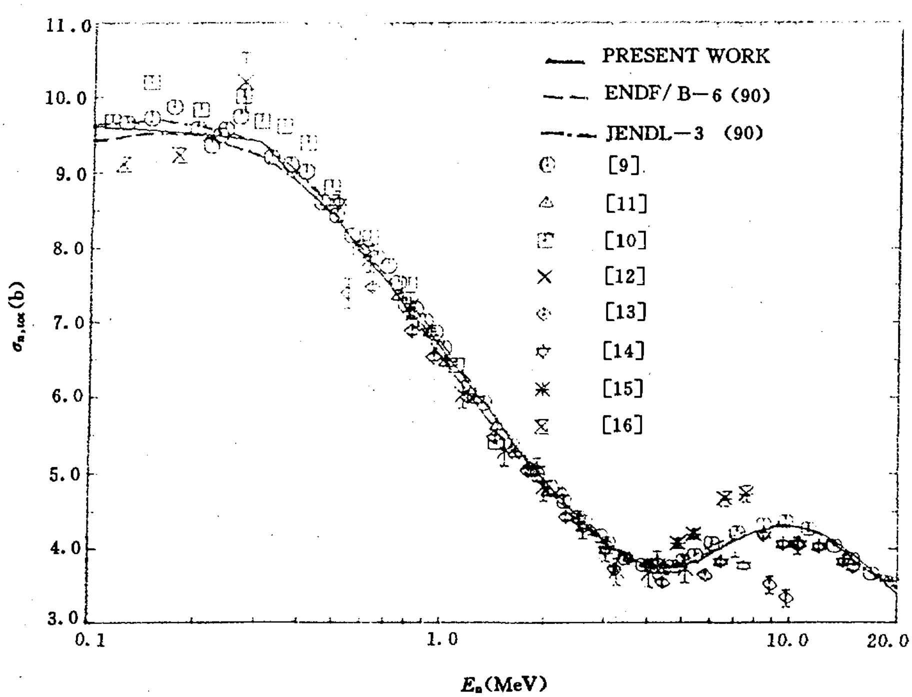

Fig. 1 Neutron total cross section of Nb

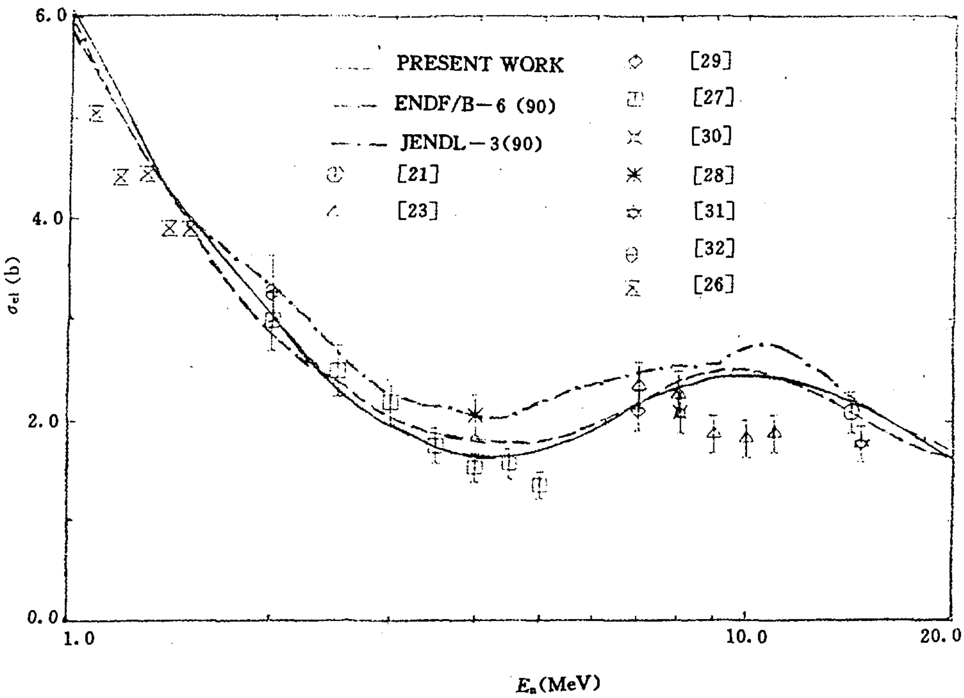

Fig. 2 Neutron elastic cross section of Nb

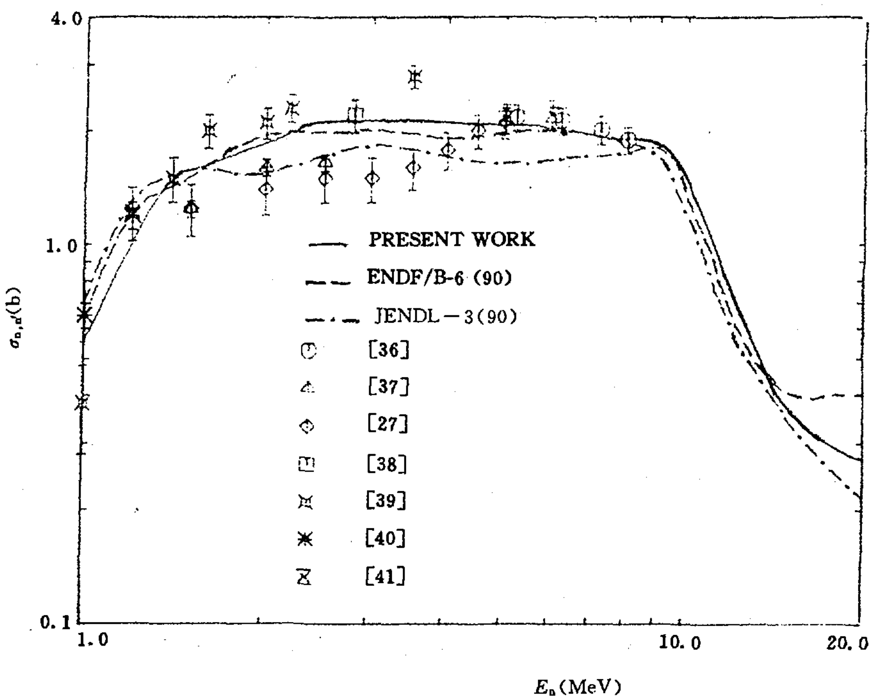

Fig. 3 (n,n′) cross section of Nb

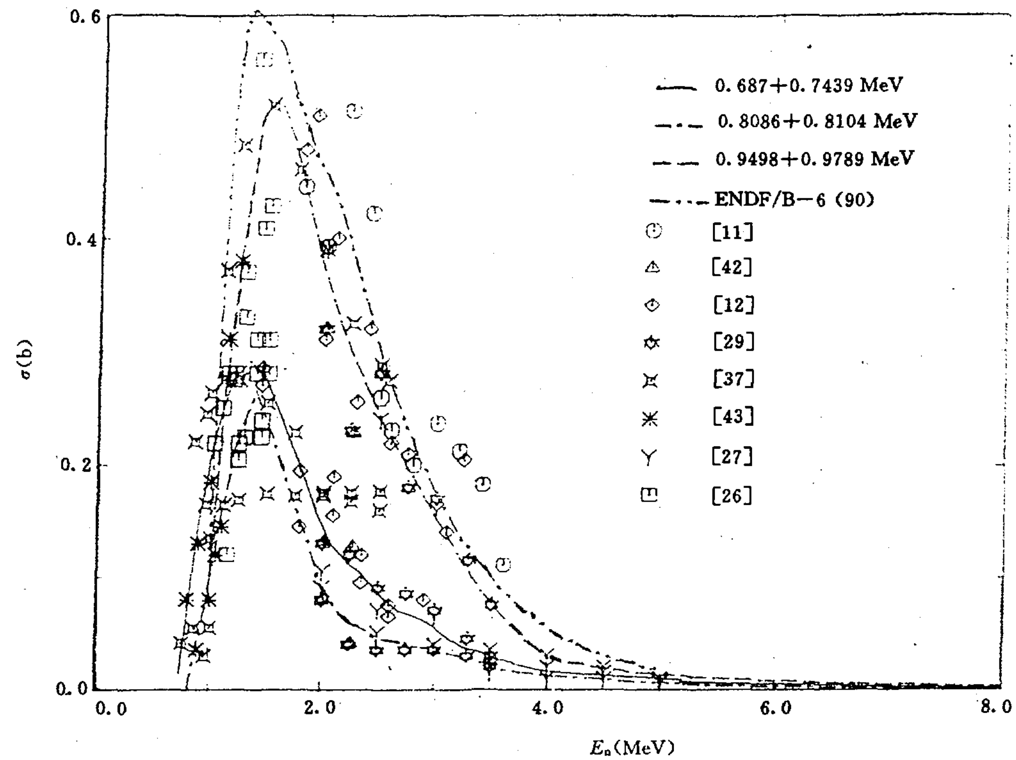

Fig. 4—1 Inelastic cross section of Nb excited states

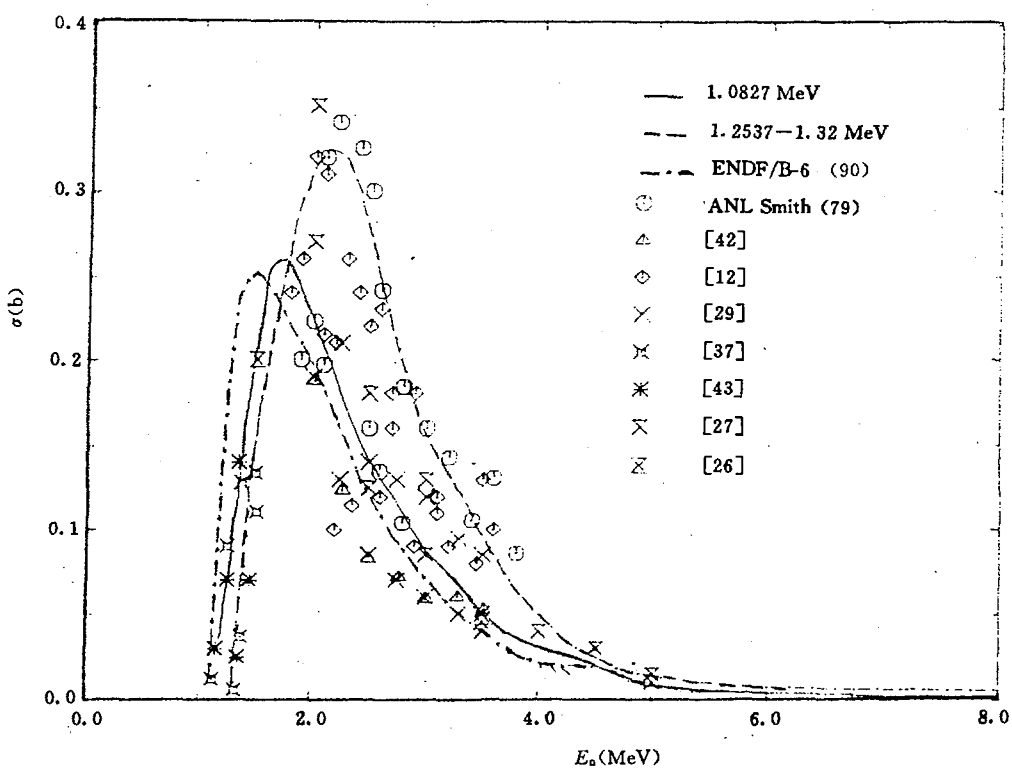

Fig. 4—2 Inelastic cross section of Nb excited states

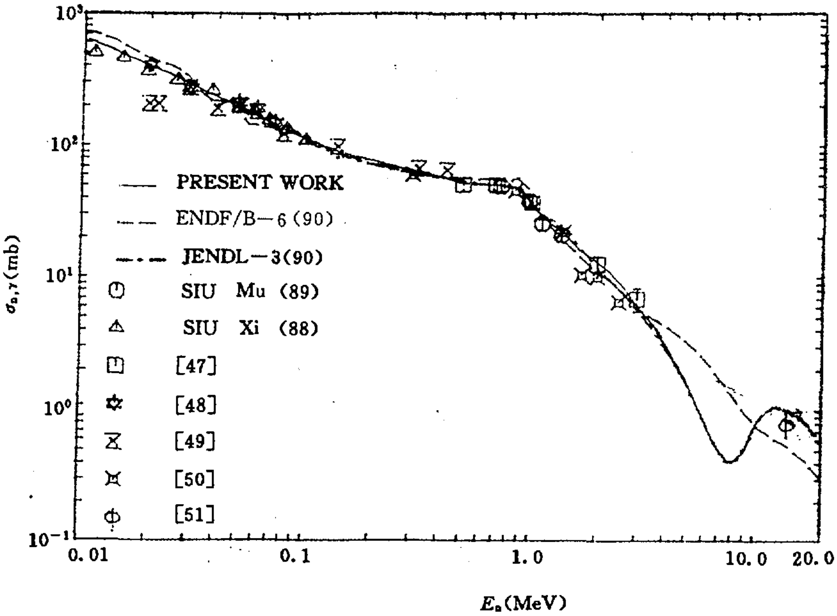

Fig. 5 (n,γ) cross section of Nb

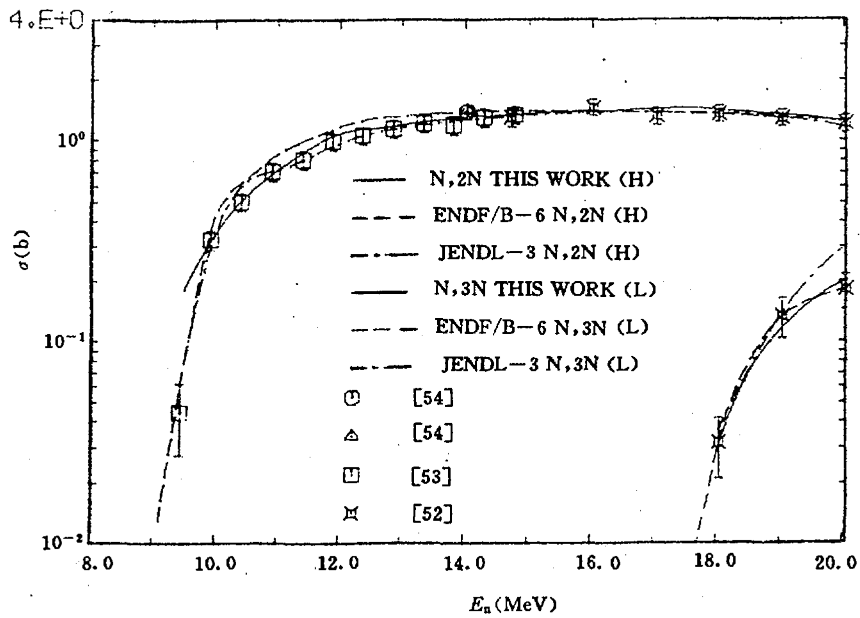

Fig. 6 (n,2n), (n,3n) cross sections of Nb

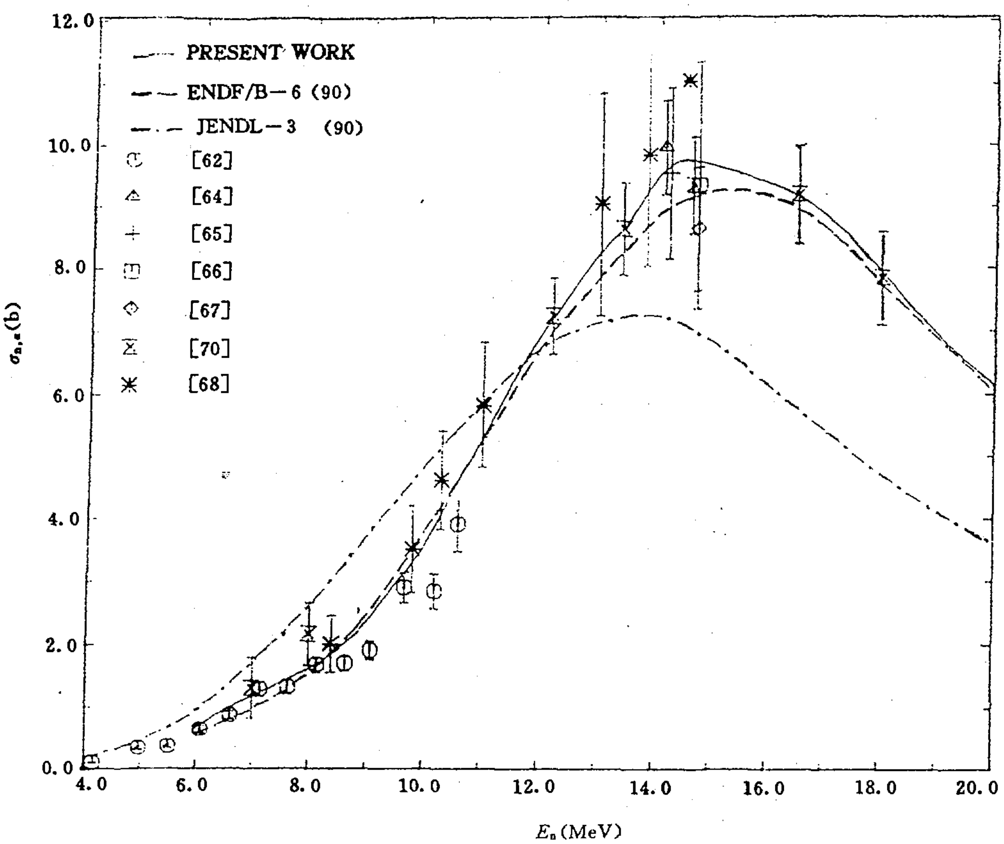

Fig. 7 (n,α) cross section of Nb

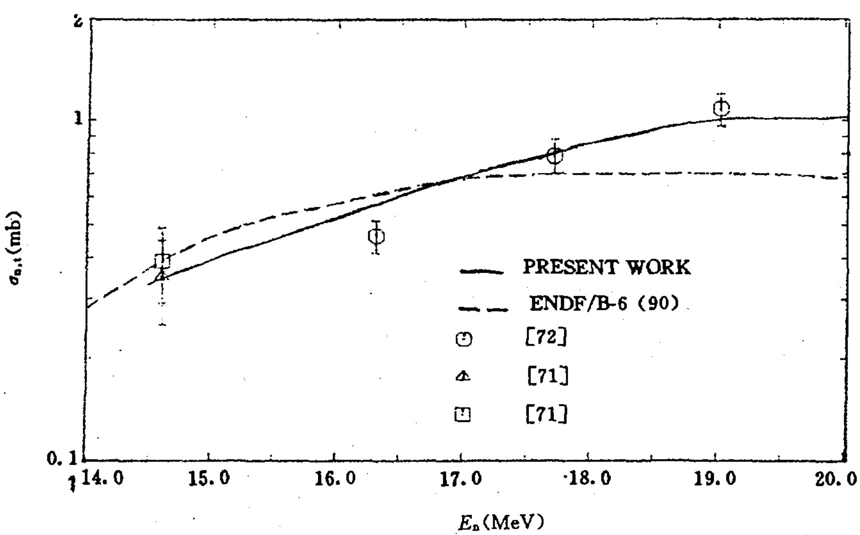

Fig. 8 (n,t) cross sections of Nb

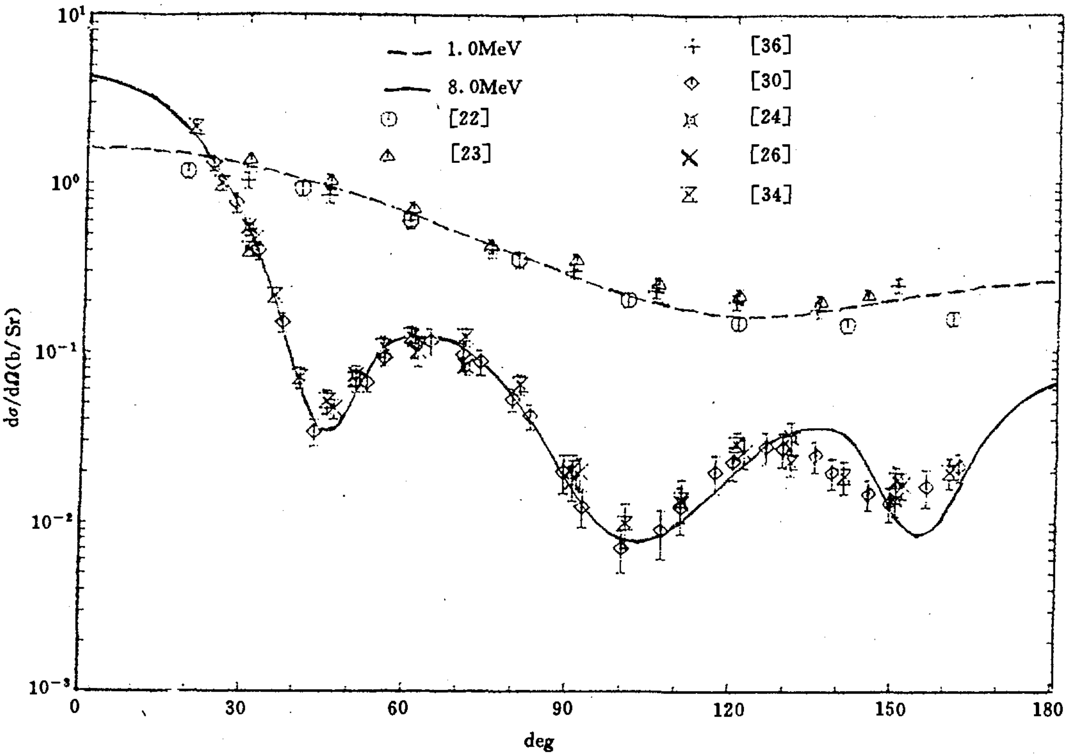

Fig. 9—1 Elastic scattering angular distributions of Nb

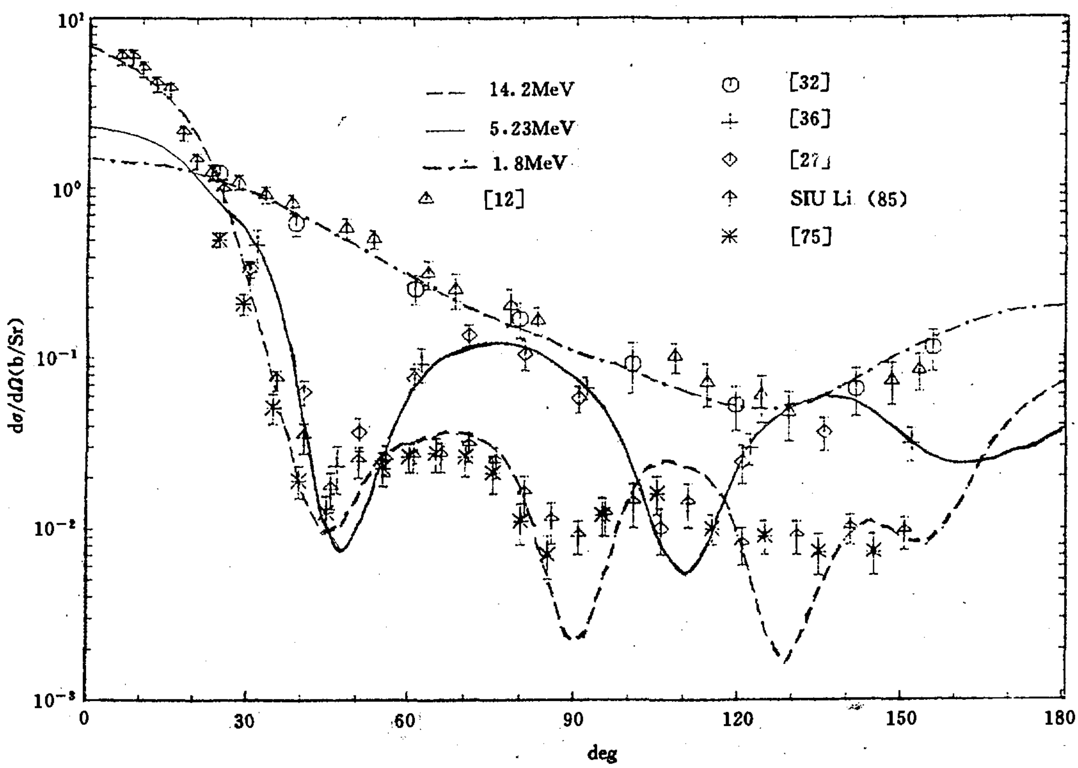

Fig. 9—2 Elastic scattering angular distributions of Nb

REFERENCES

[1] Yu Ziqiang, Cai Chonghai et al., Theoretical calculation program MUP2 for medium and heavy nuclei, inter report (1986)

[2] Zhou Hongmo, Yu Ziqiang et al., Parameter auto adjusting optical model calculation program AUJP, inter report (1986)

[3] Xu Haishan, CNDC–58010, 182(1983)

[4] S. F. Mughabghab, BNL–325 (fourth editon) (1984)

[5] A. Smith and D. Smith, ENDF / B–6 (1990)

[6] M. Kawai et al., JENDL–3 (1988)

[7] H. Sievers, Nuclear Data Sheets, 54, 99(1988)

[8] Su Zongdi et al., A new set of level density parameters for Fermi Gas model, inter report(1984)

[9] W. P. Poenitz et al., ANL–NDM–80(1983)

[10] V. Filippov et al., 83KIEV, 3, 107(1983)

[11] A. B. Smith et al., ANL–NDM–70(1982)

[12] A. B. Smith et al., Z. Phys., 264, 379(1973)

[13] L. Green et al., WAPD–TM–1073(1973)

[14] C. Foster et al., Phys. Rev., C3, 576(1971)

[15] A. Carlson et al., Phys. Rev., 158, 1142(1967)

[16] C. Uttley et al., 66PARIS, 1, 165(66)

[17] A. Saplakoglu et al., Phys. Rev., 109, 1258(1958)

[18] H. W. Newson et al., Phys. Rev., 105, 198(1957)

[19] J. H. Coon et al., Phys. Rev., 88, 562(1952)

[20] D. V. Miller et al., Phys. Rev., 88, 83(1952)

[21] Li Jingde et al., C. Nucl. Phys., 7, 106(1985)

[22] R. S. Pedroni et al., BAP, 27, 722(DE4)(1982)

[23] Adel Fawzy et al., Nucl. Instr. Meth., 169, 533(1980)

[24] S. A. Cox et al., ANL–7935(1972)

[25] I. A. Korzh et al., IZV, 35(4), 823(1971)

[26] D. Reitmann et al., Nucl. Phys., 48, 593(1963)

[27] R. E. Coles et al., AWRE–0–66 / 71(1971)

[28] G. V. Gorlov et al., Yadernaya Fizika, 6, 910(1967)

[29] M. A. Etemad et al., Sov. Atom. En., 482(1973)

[30] B. Holmqvist et al., Sov. Atom. En., 430(1971)

[31] G. T. Western et al., AFWL–TR–65–216, 2(1966)

[32] L. Y. Kazakova et al., EANDC–50, 200(1965)

[33] A. S. Longsdorf et al., Phys. Rev., 107, 1077(1957)

[34] M. Walt et al., Phys. Rev., 93, 1062(1954)
[35] A. I. Abramov et al., Sov. Atom. En., 12, 65(1962)
[36] S. P. Simakov et al., Yadernaya Fizika, 37(4), 801(1983)
[37] I. J. Vanheerden et al., Z. Phys., 260, 9(1973)
[38] H. Goebel et al., Z. Phys., 240, 430(1970)
[39] D. L. Broder et al., Sov. Atom. En., 16(2), 103(1964)
[40] I. Glazkov et al., Sov. Atom. En., 14, 400 and 15, 416(1963)
[41] D. Thomson et al., Phys. Rev., 129, 1649(1963)
[42] E. Almen Ranstiom et al., Sov. Atom. En., 503(1975)
[43] V. C. Rogers et al., Nucl. Sci. Eng., 45, 297(1971)
[44] Ju. A. Nemilov et al., Jadernye Konstanty, Obninsk Reports (3), 24(1986)
[45] Mú Yunshan et al., Priv. Com., (1989)
[46] Xi Nijun et al., C. Nucl. Phys., 10, 227(1988)
[47] J. Voignier et al., Nucl. Sci. Eng., 93, 43(1986)
[48] N. Yamamuro et al., Nucl. Sci. Tech., 17, 582(80); 15, 637(78)
[49] R. Macklin et al., Nucl. Sci. Eng., 59, 12(1976)
[50] W. Poenitz et al., ANL–NDM–8(1974)
[51] F. Rigaud et al., Nucl. Phys., A173, 551(1971)
[52] L. Veeser et al., Phys. Rev., C16, 1792(1977)
[53] J. Frehaut et al., 80BNL 399(1980)
[54] Lychagin et al., Sov. Atom. En., 57(4), 266(1984); FEI–1385(1983)
[55] Holub et al., J. P. / G2, 405(1976)
[56] M. Haering et al., Z. Phys., 244, 352(1971)
[57] A. Paulsen et al., Z. Phys., 238, 23(1970)
[58] D. Hermsdorf et al., Jour. Nucl. Eng., 27, 747(1973)
[59] Traxler et al., Nucl. Sci. Eng., 90, 174(1985)
[60] N. Koori et al., Nucl. Sci. Eng., 87, 34(1984)
[61] S. Grimes et al., Phys. Rev., C17, 508(1978)
[62] A. Mannan et al., Phys. Rev., C38, 630(1988)
[63] R. Wolfle et al., Appl. Radiat Isot, 39, 407(1988)
[64] R. Fischer et al., Ann. Nucl. Eng., 9, 409(1983)
[65] M. Bormann et al., Nucl. Phys., A186, 65(1972)
[66] P. Kulisic et al., Nucl. Phys., 54, 17(1964)
[67] E. T. Bramlitt et al., Phys. Rev., 131, 2649(1963)
[68] H. A. Tewes et al., UCRL–6028–T(1960)
[69] H. G. Blosser et al., Phys. Rev., 110, 531(1958)
[70] B. P. Bayhurst et al., Jour. Inorg. Nucl. Chem., 23, 173(1961)
[71] S. Sudar et al., Nucl. Phys., A319, 157(1979)
[72] S. M. Qaim et al., Phys. Rev., C25(1), 203(1982)

[73] Zhao Zhixiang et al., Nucl. Sci. Eng., 99, 367(1988)
[74] J. C. Ferrer et al., Nucl. Phys., A275, 325(1977)
[75] J. L. Kammerdiener et al., UCRL–51232(1972)
[76] A. Lane et al., Rev. Mod. Phys., 30, 257, 293(1958)

THE EVALUATION OF NATURAL SILVER NEUTRON DATA

Wang Yansen You Junsen Huang Fayang

(DEPT. OF NUCLEAR SCIENCE, FUDAN UNIVERSITY, SHANGHAI)

Cai Chonghai

(DEPT. OF PHYSICS, NANKAI UNIVERSITY, TIANJIN)

ABSTRACT

Based on the available experimental data and the theoretical calculations, the neutron nuclear data of the natural Ag have been evaluated and recommended in the energy range from 10^{-5} eV to 20 MeV for CENDL–2 and the comparisons with other evaluations have been done.

INTRODUCTION

Natural Ag consists of two isotopes ^{107}Ag (51.82%) and ^{109}Ag (48.18%). They are important fission products. The neutron data of natural Ag are useful to nuclear power development. The evaluated cross sections are given in three energy ranges :

10^{-5} eV ~ 7.1 keV Resolved resonance parameters.

7.1 keV ~ 100 keV Unresolved resonance parameters.

100 keV ~ 20 MeV Smooth neutron cross sections.

The recommended data of total cross section are based on the experimental data. The nonelastic cross sections are given from optical model calculation. The elastic cross section are determined by subtracting non–elastic cross section from total crosss section. All other cross sections, including inelastic scattering, (n,γ), (n,2n), (n,3n), (n,p), (n,α), the angular and energy distribution of emitted neutrons etc. are evaluated based on theoretical calculations, which can reproduce the available experimental data well.

1 EVALUATION OF EXPERIMENTAL DATA

The experimental data of total cross sections were taken from Refs. [1~9], where the values of Poenitz[83] and Foster[71] are better. Their measurements with neutron TOF spectrometer and large–liquid scintillator cover larger energy range (0.1~ 18.0 MeV) and have higher precision (2~ 4%). The fitted results to the experimental data with spline function were taken as the recommended values of total cross sections.

The experimental data of elastic, non–elastic and inelastic cross sections are less and their errors are larger. The measured values of elastic and inelastic scattering were mainly taken from Smith(82)[10] and Vonach(66)[11], which cover only 0.3~ 4.0 MeV energy range and have 5~ 20% errors. The non–elastic cross sections were measured by means of sphrical shell method and plastic scintillator in Refs. [12~ 18], which were all performed in the fifties. The experimental errors are about 2~ 15%.

The capture cross sections were obtained mainly from Refs. [1, 19~ 27], which were measured mostly by using TOF and large–liquid scintillator. The errors are about 8~ 15%.

The experimental data of elastic scattering angular distribution were taken from Refs. [10, 11, 28]. The errors are about 20%.

For comparison, the average value of 1358 ± 57 mb[29] at 14.5 MeV for ^{107}Ag (n,2n) obtained by averaging all existing experimental data was taken. Also experimental values for ^{107}Ag (n,3n)[30, 31] and ^{109}Ag (n,p)[32] were adopted.

Except total cross section, all other cross sections were theoretically calculated.

2 THEORETICAL CALCULATION

Below 7.1 keV, the resolved resonance parameters were taken from JENDL–3 given by Liu T. J. et al.[33]. The unresolved resonance parameters independent on energy in the energy range from 7.1 to 100 keV were adjusted to fit the experimental data.

Above 100 keV, the optical model, Hauser–Feshbach statistical theory and preequiblium theory[34] have been used for calculating all cross sections. In calculations the unified program MUP2 for neutron data of medium–heavy nuclei have been used. The parameters in optical model and preequiblium theory have been adjusted to reproduce the available experimental data. The comparison of the theoretical results with the measured values are shown in Figs.1 ~ 6. They are for total, nonelastic, (n,γ), (n,2n) and (n,3n), (n,p) angular distributions at several energies respectively. It can be seen from the figures that the agreement between theoretical results and experimental data are quite good.

3 COMPARISON WITH OTHER EVALUATION

3.1 Resonance parameters

The unresolved parameters have been adjusted to fit the experimental data and connect with recommended values of elastic scattering, capture and total cross sections at 100 keV. The calculated results with unresolved parameters are $\sigma_{nn} = 7.464$ b, $\sigma_{n\gamma} = 0.472$ b and $\sigma_t = 7.936$ b, and the recommended values are $\sigma_{nn} = 7.49$ b, $\sigma_{n\gamma} = 0.46$ b and $\sigma_t = 7.95$ b. The agreement is very good.

3.2 Smooth Cross Sections

The total cross sections are recommended on the basis of a lot of the experimental data same as adopted in JENDL–3, But in ENDF / B–5 the evaluated data from 0.24 to 4.5 MeV were mainly from the measured values of smith(79)[35], and from 4.5 to 20 MeV the calculated values from optical model combined with BNL–325 experimental data were adopted.

The comparison of the theoretical cross sections of ^{107}Ag (n,2n) and ^{109}Ag (n,p) from present work with the ones from ENDF / B–5 is shown in Figs. 4, 5. From the figures we can see that our calculated results are better.

3.3 Angular Distributions

From Figs. 6(a) and 6(b), it can be seen that the agreement between the theoretical angular distribution and the experimental data are quite good same as in JENDL–3.

In the general, the present work has not been inferior to any evaluation so far.

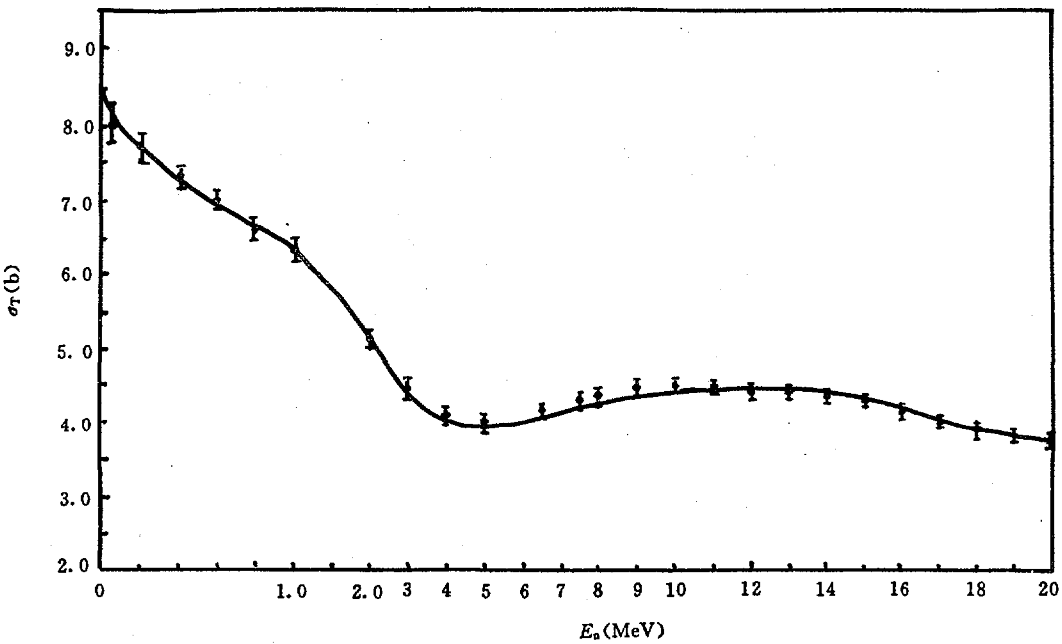

Fig. 1 Calculated total cross sections

The fitted values of the experimental data

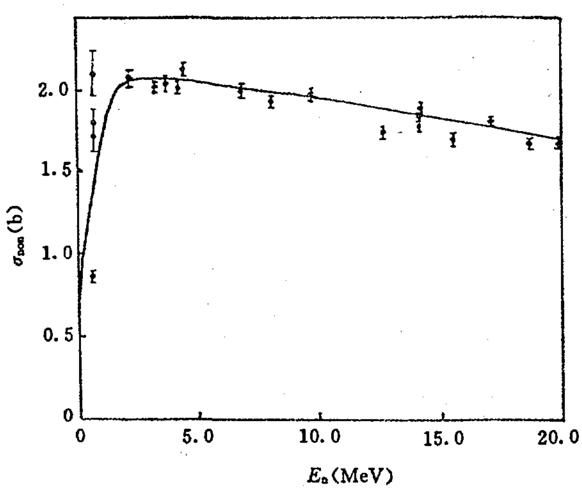

Fig. 2 The calculated nonelastic cross sections

The experimental data from Refs. [12~18]

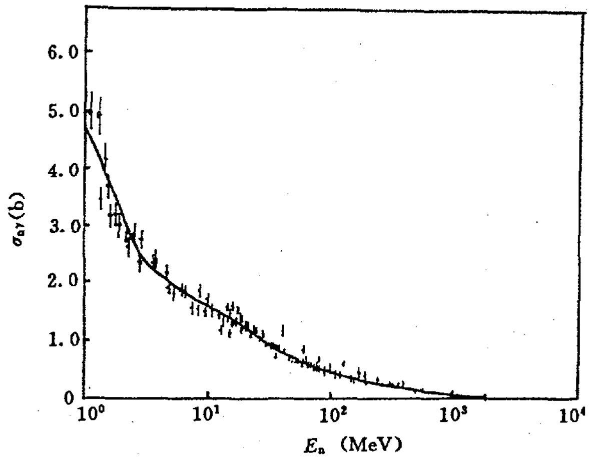

Fig. 3 The calculated (n,γ) cross sections

ɫ The experimental data from Refs. [1, 19~27]

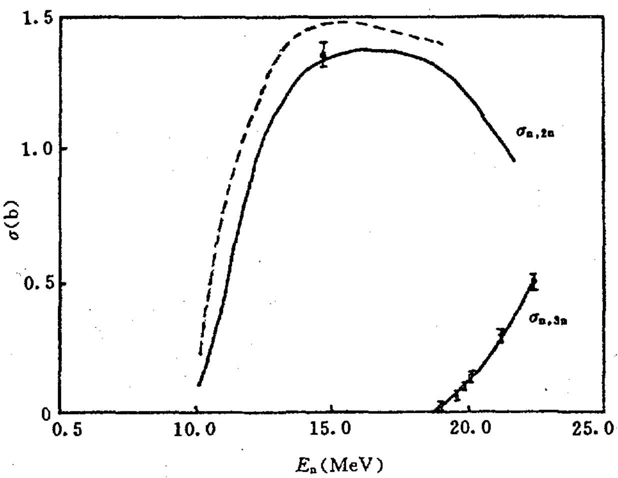

Fig. 4 The calculated cross sections of ^{107}Ag (n,2n) (n,3n)

——— The present work ——— ENDF / B-5

ɫ The average experimental values for (n,2n) from Ref. [29]

ɫ The experimental data (n,3n) from Refs. [30, 31]

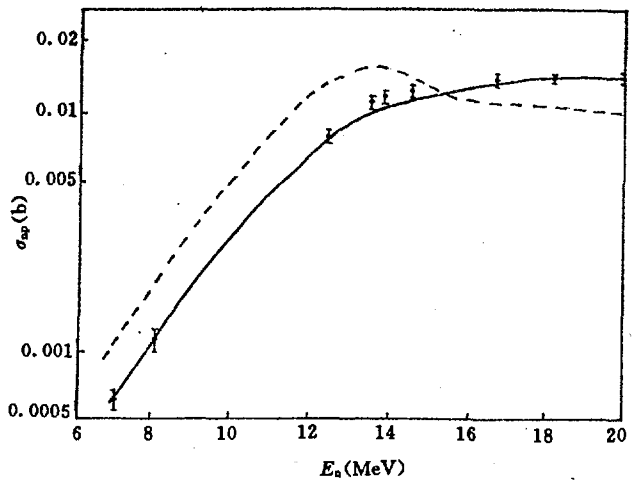

Fig. 5 The calculated ^{109}Ag (n,p) cross sections

——— The present work ——— ENDF / B–5

ǂ The experimental data from Ref. [32]

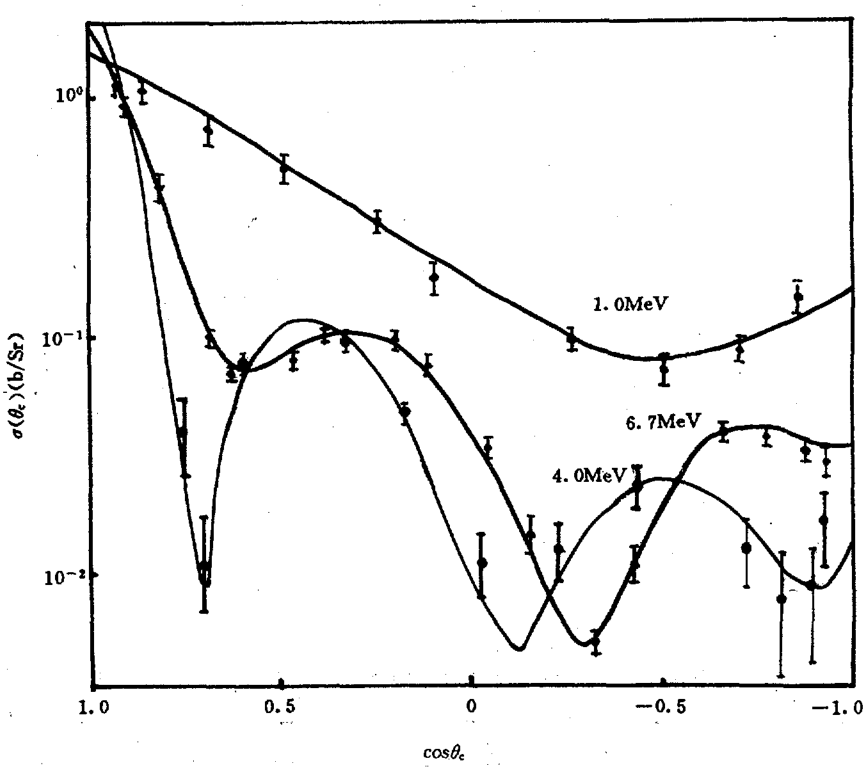

Fig. 6(a), 6(b) The calcuated angular distributions of the elastic scattering at 1.0, 4.0, 6,7 MeV

ǂ The experimental data from Refs. [10, 11, 28]

REFERENCES

[1] W. P. Poenitz et al., ANL–NDM–80(1983)

[2] D. G. Foster et al., PR / C3, 576(1971)

[3] M. Divadeenam et al., DA, B28, 3834(1968)

[4] A. D. Carlson et al., PR, 158, 1142(1967)

[5] Y. V. Dokarevich et al., NP, A92, 433(1967)

[6] J. M. Peterson et al., PR, 120, 521(1960)

[7] A. Bratenahl et al., PR, 110, 927(1958)

[8] J. H. Coon et al., PR, 88, 562(1952)

[9] D. W. Miller et al., PR, 88, 83(1952)

[10] A. B. Smith et al., ANL–NDM–66(1982)

[11] W. G. Vonach et al., NP, 178, 389(1966)

[12] M. Wlat et al., PR, 93, 1062(1954)

[13] H. L. Taylar et al., PR, 100, 174(1955)

[14] J. R. Beyster et al., PR, 98, 1216(1955)

[15] E. R. Graves et al., PR, 97, 1205(1955)

[16] J. R. Beyster et al., PR, 104, 1319(1957)

[17] M. H. Macger et al., PR, 108, 726(1957)

[18] T. W. Bonner et al., PR, 113, 1088(1959)

[19] R. L. Macklin et al., NSE, 82, 400(1982)

[20] D. Kompe et al., NP, A133, 513(1969)

[21] J. Hellstroem et al., JNE, 27, 71(1973)

[22] R. L. Macklin et al., PR, 159, 1007(1967)

[23] R. C. Block et al., Proc. NEANDC Conf. Time of Flight Methods, Saclay, p. 203(1961)

[24] J. Bergqvist et al., AF, 23, 425(1963)

[25] J. H. Gibbons et al., PR, 122, 182(1961)

[26] B. C. Diven et al., PR, 120, 556(1960)

[27] E. Haddad et al., "Radiative Capture Cross Section Measurements", GA–3874(1963)

[28] P. R. Malmberg et al., PR, 128, 351(1962)

[29] Liu Tingjin et al., JAERI–M 91–011(1991)

[30] B. P. Bayhurst et al., PR, C12, 451(1975)

[31] H. Liskien et al., NP, A118, 379(1968)

[32] B. P. Bayhurst et al., JIN, 23, 173(1961)

[33] Liu Tingjin et al., JENDL–3 (1990)

[34] Chinese Nuclear Data Center, "Theoretical Methods of Nuclear Reaction and its Applications" Atomic Energy Press, China(1980) (in Chinese)

[35] A. Smith et al., ANL–NDM–46(1979)

EVALUATION OF NEUTRON NUCLEAR DATA OF NATURAL SILVER AND ITS ISOTOPES

Liu Tingjin

(CHINESE NUCLEAR DATA CENTER, IAE)

Keiichi SHIBATA and Tsuneo NAKAGAWA

(NUCLEAR DATA CENTER, DEPARTMENT OF PHYSICS, JAERI)

Neutron nuclear data of natural silver and its isotopes (^{107}Ag and ^{109}Ag) have been evaluated in the energy range of 10^{-5} eV ~ 20 MeV. Evaluated quantities are the total, elastic and inelastic scattering, capture, (n,2n), (n,3n), (n,p), (n,α), (n,np), (n,nα) reaction and γ–ray production cross sections, the resonance parameters and the angular and energy distributions of emitted neutrons and γ–rays. The evaluation is based on available experimental data and theoretical calculations. Multi–step Hauser–Feshbach calculation played an important role in the determination of the reaction cross sections. In the calculation, the precompound process was taken into account above 5 MeV, in addition to the compound one. The evaluated data have been compiled into CENDL–2 and JENDL–3 in the ENDF / B–5 format.

INTRODUCTION

Neutron nuclear data of silver are important for nuclear applications. Stable isotopes ^{107}Ag and ^{109}Ag are formed as fission products in fission reactors. The threshold reactions such as (n,2n) and (n,p) are useful for dosimetry in fusion reactors.

The present work was attempted for CENDL–2 and JENDL–3[2]. Evaluated are the total, elastic and inelastic scattering, capture, (n,2n), (n,3n), (n,p), (n,α), (n,np), (n,nα) reaction and γ–ray production cross sections, the resonance parameters and the angular and energy distributions of emitted neutrons and γ–rays. The target nuclides considered in this work are natural silver and its stable isotopes, i. e. ^{107}Ag and ^{109}Ag. The Q–values of the neutron–induced reactions were calculated from the mass table of Wapstra & Bos[3], and are given in Table 1, together with the isotopic abundances[4] of ^{107}Ag and ^{109}Ag.

The present evaluation is based on recent experimental data and theoretical calculations.

Table 1 Isotopic abundances and reaction Q–values of ^{107}Ag and ^{109}Ag

	^{107}Ag	^{109}Ag
Abundance (%)		
	51.839	48.161
Q–values (MeV)		
(n,2n)	−9.5467	−9.1917
(n,3n)	−17.4724	−16.4614
(n,p)	0.7495	−0.3335
(n, α)	4.1947	3.2967
(n,np)	−5.7802	−6.4882
(n,nα)	−2.8049	−3.2919
(n,γ)	7.2697	6.8057

1 RESONANCE PARAMETERS

Resonance parameters were given in the energy range below 100 keV. The energy range was divided into the resolved resonance region from 10^{-5} eV to 7 keV and the unresolved resonance region from 7 to 100 keV. No background cross section was applied in the resonance region.

The resolved resonance parameters for each isotope are the same as those adopted in JENDL–2[1] except total spin values, because there are no measurements performed after the JENDL–2 evaluation. The total spin values were tentatively assumed with a random number method for the levels whose spin was not experimentally determined. The multi–level Breit–Wigner formula was adopted as a resonance formula.

The unresolved resonance parameters were determined so as to fit the experimental total and capture cross sections of each isotope by using the ASREP code[5]. In the fitting, the capture cross sections of both isotopes measured by Mizumoto et al.[6] and of Macklin[7] were used. As for the total cross section, the experimental data[8~10] of natural silver were applied to both isotopes because the isotopic data were not available in the unresolved resonance region.

The resonance capture integrals (the cut–off energy of 0.5 eV) calculated from the present resonance parameters are compared in Table 2 with the recommended values of Mughabghab et al.[11]. They agree with each other for natural silver and ^{107}Ag, whereas the calculated value for ^{109}Ag is slightly larger than the recommended one.

Table 2 Capture resonance integrals with cut–off energy of 0.5 eV

(Unit : barns)

	Calculated	Mughabghab et al.[11]
Natural	762	756 ± 20
^{107}Ag	103	100 ± 5
^{109}Ag	1,472	1,400 ± 48

2 TOTAL AND CAPTURE CROSS SECTIONS ABOVE RESONANCE REGION

The evaluation of the total and capture cross sections above 100 keV was made mainly on the basis of the experimental data, since there are a lot of measurements available for the evaluation.

The total cross section of natural silver was determined from the measurements of Foster, Jr. & Glasgow[12] and of Poenitz & Whalen[8] with the least–squares method using the spline–function. For ^{107}Ag, the experimental data of Smith et al.[13] were taken in the energy range of 250 keV ~ 4.5 MeV. In the energy ranges of 100 ~ 250 keV and of 4.5 ~ 20 MeV, the shape of the total cross section of natural silver was adopted and normalized at 250 keV and 4.5 MeV. Then, the total cross section of ^{109}Ag was obtained by subtracting that of ^{107}Ag multiplied by the isotopic abundance from that of natural silver. It is found from Fig. 1 that the 14 MeV measurements of Dukarevich et al.[14] for both isotopes are successfully reproduced in the present evaluation, and that the present evaluation is better than the ENDF / B–5 in the case of ^{107}Ag.

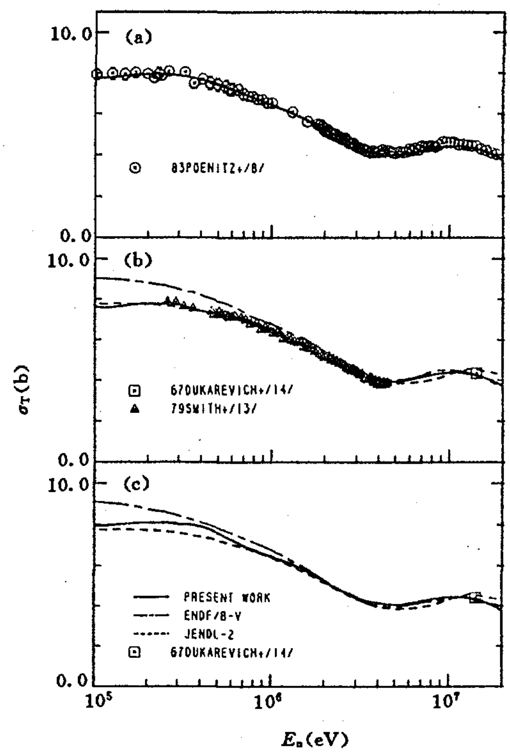

Fig. 1 Total cross sections of (a) natural silver, (b) ^{107}Ag and (c) ^{109}Ag

There are many experimental data[6, 7, 15~25] for the capture cross sections of natural silver and its isotopes up to about 3 MeV.

Among the measurements, the data of Diven et al.[15] and Johnsrud et al.[22] were renormalized in the present work since the standard cross sections they used were different from the latest recommendation. Below 2 MeV, the capture cross sections were evaluated by using the least–squares fitting these experimental data with keeping the consistency between the natural and isotopic data. Above 2 MeV, we adopted the theoretically calculated cross sections, which are described in Chap. 3. The calculated cross sections were normalized to the experimental data at 2 MeV. The evaluated capture cross sections are shown in Fig. 2. The present evaluation reproduce well the measured data of natural silver, ^{107}Ag and ^{109}Ag.

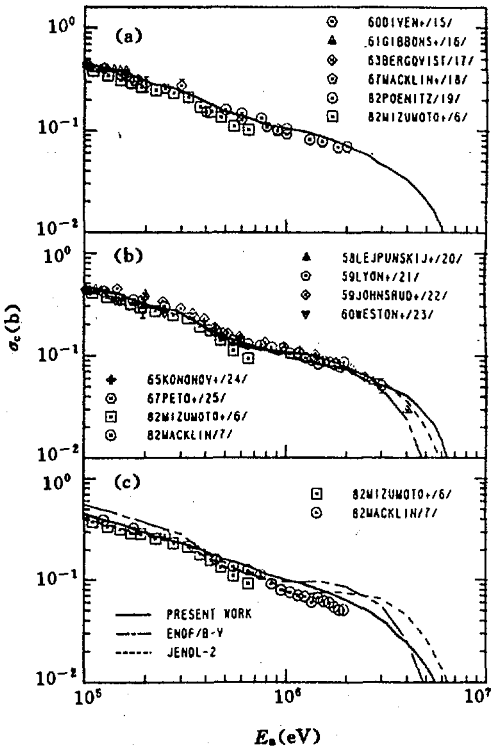

Fig. 2 Capture cross sections of (a) natural silver, (b) ^{107}Ag and (c) ^{109}Ag

3 THEORETICAL CALCULATION

3.1 Computational Methods and Procedures

The multi–step Hauser–Feshbach code TNG[26] was mainly used for calculating the neutron–induced reaction cross sections of both isotopes. The precompound process was taken into account above an incident energy of 5 MeV, in addition to the compound one. Calculated were the inelastic scattering, capture, (n,2n), (n,3n), (n,p), (n,α), (n,np) and (n,nα) reaction cross sections, the angular distributions of neutrons and the energy distributions of neutrons and γ–rays. TNG was not capable of calculating the angular distributions for the shape elastic scattering, and thus, they were calculated by using the CASTHY code[27].

The Kalbach's constant k, which represents a magnitude of the residual two–body interaction in the precompound mode, was deduced to be 600 MeV^3 through a comparison of the calculated neutron emission spectra with the experimental data.

The elastic scattering cross section was finally obtained by subtracting all the other partial cross sections from the total cross section. Isotropic angular distributions in the laboratory system were assumed for the neutrons coming from the (n,2n), (n,3n), (n,np) and (n,nα) reactions.

3.2 Parameter Determination

3.2.1 Optical–Model Potentials

The spherical optical model was used to calculate particle transmission coefficients, which were needed in the Hauser–Feshbach formalism. Concerning neutrons, Smith et al.[28] obtained the parameters for natural silver in the energy range of 1.5~ 4 MeV. Parameter search was performed using their parameters as initial values so as to reproduce the evaluated total cross sections mentioned above. The potential thus obtained has an energy–dependent imaginary term, while the original one of Smith et al.[28] has no such a term. The final parameters for neutrons are given in Table 3. It is found from Fig. 3 that the calculated non–elastic scattering cross section of natural silver is in good agreement with the measured data[29~34] up to 20 MeV.

As for charged particles, several sets of global potentials were examined. For protons, the parameters obtained by Perey[35] and by Arthur & Young[36] yielded too large (n,p) cross sections as compared with the experimental data. Then, the parameters were adjusted so as to reproduce well the experimental data of the (n,p) cross section. For α–particles, we employed the parameters of Arthur & Young[36] which were determined by modifying Lemos' potential[37]. These parameters are also given in Table 3.

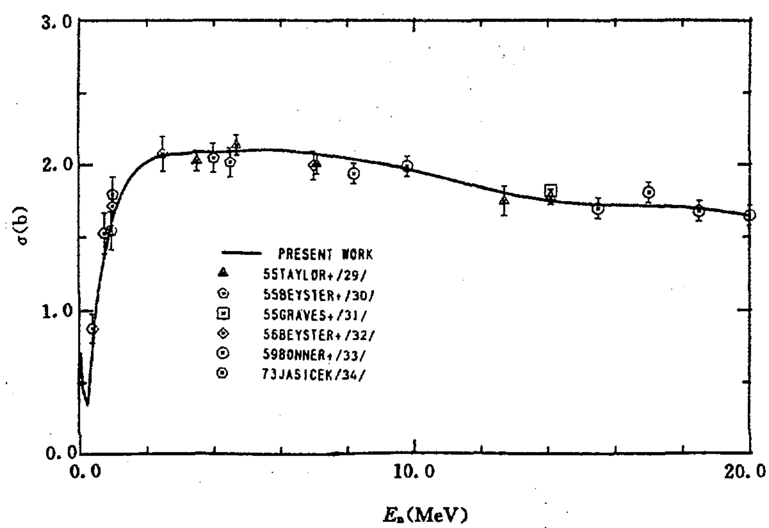

Fig. 3 Nonelastic scattering cross section of natural silver

Table 3 Optical–model potential parameters used in present calculation

Depth (MeV)	Radius (fm)	Diffuseness (fm)
Neutron		
$V=48.25-0.3\times E_n$	$r_o=1.249$	$a_o=0.603$
$W_s=8.501-0.15\times E_n$	$r_s=1.270$	$a_s=0.575$
$W_v=0.0$		
$V_{so}=6.0$	$r_{so}=1.249$	$a_{so}=0.603$
Proton		
$V=66.06-0.55\times E_n$	$r_o=1.150$	$a_o=0.650$
$W_s=12.50-0.10\times E_n$	$r_s=1.250$	$a_s=0.470$
$W_v=0.0$	$r_c=1.150$	
$V_{so}=0.0$		
α–particle		
$V=193.0-0.15\times E_n$	$r_o=1.370$	$a_o=0.560$
$W_s=21.0+0.25\times E_n$	$r_v=1.370$	$a_v=0.560$
$W_v=0.0$	$r_c=1.370$	
$V_{so}=0.0$		

3.2.2 Discrete Levels and Level Density

In the present calculations, it was necessary to input the discrete levels and level density parameters of fourteen nuclei, i. e. ^{103}Rh, ^{104}Rh, ^{105}Rh, ^{106}Rh, ^{106}Pd, ^{107}Pd, ^{108}Pd, ^{109}Pd, ^{105}Ag, ^{106}Ag, ^{107}Ag, ^{108}Ag, ^{109}Ag, and ^{110}Ag. The discrete levels were taken from the Nuclear Data Sheets[38~45], as well as the γ–ray branching ratios between the discrete levels. The levels of ^{107}Ag and ^{109}Ag are listed in Table 4.

Table 4 Discrete levels of ^{107}Ag and ^{109}Ag

N	^{107}Ag		^{109}Ag	
	E (MeV)	J^{π}	E (MeV)	J^{π}
1	0.0	$1/2^-$	0.0	$1/2^-$
2	0.0931	$7/2^+$	0.0880	$7/2^+$
3	0.1256	$9/2^+$	0.1327	$9/2^+$
4	0.3248	$3/2^-$	0.3114	$3/2^-$
5	0.4232	$5/2^-$	0.4152	$5/2^-$
6	0.7733	$11/2^+$	0.7019	$3/2^-$
7	0.7866	$3/2^-$	0.7070	$3/2^+$
8	0.9221	$5/2^+$	0.7244	$3/2^+$
9	0.9497	$5/2^-$	0.7359	$5/2^+$
10	0.9733	$7/2^-$	0.8628	$5/2^-$
11	0.9910	$13/2^+$	0.8695	$5/2^+$
12	1.0610	$1/2^-$	0.9110	$7/2^+$
13	1.1420	$1/2^+$	0.9121	$7/2^-$
14	1.1469	$7/2^-$	1.0910	$9/2^-$
15	1.2230	$5/2^+$	1.0985	$5/2^+$
16	1.2589	$3/2^+$		
17	1.3258	$3/2^+$		

For calculation of the capture γ–ray spectra, s–wave branching ratos for primary transitions from the capturing state to the lowlying discrete levels of the compound nuclei were also obtained from the compilation works[43,45].

Concerning the level density, the composite formula of Gilbert & Cameron[46] was used throughout. All pairing energy corrections Δ were taken from their table. For the spin cut–off factor, we employed the following expression given by Facchini & Saetta–Menichella[47] :

$$\sigma^2(E) \equiv ct = 0.146aA^{2/3}t, \tag{1}$$

where A is the mass number and t is the thermodynamic temperature defined by Gilbert & Cameron[46]. When E is less than the matching energy E_x , the spin cut–off factor is calculated from the relation

$$\sigma^2(E) = \sigma^2(E_c) + [\sigma^2(E_x) - \sigma^2(E_c)]E / E_x, \tag{2}$$

where E_c is the continuum cut–off energy. Here $\sigma^2(E_x)$ is obtained from Eq. (1), and $\sigma^2(E_c)$ is given by

$$\sigma^2(E_c) = [\sum_{i=1}^{M} (J_i + 1/2)^2] / 2M, \tag{3}$$

where J_i is the spin of the i–th excited state and M is the number of discrete levels considered in the calculation. The level density parameters were taken from the work of Iijima et al.[48] at first. During the course of the calculation, however, the parameters were modified so as to reproduce experimental cross section data. The LEVDENS code[49] was used to obtain a set of consistent parameters since all the parameters are not independent of one another. The parameters thus determined are given in Table 5.

3.2.3 Giant Dipole Resonances

The γ–ray transmission coefficient was calculated with the giant dipole model. The absorption cross section for the giant dipole resonance was assumed to have a two–component Lorentzian shape, i. e.

$$\sigma^{E1}(E_\gamma) = \sum_{i=1}^{2} \sigma_{mi} E_\gamma^2 \Gamma_i^2 / [E_\gamma^2 - E_{mi}^2)^2 + E_\gamma^2 \Gamma_i^2], \tag{4}$$

Table 5 Level density parameters

Residual nuclei	E_c (MeV)	E_x (MeV)	E_0 (MeV)	T (MeV)	a (MeV^{-1})	c	Δ (MeV)
^{103}Rh	0.990	5.409	−0.612	0.655	15.50	49.73	0.94
^{104}Rh	0.230	4.351	−1.476	0.650	15.43	49.82	0.00
^{105}Rh	0.770	5.700	−0.582	0.630	16.80	54.59	1.24
^{106}Rh	0.150	3.869	−1.193	0.575	17.50	57.23	0.00
^{106}Pd	2.380	8.004	0.326	0.666	17.17	56.15	2.59
^{107}Pd	0.700	7.693	−1.290	0.769	14.98	49.29	1.35
^{108}Pd	1.900	7.957	0.362	0.646	17.90	59.27	2.60
^{109}Pd	0.360	7.380	−1.288	0.687	17.50	58.30	1.35
^{105}Ag	1.230	5.830	−1.052	0.609	18.57	60.34	0.94
^{106}Ag	0.400	3.549	−1.277	0.563	17.16	56.11	0.00
^{107}Ag	1.420	5.918	−0.356	0.693	14.55	47.88	1.24
^{108}Ag	0.270	3.014	−0.715	0.576	15.04	49.80	0.00
^{109}Ag	1.180	6.112	−0.445	0.705	14.50	48.31	1.25
^{110}Ag	0.320	3.150	−0.060	0.454	17.01	57.02	0.00

The meaning of the symbols used is given in Ref. [46] and in the text.

where E_γ is the γ−ray energy. The symbols E_{mi} , σ_{mi} and Γ_i are the resonance energy, peak cross section and full width at half maximum, respectively. As to E_{mi} ,σ_{mi} and Γ_i, the following empirical formulas[50] were used for all nuclei except ^{108}Ag and ^{110}Ag :

$$\begin{aligned} \sigma_{m1} &= 168NZ/(\pi A\Gamma_1)\,(\text{mb}), & \sigma_{m2} &= 0.0\,(\text{mb}), \\ E_{m1} &= 163(NZ)^{1/2}/A^{4/3}(\text{MeV}), & E_{m2} &= 0.0\,(\text{MeV}), \\ \Gamma_1 &= 5.0\quad(\text{MeV}), & \Gamma_2 &= 0.0\,(\text{MeV}), \end{aligned}$$

where Z is the atomic number and $N=A-Z$. On the other hand, the parameters for ^{108}Ag and ^{110}Ag were derived so as to reproduce experimental capture cross sections, and they are given as follows :

$$\begin{aligned} \sigma_{m1} &= 120.0\,(\text{mb}), & \sigma_{m2} &= 100.0\,(\text{mb}), \\ E_{m1} &= 17.5\,(\text{MeV}), & E_{m2} &= 21.5\,(\text{MeV}), \\ \Gamma_1 &= 5.0\,(\text{MeV}), & \Gamma_2 &= 5.0\,(\text{MeV}). \end{aligned}$$

3.3 Calculated Results

The inelastic scattering cross section of ^{107}Ag is shown in Fig. 4. The present calculations are almost consistent with the experimental data of Nishimura et al.[51] and Smith et al.[13].

The (n,2n) reaction cross section of ^{107}Ag is illustrated in Fig. 5. Most of the experimental data were given around 14 MeV as the activation cross sections to the ground state or to the isomeric state of ^{106}Ag. Averaging the two kinds of partial cross sections separately and adding them, we obtained a value of 1,358 ± 57 mb for the total (n,2n) cross section at 14.5 MeV. The present calculation of 1,377 mb at 14.5 MeV is in very good agreement with the average cross section.

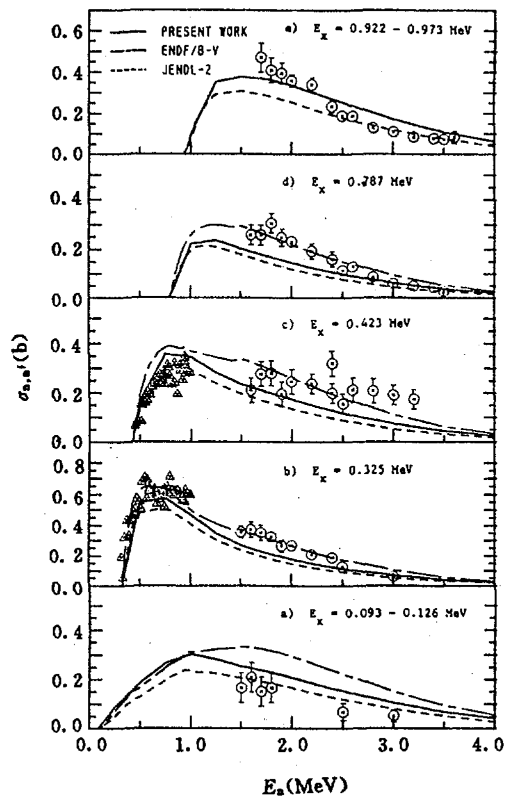

Fig. 4 Inelastic scattering cross section of ^{107}Ag

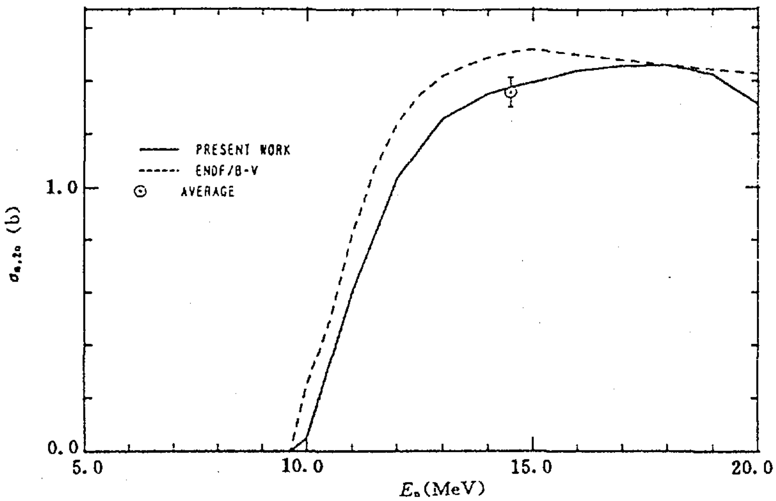

Fig. 5 (n,2n) reaction cross section of ^{107}Ag

Fig. 6 shows the (n,p) cross section of ^{109}Ag. It is found from the figure that the present calculations reproduce the experimental data[52~58] , while the ENDF / B–5 data have a somewhat strange structure as compared with the experimental data.

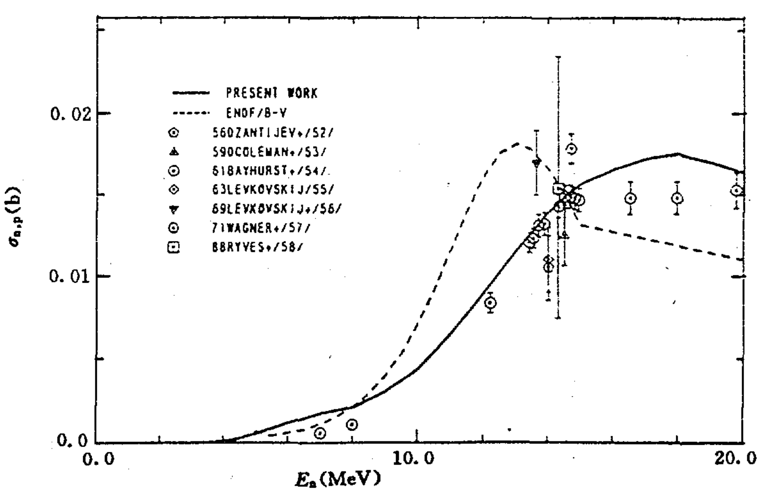

Fig. 6 (n,p) reaction cross section of ^{109}Ag

The calculated (n,α) cross section of ^{107}Ag is shown in Fig. 7, together with ENDF / B–5 and the measurements of Bormann et al.[59]. It should be noted that the present calculation is much smaller than the ENDF / B–5 evaluation and in good agreement with the experimental data of Bormann et al. Recently, Kneff et al.[60] reported a value of 7.6 ± 0.6 mb for the helium production cross section of natural silver at 14.8 MeV, which is close to the present evaluation of 6.7 mb at 15 MeV.

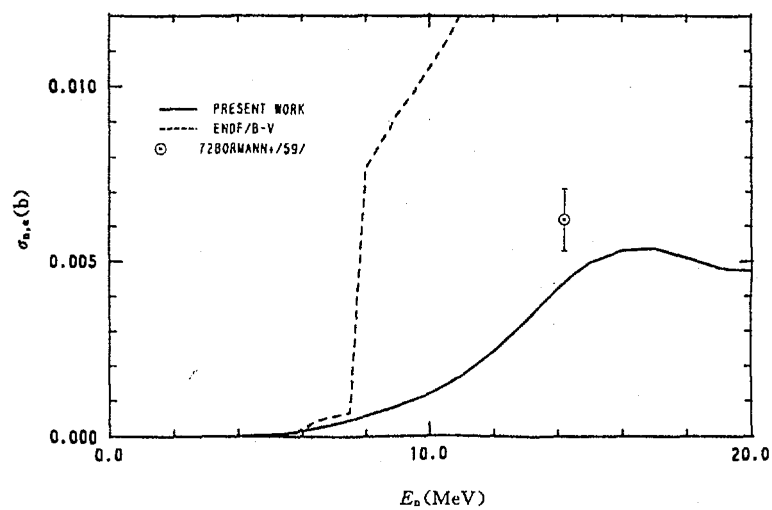

Fig. 7 (n,α) reaction cross section of ^{107}Ag

Neutron and γ–ray emission spectra from natural silver are shown in Figs.8 and 9, respectively. The agreement between the calculated values and the experimental data[61~63] is quite satisfactory in both cases. The γ–ray production data for silver are not given in ENDF / B–5 and JENDL–2.

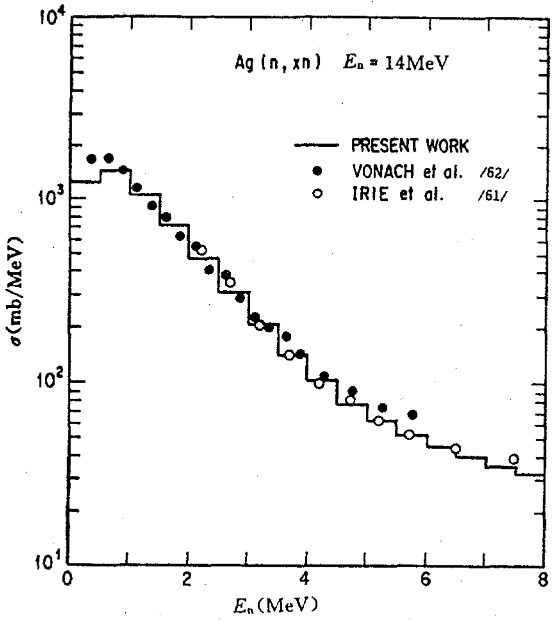

Fig. 8 Neutron emission spectra at E_n = 14 MeV

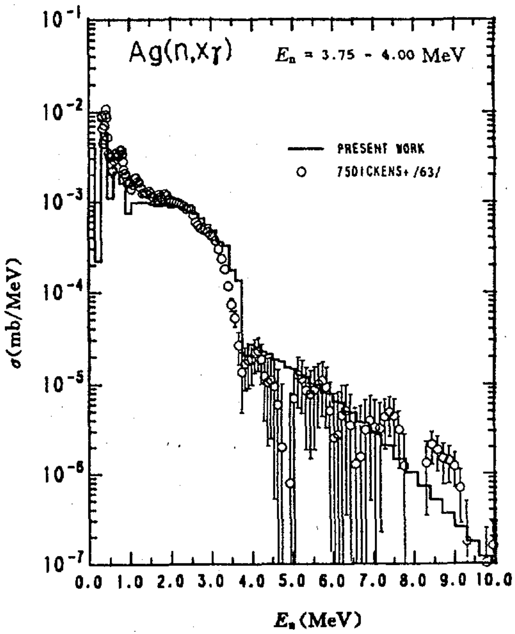

Fig. 9 γ–ray emission spectra at $E_n = 4$ MeV

4 CONCLUDING REMARKS

The neutron nuclear data of natural silver and its isotopes were evaluated in the energy range of 10^{-5} eV ~ 20 MeV. The present evaluation is based on the available experimental data and the theoretical calcuations.

Most of the reaction cross sections were calculated with the Hauser–Feshbach theory by using the TNG code. The γ–ray production cross section was obtained for each reaction from the TNG calculations. The neutron emission spectra were well reproduced by the calculations.

The unresolved resonance parameters were obtained by fitting the calculated cross sections to the experimental ones for the total and capture cross sections. The resolved resonance parameters for the multi–level Breit–Wigner formula were taken from those of JENDL–2, by assuming the total spin values for the levels whose spin was not measured. The experimental data were adopted for the total and capture cross sections above the resonance region with keeping the consistency between the natural and isotopic data.

On the whole, the present evaluation reproduces the experimental data more satisfactorily than the JENDL−2 and ENDF / B−5 data. The present evaluated data have been compiled into CENDL−2 and JENDL−3 in the ENDF / B−5 format, and will be utilized in the various fields of nuclear engineering.

ACKNOWLEDGMENT

The authors would like to thank S. Igarasi, Y. Kikuchi, Y. Nakajima and T. Fukahori for their helpful discussion during the course of this work. They are indebted to S. Iijima for his advice on the level density and optical−model parameters and to M. Mizumoto for his comment on the capture cross−section measurement.

REFERENCES

[1] Kikuchi, Y., et al., J. Nucl. Sci. Technol., 22 [8], 593(1985);
Aoki, T., et al., Proc. Int. Conf. Nuclear Data for Basic and Applied Science, Santa Fe, 1985, Vol. 2, p. 1627(1986)

[2] Shibata, K., et al., Japanese evaluated nuclear data library, Version−3, JAERI−1319 (1990)

[3] Wapstra, A. H., Bos, K., At. Data Nucl. Data Tables, 19, 177 (1977)

[4] Holden, N. E., et al., Pure Appl. Chem., 56, 675(1984)

[5] Kikuchi, Y., Private communication, (1987)

[6] Mizumoto, M., et al., Proc. Int. Conf. Nuclear Data for Science and Techonlogy, Antwerp, 1982, p. 226(1983)

[7] Macklin, R. L., Nucl. Sci. Eng. 82, 400(1982)

[8] Poenitz, W. P., Whalen, J. F., Neutron total cross section measurements in the energy region from 47 keV to 20 MeV, ANL / NDM−80,(1983)

[9] Seth, K. K., et al., Phys. Lett., 16, 306(1965)

[10] Jain, A. P., et al., Phys. Rev. B137, 83(1965)

[11] Mughabghab, S. F., et al., "Neutron Cross Sections", Vol. 1, Part A, (1981), Academic Pross

[12] Foster, Jr., D. G., Glasgow, D. W., Phys. Rev., C3, 576(1971)

[13] Smith, A., et al., Nucl. Phys., A332, 297(1979)

[14] Dukarevich, Ju, et al., ibid., A92, 433(1967)

[15] Diven, B. C., et al., Phys. Rev., 120, 556(1960)

[16] Gibbons, J. H., et al., ibid., 122, 182(1961)

[17] Bergqvist, I., Ark. Fys., 23, 425(1963)

[18] Macklin R. L., Gibbons, J. H., Phys. Rev., 159, 1007(1967)

[19] Poenitz, W. P., Fast–neutron capture–cross section measurements with the Argonne National Laboratory large–liquid–scintillator tank, ANL– 83–4, p. 239(1982)
[20] Lejpunskij, A. I., et al., Proc. 2nd UN Conf. Peaceful Uses of Atomic Energy, Geneva, Vol. 15, p. 50(1958)
[21] Lyon, W. S., Macklin, R. L. Phys. Rev., 114, 1619(1959)
[22] Johnsrud, A. E., et al., ibid., 116, 927(1959)
[23] Weston, L. W., et al., Ann. Phys., 10, 477(1960)
[24] Kononov, V. N., et al., At. Energ., 19, 457(1965)
[25] Peto, G., et al., J. Nucl. Energy, 21, 797(1967)
[26] Fu, C. Y., A consistent nuclear model for compound and precompound reactions with conservation of angular momentum, ORNL / TM–7042, (1980)
[27] Igarasi, S. J., Nucl. Sci. Technol., 12 [2], 67(1975)
[28] Smith, A. B., et al., Nucl. Phys., A415, 1(1984)
[29] Taylor, H. L., et al., Phys. Rev., 100, 174(1955)
[30] Beyster, J. R., et al., ibid., 98, 1216(1955)
[31] Graves, E. R., Davis, R. W., ibid., 97, 1205(1955)
[32] Beyster, J. R., et al., ibid., 104, 1319(1956)
[33] Bonnrt, T. W., Slattery, J. H., ibid., 113, 1088(1959)
[34] Jasicek, H. A., Taken from EXFOR (1973)
[35] Perey, F. G., Phys. Rev., 131, 745(1963)
[36] Arthur, E. D., Young, P. G., Evaluated neutron–induced cross sections for $^{54,56}Fe$ to 40 MeV, LA–8626–MS, (1980)
[37] Lemos, O. F., Diffusion elastique de particules α de 21 a 29.6 MeV sur des noyaux de la region Ti–Zn, Orsay Rep., Ser. A, No. 136(1972)
[38] De Frenne, D. et al., Nucl. Data Sheets, 45, 363(1985)
[39] Blachot, J. et al., ibid., 41, 325(1984)
[40] De Frenne, D., et al., ibid., 47, 261(1986)
[41] Harmatz, B., ibid., 30, 305(1980)
[42] idem, ibid., 34, 643(1981)
[43] Haese, R. L., et al., ibid., 37, 289(1982)
[44] Blachot, J., ibid., 41, 111(1984)
[45] De Gelder, P., et al., ibid., 38, 545(1983)
[46] Gilbert, A., Cameron, A. G. W., Can. J. Phys., 43, 1446(1965)
[47] Facchini, U., Saetta–Menichella, E. Energ. Nucl., 15, 54(1968)
[48] Iijma, S., et al., J. Nucl. Sci. Technol., 21 [1], 10(1984)
[49] Iijma, S., Private communication, (1987)
[50] Fuller, E. G., Hayward, E., "Nuclear Reactions", Vol. 2, (Endt, P. M., Smith, P. B., Eds.), p. 113(1962), North–Holland Publ.
[51] Nishimura, K., et al., Nucl. Phys., 70, 421(1965)

[52] Dzantijev, B. G., et al., Doklady Akademii Nauk SSSR, 113, 537(1956)
[53] Coleman, R. F., et al., Proc. Phys. Soc. (London), 73, 215(1959)
[54] Bayhurst, B. P., Prestwood, R. J., J. Inorg. Nucl. Chem., 23, 173(1961)
[55] Levkovskij, V. N., Zh. Eksp. Teor. Fiz., 45, 305(1963)
[56] Levkovskij, V. N., et al., Nucl. Phys., 10, 44(1969)
[57] Wagner, I., Uhl, M., Oesterr. Akad. Wiss. Math. Naturw. Anzeiger. 108, 185(1971)
[58] Ryver, T. B., et al., J. Phys., G14, 77(1988)
[59] Bormann, M. et al., Nucl. Phys., A186, 65(1972)
[60] Kneff, D. W., et al., Nucl. Sci. Eng., 92, 491(1986)
[61] Irie, Y. et al., Precompound processes in inelastic scattering of 14.1 MeV neutrons by Cu, As, Nb and Ag, Mem. Fac. Eng., Kyushu Univ., 37, 19(1977)
[62] Vonach, H., et al., Measurement of the angle integrated secondary neutron spectra from interaction of 14 MeV neutrons with medium and heavy nuclei, Proc. Symp. Neutron Cross Sections from 10 to 50 MeV, BNL, 1980, p. 343(1980)
[63] Dickens, J. K., et al., γ–ray production due to neutron interactions with silver for incident neutron energies between 0.3 and 20 MeV, ORNL / TM–5081, (1975)

EVALUATION OF NEUTRON DATA FOR NATURAL TIN

Yao Lishan

(INSTITUTE OF NUCLEAR RESEARCH, LANZHOU UNIVERSITY)

ABSTRACT

The complete neutron nuclear data of natural tin for CENDL–2 have been evaluated in the neutron energy range from 10^{-5} eV to 20 MeV. Some of the data have been calculated by means of theoretical models[1, 2], and a good agreement was obtained with the measured values. The recommended data were compared with other evaluated results.

INTRODUCTION

Natural tin consists of ten stable isotopes. It's one of fission, and fusion reactor structure materials. All reaction threshold energies of tin with neutrons are given in Table 1.

The evaluation of tin data has been performed based on CENDL−1 (MAT = 1700)[3]. The evaluated quantities include the resonance parameters, reaction cross sections, angular and energy distributions of secondary neutrons etc.

1 RESONANCE PARAMETERS

The resonance parameters are consist of its isotopes in neutron energy range from 10^{-5} eV to 14.27 keV. The data of isotopes were taken from ENDF / B−6. The evaluated cross sections were compared with the measured data, and the background cross sections are given in the relative sections of File 3.

Table 1 Reaction threshold energies of Sn with neutrons

Reaction channels	Threshold energies (MeV)
n,n′	0.024072
n,2n	6.5411
n,3n	15.724
n,p	0.67739
n,t	7.8078
n, ^{3}He	9.2434
n,d	7.1145
n,α	(Q = 5.2731)
n,n′p	9.3585
n,n′t	16.911
n,n′ ^{3}He	15.437
n,n′d	14.119
n,n′α	3.3949
n,γ	(Q = 6.3480)

2 REACTION CROSS SECTIONS

2.1 Total Cross Section

New data were mainly measured by Poenitz(83)[4] and Rapaport(80)[5] from 47 keV to 18.8 MeV, and 5 to 8 MeV respectively. The measured errors were 1 to 2 per–cent. The results of them were in good agreement with Foster(71)[6] within the measured errors. In addition, the data measured by Refs. [7~ 10] were also adopted in order to extend evaluated energy range. For E_n < 2 MeV, the evaluated results are well consistent with ENDL–78[11]. For E_n > 2 MeV, the results are shown in Fig. 1.

2.2 Elastic Nonelastic and Inelastic Scattering Cross Sections

Because no new experimental data are available, the elastic and nonelastic scattering cross sections were taken from the measured values recommended by CENDL–1. Recent data measured by Pal(80)[12] were also adopted for elastic scattering. The evaluated results are shown in Fig. 2 and 3, respectively. For inelastic scattering cross sections, there are three sets of data given by Refs. [13 ~ 15]. The great difference exists among them. Therefore, the recommended data were given by theoretical calculations.

2.3 (n,2n), (n,3n) Reaction Cross Sections

For (n,2n) reaction, there is only a value measured by Lebedev(58)[16] at 14 MeV. For (n,3n) reaction,no measured data are available. Therefore, the recommended data of them were taken from calculated results.

2.4 Radiative Capture Cross Section

The evaluated results are given in Fig. 4. It can be seen that the results are in good agreement with measured values.

2.5 (n,p) Reaction Cross Section

There is only a value measured by Allan(61)[17] at 14 MeV. The recommended data were taken from calculated results.

2.6 Other Reaction Cross Sections

For (n,x) reactions (x = t, ^{3}He, d, α) and the secondary reactions of them, because no experimental data are available, the recommended data are given by model calculations.

2.7 Inelastic Scattering Cross Sections of Discrete Levels

The recommended 22 level's parameters are given in Table 2. The evaluated results and the data measured by Konobeevsky(73)[18] are given in the Fig 5. Some of the data are normalized to the measured values, and others are calculated.

Table 2 Discrete level parameters of Sn

U(MeV)	J^{π}	U(MeV)	J^{π}	U(MeV)	J^{π}
0.0	0^+	1.005	$3/2^+$	2.043	2^+
0.02387	$3/2^+$	1.171	2^+	2.057	0^+
0.08953	$11/2^-$	1.230	2^+	2.097	2^+
0.1586	$3/2^+$	1.294	2^+	2.113	2^+
0.3145	$11/2^-$	1.757	0^+	2.194	4^+
0.7115	$7/2^+$	1.758	0^+	2.225	2^+
0.7870	$7/2^+$	1.875	0^+	2.284	5^-
0.9205	$3/2^+$	2.027	0^+		

3 ANGULAR DISTRIBUTIONS OF SECONDARY NEUTRONS

For angular distributions of elastic scattering the data measured by Smith(84)[19] were adopted. In addition, the data measured by Wilenzick(65)[13], Rayburn(59)[20] and Beyster(56)[21] were recommended respectively. Some of the data were calculated with model code. The evaluated results are shown in Fig 6.

For angular distributions of inelastic scattering and other reactions, the isotropic in the center of mass system is assumed.

4 ENERGY DISTRIBUTIONS OF SECONDARY NEUTRONS

For (n,n′), (n,2n) and (n,3n) etc., no experimental data of the secondary neutron energy distributions are available, and the calculated data were recommended.

5 CONCLUDING REMARKS

In the present work, the neutron nuclear data of natural tin are reevaluated based on CENDL−1[3]. Due to using the newly measured data in this evaluation , the previous evaluation was modified. The evaluated data of natural tin haven′t been included in JENDL−3 and in ENDF / B−6 the evaluated data were given for its isotopes. Comparing our evaluated data with ENDL−78, it can be seen that the total cross sections were improved. And the elastic scattering and capture cross sections, the excitation functions of inelastic scattering and angular distributions of elastic scattering were modified more or less; (n,x) reaction cross sections (x = p, t, ^{3}He, d,α) were newly evaluated. The recommended data were given ENDF / B–5 format and stored in Chinese Evaluated Nuclear Data Library, Version 2 (CENDL–2, MAT = 2500).

ACKNOWLEDGEMENTS

The author would like to thank Profs. Yuan Hanrong, Liang Qichang and Cai Dunjiu for their warm support and help of this work. He also thanks Drs. Cai Chonghai, Ma Gonggui for their help in the calculation.

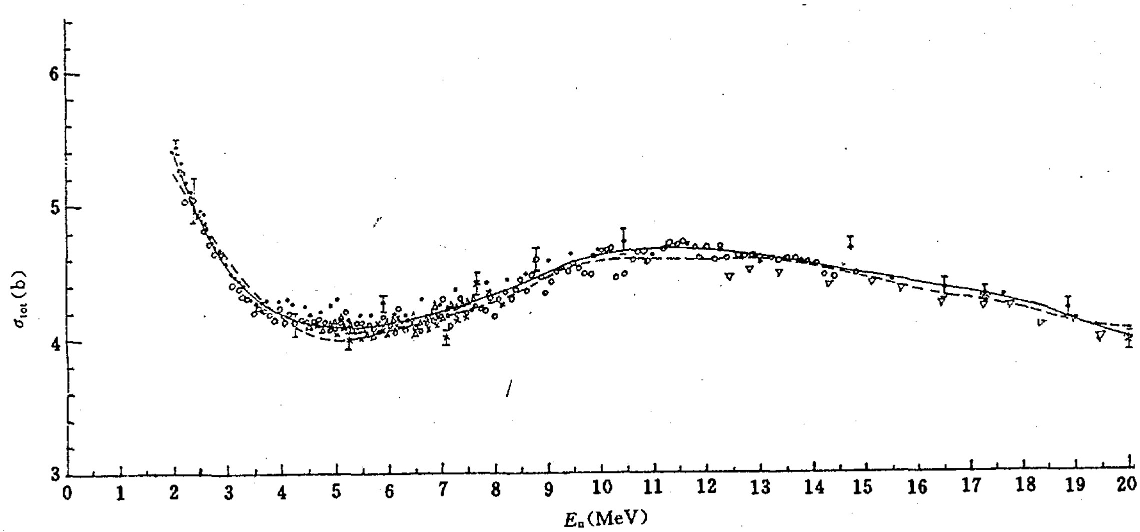

Fig. 1 The comparison between evaluated results with experimental values for total cross sections of Sn

• [4] × [5] ○ [6] △ [7] + [8] ▽ [9] ※ [10]

---- ENDL–78 —— Present work

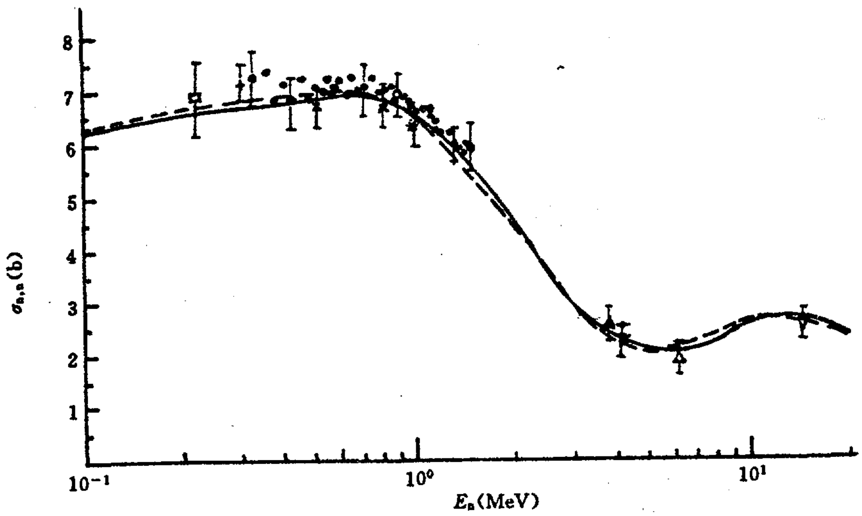

Fig. 2 The comparison between evaluated results with experimental values for the elastic scattering cross sections of Sn

The experimental values of recommendation were taken from CENDL–3;

---- ENDL–78 ——— Present work

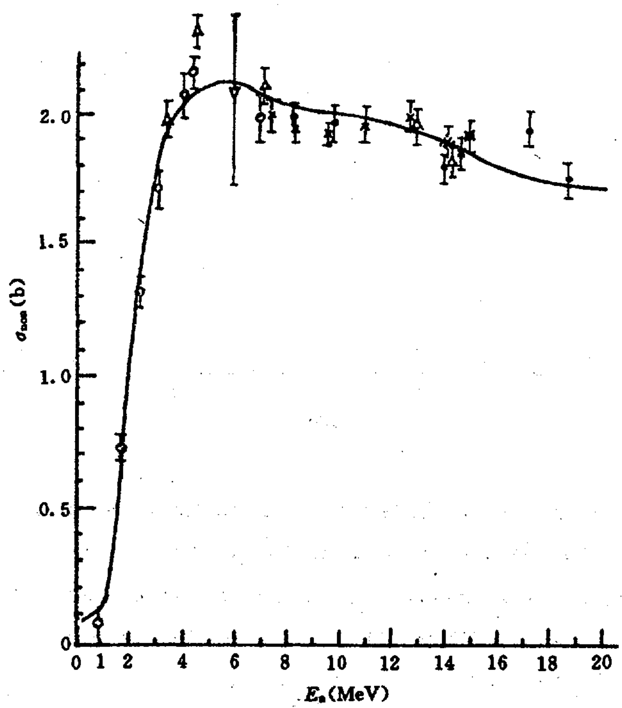

Fig. 3 The comparison between evaluated results with experimental values for nonelastic scattering cross sections of Sn

The experimental values of recommendation were taken from CENDL–3;

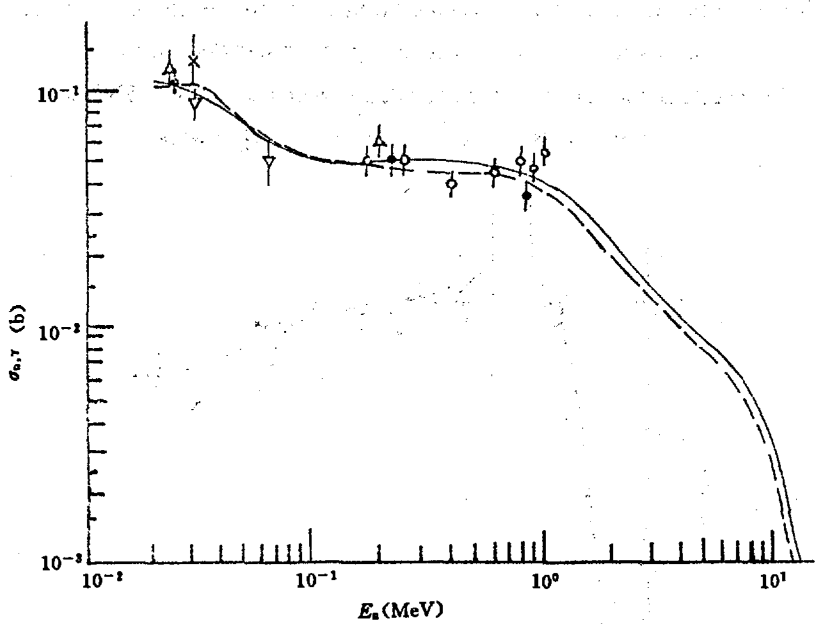

Fig. 4 The comparison between evaluated results with experimental values for Sn(n,γ) reaction cross sections of Sn

The experimental values of recommendation were taken from CENDL−1

– – – – ENDL−78 ——— Present work

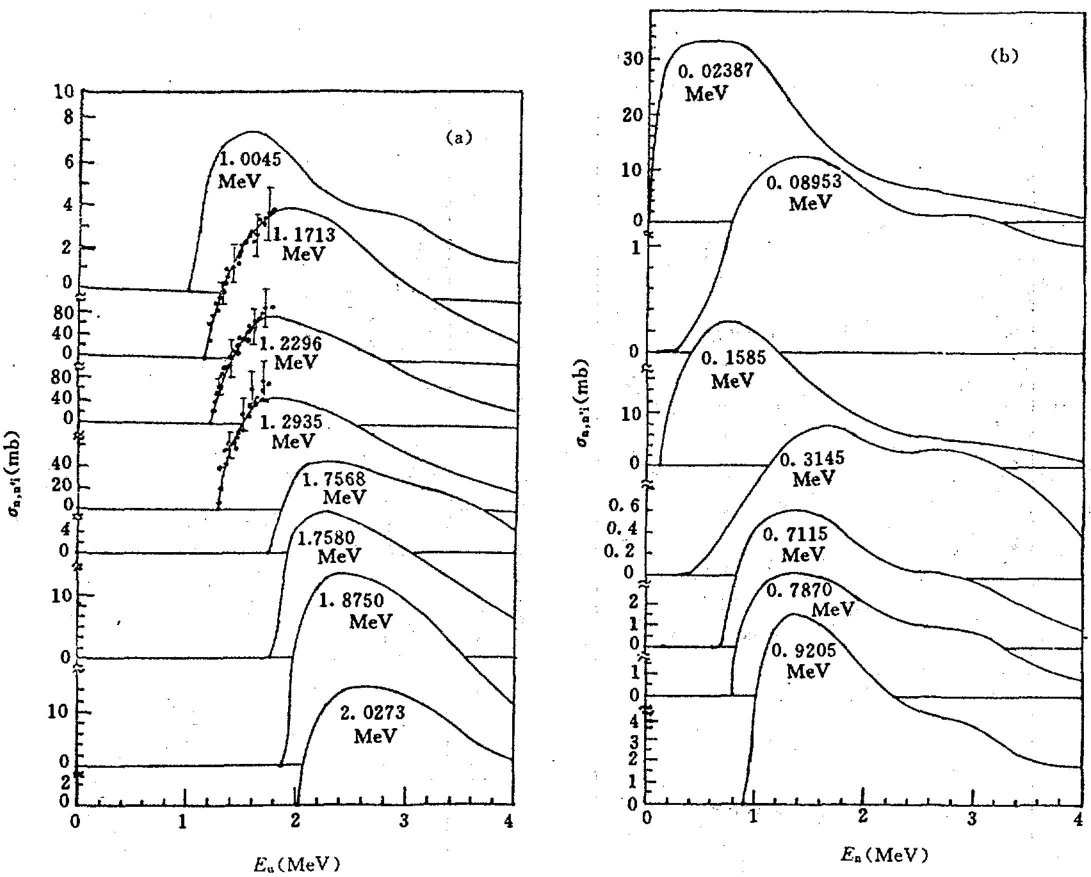

Fig. 5 The comparison between evaluated results with experimental values of the inelastic scattering cross sections to discrete levels for Sn

• [18] —— Present work

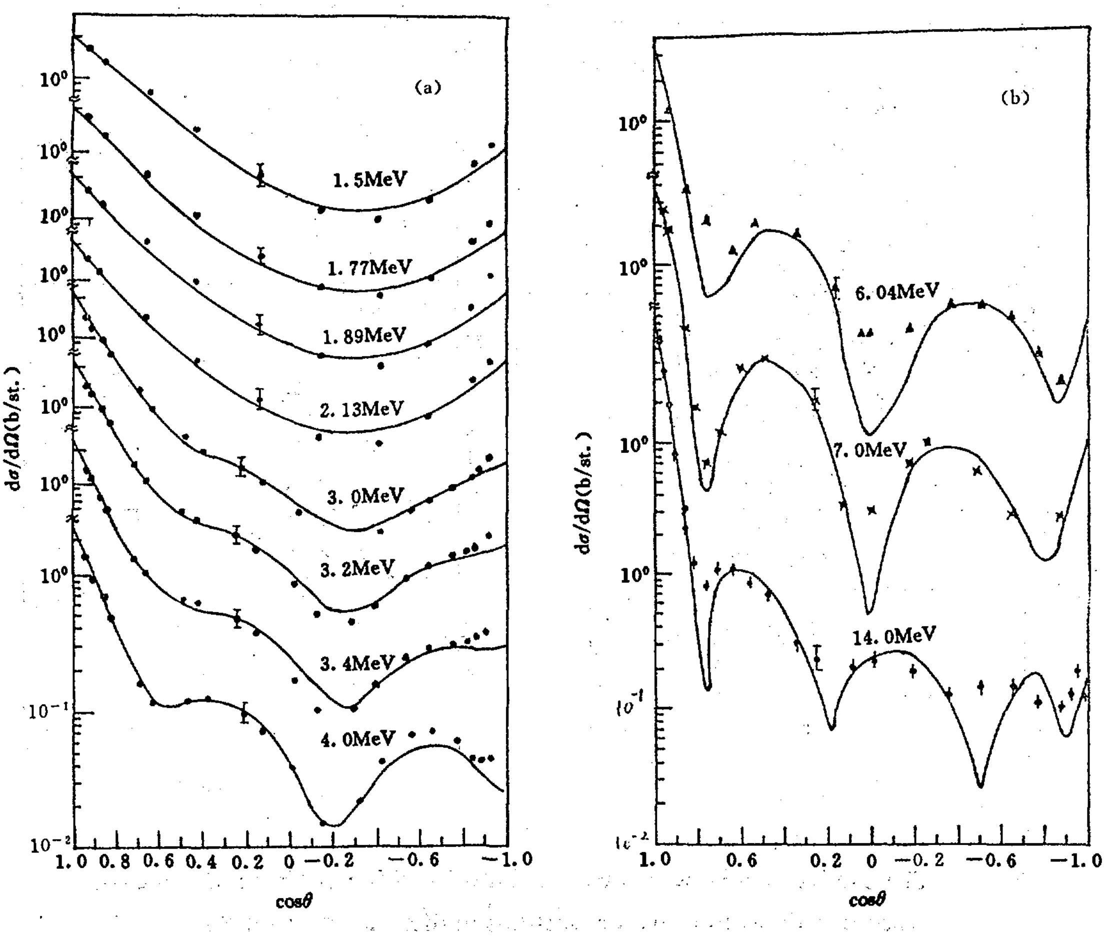

Fig. 6 The comparison between evaluated results with experimental values of the elastic scattering angular distributions for Sn

▲ [13] · [19] ✖ [20] ⧫[21] —— Present work

REFERENCES

[1] Zhou Hongmo et al., AUJP (CNDC0011) (1989)

[2] Cai Chonghai et al., MUP2 (CNDC0013) (1989)

[3] Yang Huazhong, CENDL−1, MAT = 1700, 218(1986)

[4] W. P. Poenitz et al., ANL−NDM−80, (1983)

[5] J. Rapaport et al., Nucl. Phys., A−341, 56(1980)

[6] D. G. Foster et al., Phys. Rev., C−3, 576(1971)

[7] A. D. Carlson et al., Phys. Rev., 158, 1142(1967)

[8] A. I. Tutubalin, 4th All Union Conf. on Neutron Physics, Kiev,18−22 April 1977, 2, 65(1977)

[9] G. J. Mc Callun et al., Nucl. Phys., 16, 313(1960)

[10] J. M. Peterson et al., Phys. Rev., 120, 521(1960)

[11] R. J. Howerton et al., ENDL−78, MAT = 7850,(1979)

[12] B. Pal et al., Nucl. Instr. & Method, 171, 347(1980)

[13] R. M. Wilenzick et al., Nucl. Phys., 62, 511(1965)

[14] R. O. Owens et al., Nucl. Phys., A−112, 337(1968)

[15] R. M. Wilenzick et al., Bull. Amer. Phys., 7, 23(1962)

[16] P. P. Lebedev et al., Atomnaja Energija, 5, 522(1958)

[17] D. L. Allan, Nucl. Phys., 24, 274(1961)

[18] E. S. Konobeevsky et al., Izv. Akad. Nauk SSSR, Ser. Fiz. 37., 1900(1973)

[19] A. B. Smith et al., Nucl. Phys., A−415, 1(1984)

[20] L. A. Rayburn et al., Phys. Rev., 116, 1571(1959)

[21] J. R. Beyster et al., Phys. Rev., 104, 1319(1956)

EVALUAION OF NEUTRON DATA FOR NATURAL ANTIMONY

Yao Lishan

(INSTITUTE OF NUCLEAR RESEARCH, LANZHOU UNIVERSITY)

ABSTRACT

The complete neutron nuclear data of natural antimony have been performed for CENDL–2 in neutron energy range from 10^{-5} eV to 20 MeV. Some of the data have been calculated by means of theoretical model. A good agreement was obtained with measured values. The recommended data were compared with the evaluations of JENDL–3 and ENDF / B–6.

INTRODUCTION

Natural antimony consists of stable isotopes ^{121}Sb and ^{123}Sb. The abundances of them are 57.25 and 42.75 per–cent respectively. It's one of the fission and fusion reactor structure materials. All reaction threshold energies of atimony with neutrons are given in Table 1.

The complete neutron nuclear data of natural antimony(Sb) have been evaluated. The evaluated quantities include resonance parameters, reaction cross sections (σ_{tot}, σ_{nn}, σ_{non}, $\sigma_{nn'}$, σ_{n2n}, σ_{n3n}, $\sigma_{n\gamma}$, σ_{nx} (x = p, t, ^{3}He, d, α), $\sigma_{nn'x}$), angular and energy distributions of secondary neutrons etc.

1 RESONANCE PARAMETERS

The resolved resonance parameters of natural antimony are consist of ones of its isotopes in incident neutron energy range from 10^{-5} eV to 1.5096 MeV. The data of isotopes are taken from ENDF / B–6. The evaluated cross sections were compared with the experimental data, and the background cross section is given in the relative sections of File 3.

Table 1 Reaction threshold energies of Sb with neutrons

Reaction channels	Threshold energies (MeV)
n,n′	0.037442
n,2n	9.0386
n,3n	15.901
n,p	(Q=0.39522)
n,t	6.4602
n, ^{3}He	8.8159
n,d	3.5898
n,α	(Q=3.5034)
n,n′p	5.8329
n,n′t	12.999
n,n′ ^{3}He	17.216
n,n′d	12.769
n,n′α	3.1117
n,γ	(Q=6.6616)

2 REACTION CROSS SECTIONS

2.1 Total Cross Section

New data were mainly measured by Smith(84)[1] from 0.8 to 4.5 MeV, with errors 1.3 to 2.8 per–cent. The experimental results are in good agreement with Foster(71)[2] from 2.271 to 14.8 MeV within the measured errors. In addition, the data measured by Camarda(74)[3] from 1 to 600 keV were also adopted. Early data measured by Backelman(49)[4] were given for E_n = 1 keV to 1 MeV, the results evaluated with new data[1] are systematically higher by about 5 to 8 per–cent than those of JENDL–3 and ENDF / B–6 which were evaluated on the basis of older data measured by Tabony(68)[5]. For E_n > 1 MeV, the results are basically consistent with JENDL–3, but the evaluated data of ENDF / B–6 are lower than ours. The present evaluated results are shown in Fig. 1.

2.2 Elastic, Nonelastic and Inelastic Scattering Cross Sections

Elastic scattering cross sections were obtained by subtracting nonelastic scattering from total cross sections. For nonelastic and inelastic scattering, the recommended data are basically consistent with JENDL–3 and ENDF / B–6, in addition, ENDF / B–6 is higher than ours in E_n > 10 MeV. The present evaluated results are shown in the Figs. 2,3 respectively.

2.3 (n,2n), (n,3n) Reaction Cross Sections

For (n,2n) reaction, the data were measured by Ghrai(80)[6] and

Bormann(68)[7] systematically. In addition, the experimental data of Refs. [8,9] were also adopted. The evaluated results are shown in Fig. 4. It can be seen a good agreement was obtained comparing with INDL / V, and the evaluation of JENDL−3 is higher systematically in $E_n > 18$ MeV, and lower at $E_n > 18$ MeV than ours. For (n,3n) reaction, no measured data are available. Therefore, the recommended data are taken from calculated results by means of the model code.

2.4 Radiative Capture Cross Section

For (n,γ) reaction, a lot of experimental data are available, but most of them are the old data. The more recent data are those measured by Poenitz(82)[10] from 0.6 to 3.5 MeV. Other adopted data were mainly taken from Refs. [11 ~ 16]. Comparing our results with JENDL−3 and ENDF / B−6, it can be seen that present evaluated data are located at below above ones.But it is in good agreement with the experimental data (see Fig. 5).

2.5 (n,p) Reaction Cross Section

There are only two data measured by Allan(61)[17] and Peck(61)[18] at 14 MeV. The recommended data were taken from calculated, and normalized to the experimental data.

2.6 Other Reaction Cross Sections

For (n,x) reactions(x = t, ^{3}He, d, α) and the secondary process of them, because no experimental data are available, the recommended data are given by model calculations.

2.7 Inelastic Scattering Cross Sections for Discrete Level

The recommended 32 level's parameters are given in Table 2. Because the data measured by Smith(84)[1] and (67)[19] were largely dispersed, and measured levels were overlapped each other,the evaluated results can not be normalized to the experimental data.The recommended data were then taken from the calculated results.

Table 2 Discrete level parameters of Sb

U(MeV)	J^π	U(MeV)	J^π	U(MeV)	J^π
0.0	$5/2^+$	1.0866	$9/2^+$	1.740	$3/2^+$
0.037133	$7/2^+$	1.1393	$11/2^+$	1.754	$7/2^+$
0.16033	$5/2^+$	1.1447	$9/2^+$	1.884	$1/2^+$
0.5076	$3/2^+$	1.1813	$7/2^+$	2.100	$3/2^+$
0.5418	$3/2^+$	1.2609	$5/2^+$	2.235	$1/2^+$
0.57314	$1/2^+$	1.3342	$7/2^+$	2.520	$1/2^+$
0.7128	$1/2^+$	1.4480	$3/2^+$	2.636	$7/2^+$
0.94699	$9/2^+$	1.5104	$3/2^+$	2.750	$3/2^+$
1.0240	$7/2^+$	1.643	$11/2^+$	2.915	$7/2^+$
1.0302	$9/2^+$	1.6590	$3/2^-$	3.178	$7/2^+$
1.0352	$9/2^+$	1.7290	$1/2^-$	3.327	$1/2^-$

3 ANGULAR DISTRIBUTIONS OF SECONDARY NEUTRONS

For angular distributions of elastic scattering cross sections, the calculated data were used. The experimental data from Refs. [20～26] were used for adjusting the parameters.

For angular distributions of inelastic scattering cross sectionand other reactions, the isotropic in the center of mass system is assumed.

4 ENERGY DISTRIBUTIONS OF SECONDARY NEUTRONS

For (n,n′),(n,2n) and (n,3n) etc., no experimental data of the secondary neutron energy distributions are available, and the calculated data were recommended.

5 THEORETICAL CALCULATION

The theoretical models for calculating neutron data consist of the optical model (OPM), Hauser–Feshbach theory with width fluctuation correction (WHF) and evaporation model including the preequilibrium emission (PEM). The neutron nuclear data of Sb were calculated with AUJP code[27] and MUP2 code[28]. The calculated quantities are the cross sections, angular and energy distributions of emitted neutrons for all reactions.

The optimal optical model parameters used are given in the Table 3.

Table 3 Optical model parameters of various reaction channels

Channels / Parameters	n	p	t	^{3}He	d	a
AR= ASO	0.655	0.85	0.72	0.72	0.95	0.59
AS= AVV	0.415	0.51	0.84	0.88	0.82	0.30
XR= XSO	1.264	1.70	1.20	1.20	1.75	1.48
XS= XVV	1.284	1.32	1.40	1.40	1.43	1.73
XC	1.25	1.30	1.30	1.30	1.54	1.54
U0	1.753	0.0	28.73	48.61	0.0	0.0
U1	−0.072	0.0	−0.33	−0.33	0.0	0.0
V0	50.993	54.0	165.0	151.9	91.13	186.6
V1	−0.320	− 0.32	−0.17	−0.17	0.0	0.0
V2	−0.00113	0.0	0.0	0.0	0.0	0.0
V3	−24.0	24.0	50.0	50.0	0.0	0.0
V4	0.0	0.40	0.0	0.0	2.2	0.0
VSO	7.0	6.2	2.5	2.5	7.0	0.0
W0	10.647	11.8	0.0	0.0	8.91	36.43
W1	−0.0792	−0.25	0.0	0.0	0.0	0.0
W2	−12.0	12.0	0.0	0.0	0.0	0.0
A2S	0.70					
A2V	0.70					

6 CONCLUDING REMARKS

In the present work, the neutron nuclear data of natural atimony were evaluated. Due to using the newly measured data in this evaluation , the previous evaluation is modified. Comparing the evaluated data with JENDL−3 and ENDF / B−6, it can be seen that the total cross sections were improved. The nonelastic, inelastic scattering, (n,2n) and the capture cross sections were modified more or less; (n,x) reaction cross sections (x = p, t, ^{3}He, d, α) were also evaluated. The recommended data were given in the ENDF / B−5 format and stored in the Chinese Evaluated Nuclear Data Library, Version 2 (CENDL−2, MAT = 2510).

ACKNOWLEDGEMENTS

The author would like to thank Profs. Yuan Hanrong, Liang Qichang and Cai Dunjiu for their warm support and help of this work. He also thanks Dr. Cai Chonghai, Dr. Ma Gonggui for their help in the calculation.

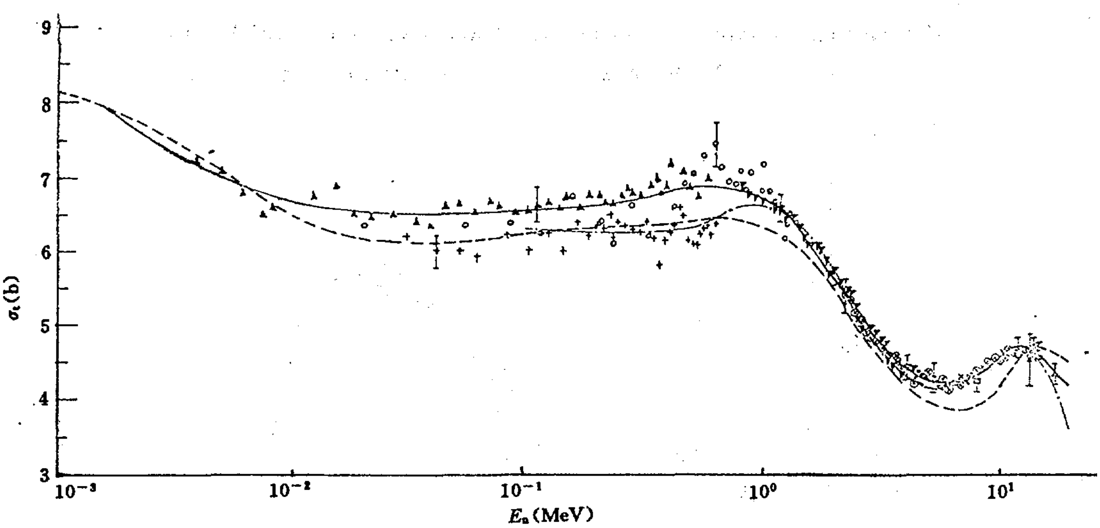

Fig. 1 The comparison between evaluated results with experimental values for total cross sections of Sb

▼ [1] ⊗ [2] ▲ [3] ○ [4] + [5]

—·—·— JENDL–3 ---- ENDF / B–6 ——— Present work

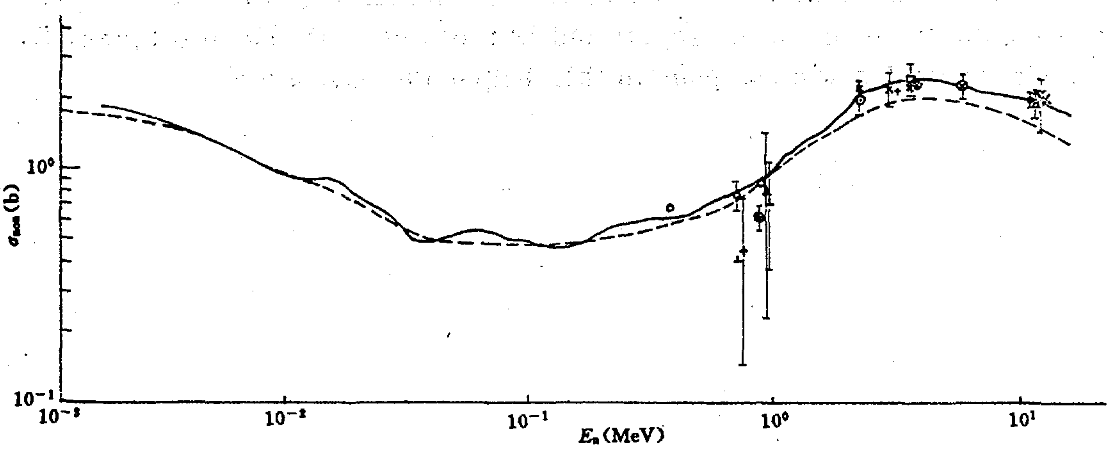

Fig. 2 The comparison between evaluated results with experimental values for nonelastic scattering cross sections of Sb

The experimantal values of recommendation were taken from EXFOR data

---- ENDF / B-6 ——— Present work

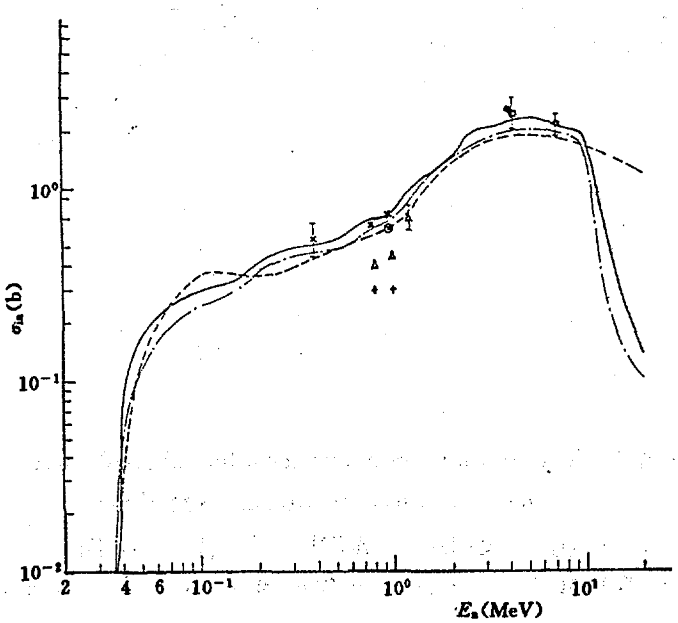

Fig. 3 The comparison between evaluated results with experimental values for inelastic scattering cross sections of Sb

The experimantal values of recommendation were taken from EXFOR data

—·—·— JENDL-3 ---- ENDF / B-6 ——— Present work

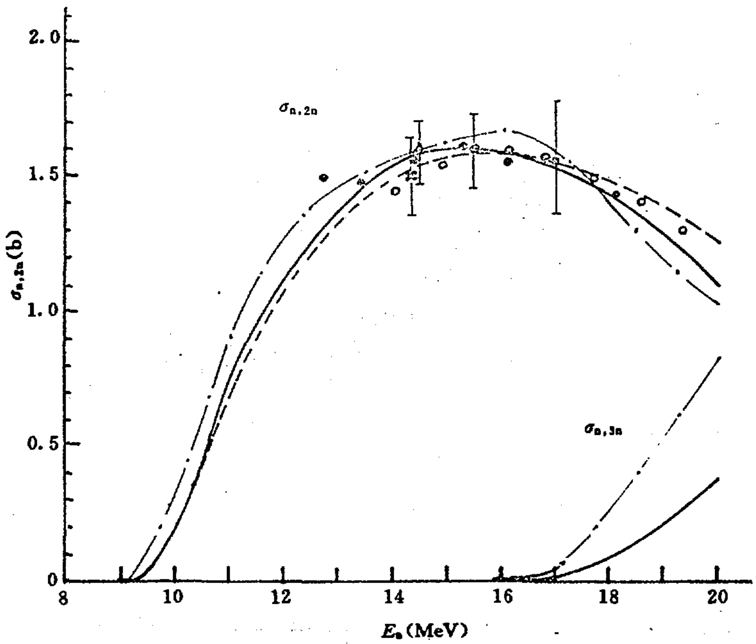

Fig. 4 The comparison between evaluated results with experimental values for Sb(n,2n), (n,3n) reaction cross sections of Sb

• [6] ○ [7] △ [8] × [9]

—·—·— JENDL–3 - - - INDL / V ——— Present work

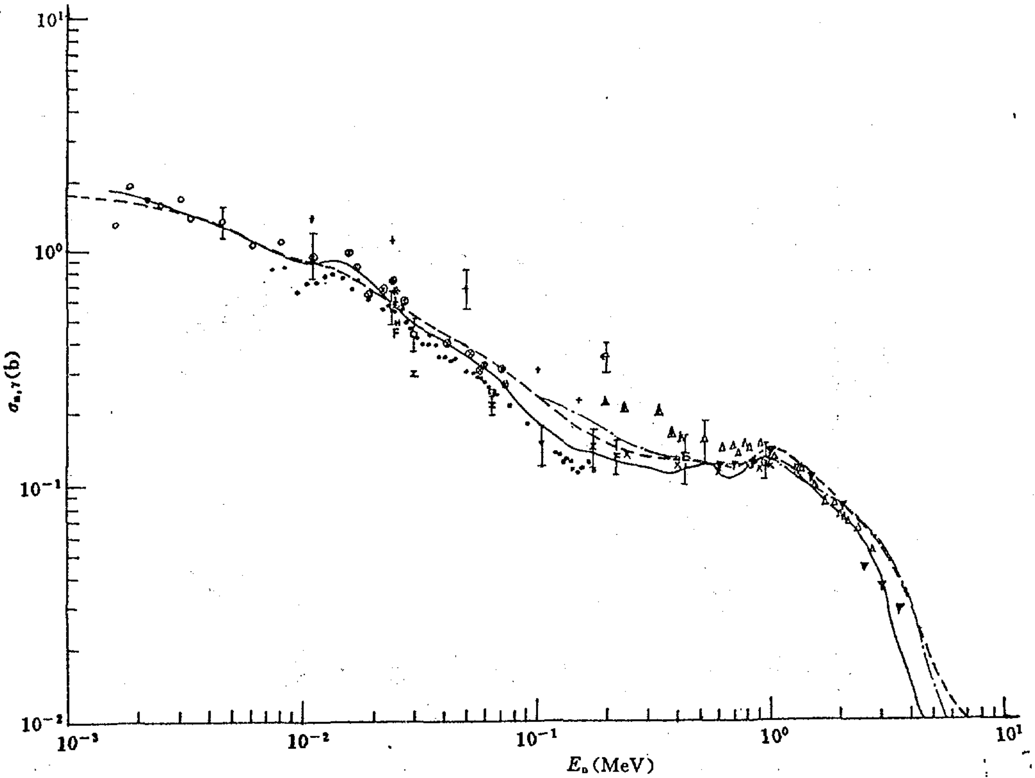

Fig. 5 The comparison between evaluated results with experimental values for Sb(n,r) reaction cross sections

▼ [10] + [11] ⊗ [12] △ [13] • [14] × [15] O [16]

—•—•— JENDL-3 - - - - ENDF / B-6 ——— Present work

REFERENCES

[1] A. B. Smith et al., Nucl. Phys., A–415, 1(1984)
[2] D. G. Foster et al., Phys. Rev., C–3, 576(1971)
[3] H. S. Camarda et al., Phys. Rev., C–9, 28(1974)
[4] C. K. Backelman et al., Phys. Rev., 76, 277(1949
[5] H. Tabony et al., Ann. Phys., 46, 401(1968)
[6] S. K. Ghrai et al., J. Phys., G–6, 393(1980)
[7] M. Bormann et al., Nucl. Phys., A–115, 309(1968)
[8] Lu Wenden et al., Phys. Rev., C–1,350(1970)
[9] C. S. Khurana et al., Nucl. Phys., 28, 560(1961)
[10] W. P. Poenitz et al., ANL–83–4, 239(1982)
[11] A. G. Dovbenko et al., Atomnaya Energiya, 27, 406(1969)
[12] L. M. Spitz et al., Phys. Rev., A–121, 655(1968)
[13] V. A. Tolstikov et al., Atomnaya Energiya, 24, 576(1968)
[14] J. H. Gibbons et al., Phys. Rev., 122, 182(1961)
[15] B. C. Diven et al., Phys. Rev., 120, 556(1960)
[16] R. C. Block et al., EANDC Conf. on Time of Flight Methods, Saclay, 24–27 July, 203(1961)
[17] D. L. Allan, Nucl. Phys., 24, 274(1961)
[18] R. A. Peck et al., Phys. Rev., 123, 1738(1961)
[19] A. B. Smith et al., Nucl. Phys., 93, 609(1967)
[20] M. A. Etemad et al., AE–482(1973)
[21] B. Holmqvist et al., AE–430(1971)
[22] R. L. Becker et al., Nucl. Phys., 89, 154(1966)
[23] S. G. Buccino et al., Z. Physik, 196, 103(1966)
[24] I. O. Korzh et al., Ukrainskij Fizichnii Zhurnal, 3, 929(1964)
[25] L. D. Vincent et al., WADD–TR–60–217(1960)
[26] L. A. Rayburn, Phys. Rev., 116, 1571(1959)
[27] Zhou Hongmo et al., AUJP(CNDC0011)(1989)
[28] Cai Chonghai et al., MUP2(CNDC0013)(1989)

EVALUATION OF NEUTRON DATA FOR ^{181}Ta

Yao Lishan

(INSTITUTE OF NUCLEAR RESEARCH,
LANZHOU UNIVERSITY)

ABSTRACT

The evaluation of the complete neutron data has been performed for ^{181}Ta in neutron energy range from 10^{-5} eV to 20 MeV. Some of the data have been calculated by means of the model code[1, 2] and a good agreement was obtained with the measured values. The recommended data are compared with other evaluated results.

INTRODUCTION

Natural tantalum is one of the fission, and fusion reactor structure materials. All reaction threshold energies of ^{181}Ta with neutrons are given in Table 1.

The evaluation of ^{181}Ta has been performed on the basis of CENDL−1 (MAT = 1800)[3]. The evaluated quantities include the resonance parameters, reaction cross sections, angular and energy distributions of secondary neutrons etc.

1 RESONANCE PARAMETERS

The resolved (10^{-5} eV to 2.4 keV) and unresolved (2.4 keV to 100 keV) resonance parameters are taken from JENDL−3[4]. The evaluated cross sections were compared with experimental data, the background cross sections were given in the relative sections of File 3.

Table 1 Reaction threshold energies of ^{181}Ta with neutrons

Reaction channels	Threshold energies (MeV)
n,n′	0.006255
n,2n	7.687
n,3n	14.30
n,p	0.2426
n,t	4.867
n, ^3He	6.207
n,d	3.732
n,α	(Q=7.405)
n,n′p	5.969
n,n′ t	11.00
n,n′ ^3He	13.24
n,n′ d	11.16
n,n′ α	(Q=1.534)
n,γ	(Q=6.063)

2 REACTION CROSS SECTIONS

2.1 Total Cross Section

Most of them have been measured with white light neutron source and TOF method since 1970. Recent data were measured by Tsubone(84)[5] from 24.3 keV to 1 MeV, the result was in good agreement with Poenitz(81)[6]. The data measured by Poenitz(83)[7] were from 48 keV to 18 MeV, and an improvement on the data was given on the basis of Ref. [4]. The measured error was nearly 1.0 per–cent. The data measured by Foster(71)[8] Islam(73)[9] and Byoun(73)[10] were recommended also. The uncertainty of them is about 2 to 3 per–cent. When $E_n <$ 1 MeV, a good agreement between our evaluation and JENDL–3 is obtained. The evaluated data of ENDF / B–6 is lower than ours. The evaluated results for $E_n >$1 MeV are shown in Fig 1.

2.2 Elastic and Inelstic Scattering Cross Sections

Because no new experimental data are available, the evaluation was performed on basis of CENDL–1[3]. The evaluated results are shown in Fig. 2. From Fig. 2, it can be seen that ENDF / B–6 is lower than measured values. The recommended data of them are consistent basically with those of JENDL–3.

2.3 (n,2n), (n,3n) Reaction Cross Sections

Recent data were measured by Vesser(77)[11] and Frehaut(80) [12] in the energy range from 14.7 MeV to 24 MeV and 8.44 MeV to 14.76 MeV with errors 5 and 7 per–cent respectively.The evaluated results are shown in the Fig. 3. The recommended data compared with JENDL–3 and ENDF / B–6 are greatly improved.

2.4 Radiative Capture Cross Section

The evaluated results are shown in Fig. 4. When $E_n > 1$ MeV, a better agreement is obtained between the data measured by Xu(90)[13], Xi(88)[14] and Voignier(86)[15] . The data measured by Macklin(84)[16] and Kononov(78)[17] are systematically inconsistent with each other. The evaluated results are shown in the Fig. 4.

2.5 (n,p) Reaction Cross Section

Recent data measured by Woelfle(88)[18] and Lu(82)[19] are well consistent in $E_n < 16$ MeV. When $E_n > 16$ MeV, the difference between Refs. [18] and [19] becomes large. The data measured by Brzosko(69)[20] are systematically higher than above ones and the errors given are 8 to 30 per–cent. The evaluated results are shown in the Fig. 5.

2.6 Other Reaction Cross Sections

For (n, ^{3}He) and (n,α) reactions there is only a value measured by Qaim(74)[21] and Mukherjee(63)[22] at 14 MeV respectively. Therefore for (n,x) reactions (x = t, ^{3}He, d, α) and secondary reactions of them, the recommended data were given by the model calculation.

2.7 Inelastic Scattering Cross Sections for Discrete Levels

The recommended 12 level's parameters are given in the Table 2. The evaluated results and data measured by Smith(67)[23] and Rogers(71)[24] are given in the Fig. 6. Some of the data are normalized to the measured values, and the others calculated with the model code.

Table 2 Discrete level parameters of ^{181}Ta

$U_{J\pi}$ (MeV)	0.0	0.00622	0.1363	0.1585	0.3018	0.3375	0.4822	0.4952
	$7/2^+$	$9/2^-$	$9/2^+$	$11/2^-$	$11/2^+$	$13/2^-$	$5/2^+$	$13/2^+$
$U_{J\pi}$ (MeV)	0.5425	0.6152	0.6191	0.7167	0.9650			
	$15/2^-$	$1/2^+$	$3/2^+$	$16/2^+$	$19/2^+$			

3 ANGULAR DISTRIBUTIONS OF SECONDARY NEUTRONS

For angular distributions of elastic scattering cross section, the data measured by Smith(68)[25], Holmqvist(70)[26] and Cross(60)[27] were recommended respectively. Some of the data were calculated with model code. The evaluated result is shown in Fig. 7.

For angular distributions of inelastic scattering and other reactions, isotropic in the center of mass system is assumed.

4 ENERGY DISTRIBUTIONS OF SECONDRAY NEUTRONS

For (n,n'), (n,2n) and (n,3n) etc., no experimental data of the secondary neutron energy distributions are available, and the calculated data are recommended.

5 CONCLUDING REMARKS

In the present work, the neutron nuclear data of ^{181}Ta are reevaluated on basis of CENDL–1[3]. Due to new experimental data are used and reviewed, previous evaluation was modified. Comparing our evaluated data with JENDL–3 and ENDF / B–6, it can be seen that the total, (n,2n), (n,3n),(n,γ) and (n,p) cross sections are improved; the inelastic scattering cross sections of discrete levels and angular distributions of the elastic scattering are modified more or less; the (n,x) reactions are newly evaluated. The recommended data are given in ENDF / B–5 format and stored in Chinese Evaluated Nuclear Data Library, Version 2 (CENDL–2, MAT = 2730).

ACKNOWLEDGMENTS

The author would like to thank Profs. Yuan Hanrong, Liang Qichang, Cai Dunjiu for their warm support and help of this work. He also thanks Dr. Cai Chonghai and Dr. Ma Gonggui for their help in the calculation.

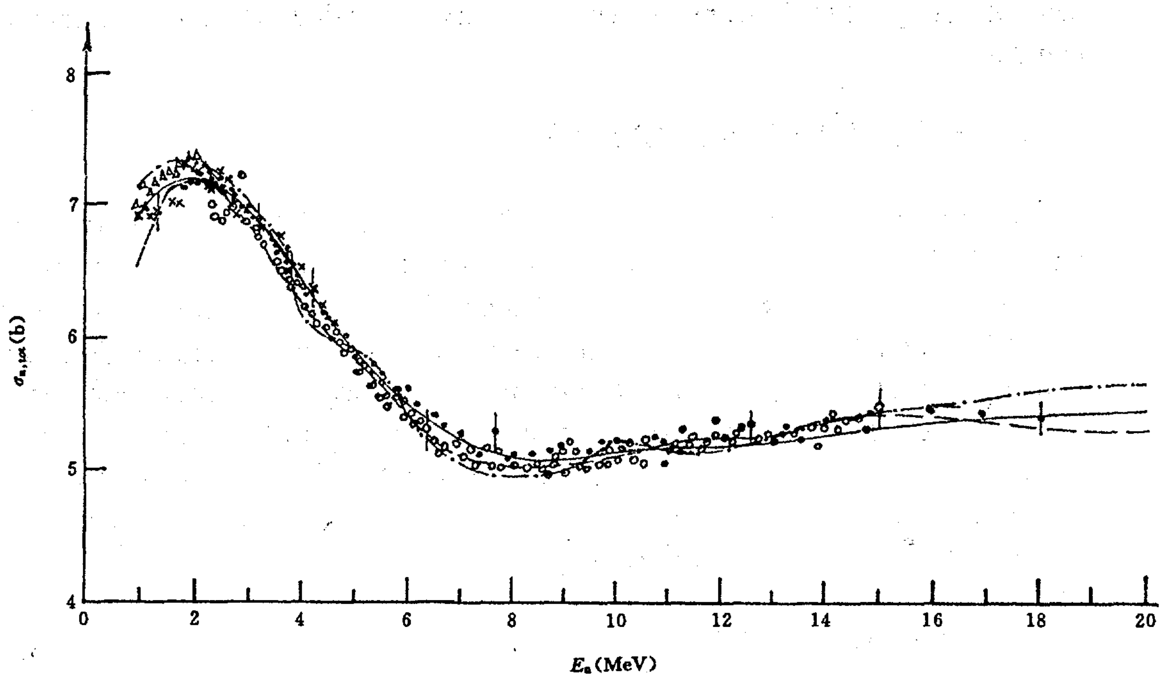

Fig. 1 The comparison between evaluated results with experimental values for total cross sections of ^{181}Ta

× [6] · [7] ○ [8]

—·—·— JENDL-3 - - - ENDF / B-6 ——— Present work

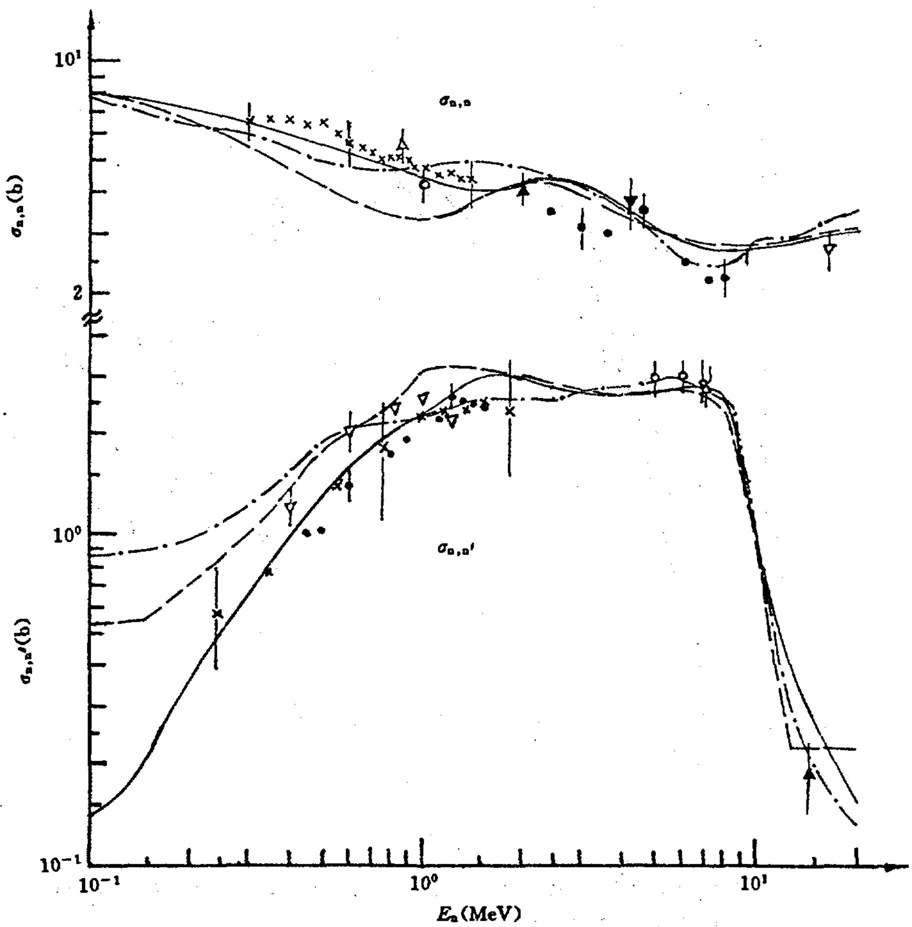

Fig. 2 The comparison between evaluated results with experimental values for elastic and inelastic scattering cross sections of ^{181}Ta

The experimenal values of recommendation were taken from CENDL−1

—·—·— JENDL−3 - - - ENDF / B−6 ——— Present work

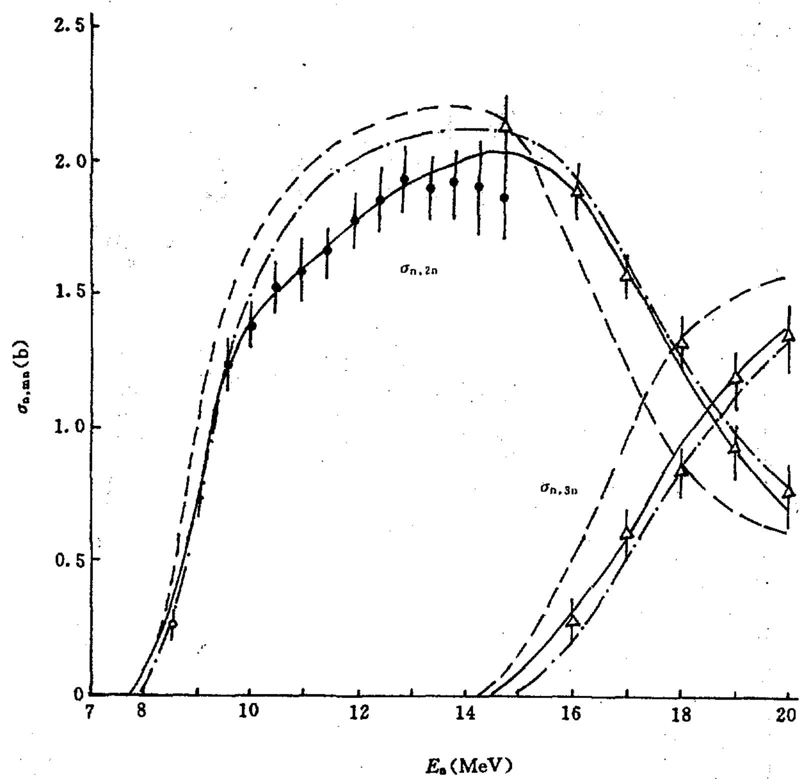

Fig. 3 The comparison between evaluated results with experimental values for $^{181}Ta(n,2n)$, (n,3n) reaction cross sections

△ [11] • [12] —·—·— JENDL–3

– – – ENDF / B–6 ——— Present work

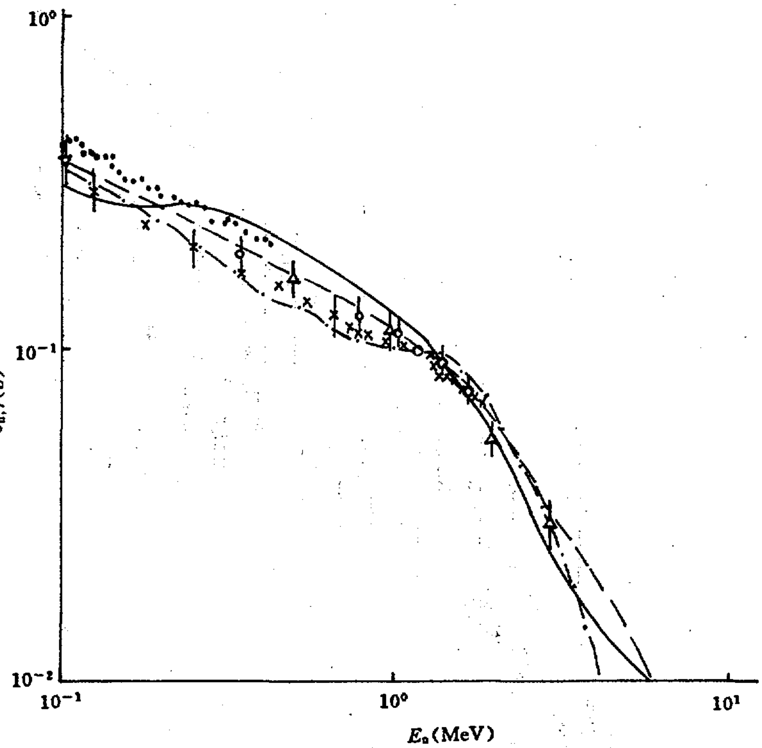

Fig. 4 The comparison between evaluated results with experimental values for $^{181}Ta(n,\gamma)$ reaction cross sections

○ [13] ▽ [14] △ [15] × [16] • [17]

—·—·— JENDL-3 —— ENDF / B-6 ---- Present work

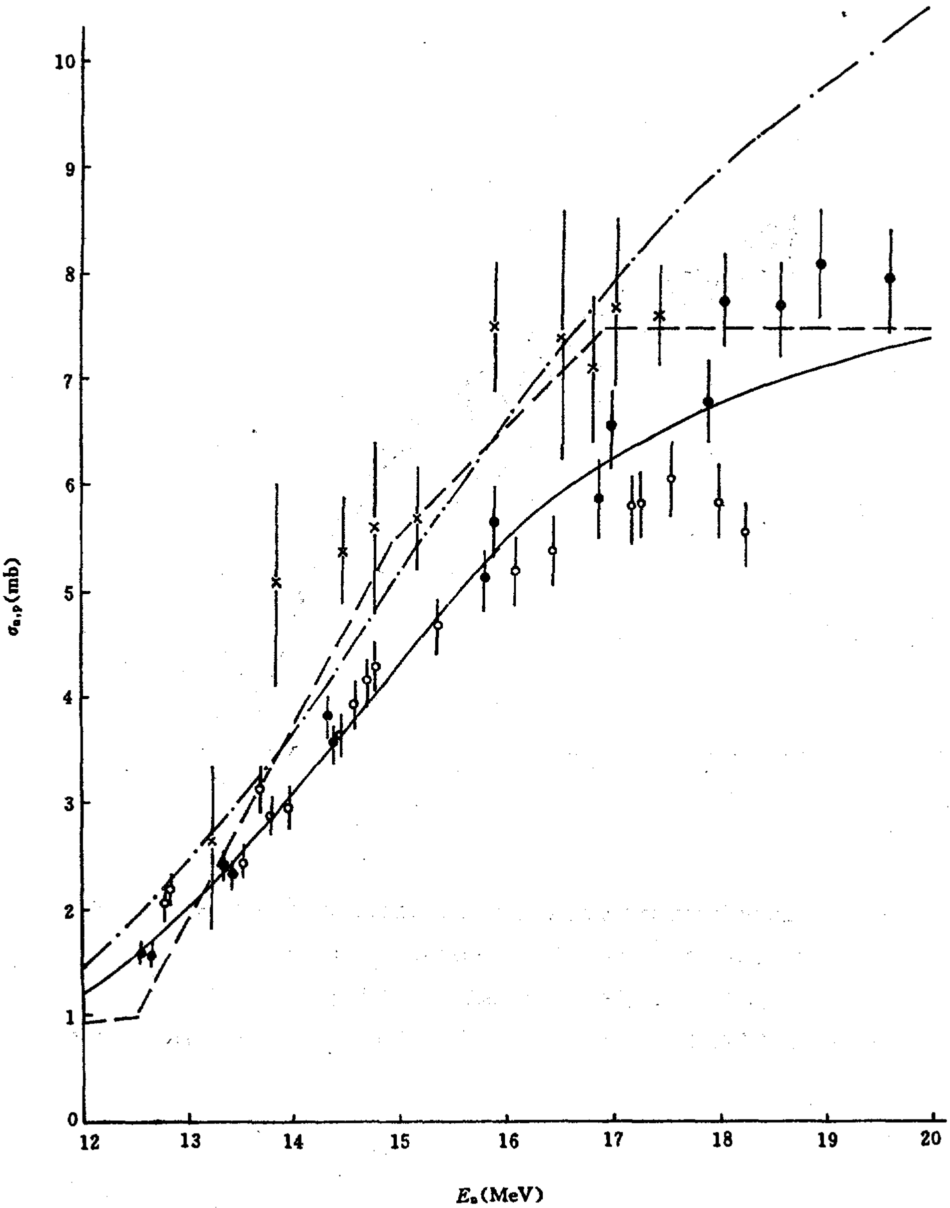

Fig. 5 The comparison between evaluated results with experimental values for $^{181}Ta(n,p)$ reaction cross sections

• [18] ○ [19] × [20]

—·—·— JENDL–3 - - - - ENDF / B–6 ——— Present work

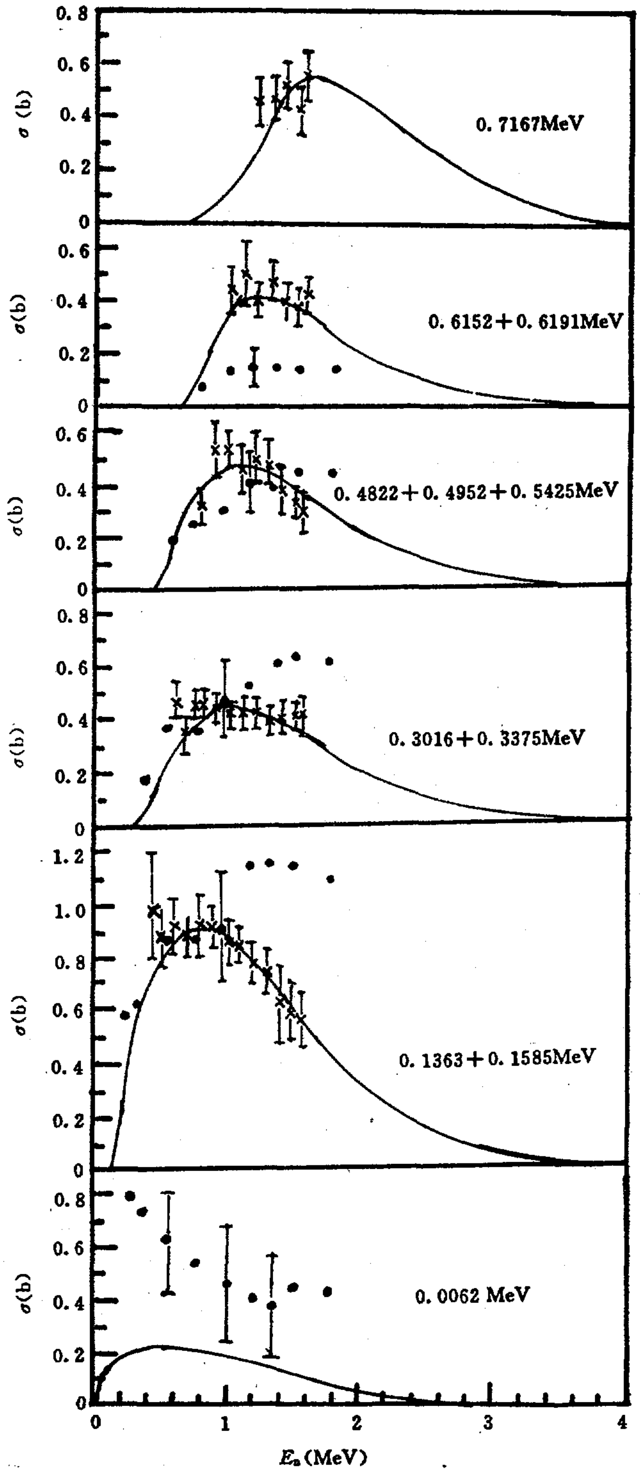

Fig. 6 The comparison between evaluated results with experimental values of the inelastic scattering cross sections to discrete levels for ^{181}Ta

• [23] × [24] ——— Present work

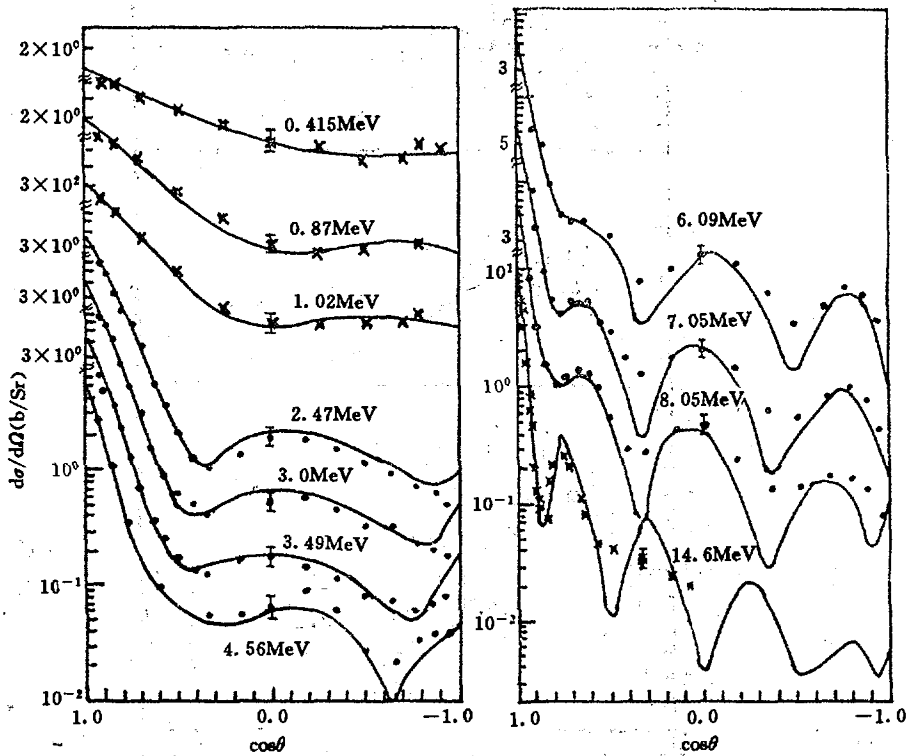

Fig. 7 The comparison between evaluated results with experimental values of the elastic scattering angular distributions for ^{181}Ta

× [25] • [26] ✱ [27] ——— Present work

REFERENCES

[1] Zhou Hongmo et al., AUJP (CNDC−0011) (1989)

[2] Cai Chonghai et al., MUP2 (CNDC−0013) (1989)

[3] Yao Lishan, CENDL−1, MAT = 1800, 228(1986)

[4] N. Yamamuro, JENDL−3, MAT = 3731, 323(1990)

[5] I. Tsubone et al., Nucl. Sci. Eng., 88, 579(1984)

[6] W. P. Poenitz et al., Nucl. Sci. Eng., 78, 333(1981)

[7] W. P. Poenitz et al., ANL−NDM−80(1983)

[8] D. G. Foster et al., Phys. Rev., C−3, 576(1971)

[9] E. Islam et al., Nucl. Phys., A−209, 189(1973)

[10] T. Y. Byoun et al., COO−3058−34, 7(1973)

[11] L. R. Vesser et al., Phys. Rev., C−16, 1792(1977)

[12] J. Frehaut et al., Proc. Symp. on Neutron Cross Sections for 10 ~ 50 MeV, BNL, Upton, N. Y., 12 ~ 14 May 1980, 399(1980)

[13] Xu Haishan et al., High Energy Phys. & Nucl. Phys., 14, 340(1990)

[14] Xia Yijun et al., INDC(CPR)−011 / GI, 145(1988)

[15] J. Voignier et al., Nucl. Sci. Eng., 93, 43(1986)

[16] R. L. Macklin, Nucl. Sci. Eng., 86, 362(1984)

[17] V. N. Kononov et al., Jadernaja Fizika, 27, 10(1978)

[18] R. Woelfle et al., Appl. Radiat. Isot., 39, 407(1988)

[19] Lu Hanlin et al., Chin. Nucl. Phys., 4, 272(1982)

[20] J. S. Brzosko et al., Nucl. Phys., A−123, 603(1969)

[21] S. M. Qaim et al., J. Inorg. Nucl. Chem., 36, 239(1974)

[22] S. K. Mukherjee et al., Proc. Symp. on Nucl. Phys. & , Solid State Physics, Bombay, 27 Feb ~ 2 March 1963, 244(1963)

[23] A. B. Smith et al., ANL−7363(1967)

[24] V. C. Rogers et al., Nucl. Sci. Eng., 45, 297(1971)

[25] A. B. Smith et al., Phys. Rev., 168, 1344(1968)

[26] B. Holmqvist et al., AE−430(1970)

[27] W. G. Cross et al., Nucl. Phys., 15, 155(1960)

NEUTRON DATA THEORETICAL CALCULATION AND EVALUATION FOR NATURAL TUNGSTEN

Ma Gonggui Wang Shiming Zou Yiming

(INSTITUTE OF NUCLEAR SCIENCE AND TECHNOLOGY
OF SICHUAN UNIVERSITY, CHENGDU)

ABSTRACT

The neutron nuclear data of natural tungsten were evaluated and recommended for reaction channels of total, elastic, inelastic, nonelastic , radiation capture, (n,p), (n,n′p), (n,2n), and (n,3n) in the energy range of 10^{-5} eV to 20 MeV. The experimental data were selected up to 1988. This evaluation work is on the basis of CENDL–1[1] . For theoretical calculation the program AUJP[2] and MUP–2[3] were used.

INTRODUCTION

Natural tungsten is nuclear structure material. Therefore the neutron nuclear data of natural tungsten are important for improvement of reactor design.

Except the total cross section, in recent years a lot of new experimental data for elastic, inelastic, nonelastic, radiation capture, charge particle, (n,2n) and (n,3n) cross sections have been available,so the evaluation has been greatly improved for natural tungsten.

All cross sections were calculated using the programs AUJP and MUP2. The calculated data also include angular distributions of elastic, inelastic, (n,n′p) reactions and energy distribution of secondary neutrons of (n,2n) (n,3n), (n,n′p) reactions and inelastic continuum excitation.

Some measured data were used for adjusting the model parameters. All data were recommended in ENDF / B–5 format. The discrete levels of tungsten are listed in Table 1.

Table 1 Disctete levels of tungsten (Abundance %)

^{182}W (26.3)		^{183}W (14.3)		^{184}W (30.7)		^{186}W (28.7)	
level (MeV)	spin parity	level (MeV)	spin parity	level (MeV)	spin parity	level (MeV)	spin parity
0.1001	2^+	0.0465	$3/2^-$	0.1112	2^+	0.1223	2^+
0.3294	4^+	0.0991	$5/2^-$	0.3641	4^+	0.3965	4^+
0.6805	6^+	0.207	$7/2^-$	0.69	0^+	0.7375	2^+
		0.2088	$3/2^-$	0.7483	6^+	0.8085	6^+
		0.2917	$5/2^-$	0.9033	2^+	0.8618	(3^+)
						0.882	0^+
						0.9524	(2^-)

1 TOTAL CROSS SECTION

Since 1975 most of the total cross sections have been measured with white light neutron source and TOF method.There are structures below the energy range 10 keV.In the energy range of 10^{-4} to 0.1 eV and 0.1 eV to 100 keV evaluated data of ENDL / 84 and UNC−509 were adopted respectively. In the energy range of 100 keV to 20 MeV, the experimental data fitted with spline function[4] were taken as recommended one. In the energy range of 10^{-5} to 10^{-4} eV, the data were extrapolated one.

2 CAPTURE CROSS SECTION

The evaluated data from 100 keV to 4 MeV have obviously been improved, because the new measured data of Xiang[5], Macklin[6], Poenitz[7], Joly[8], Fricke[9] and Budnar[10] were used (Fig. 1).

3 (n,2n), (n,3n) REACTION CROSS SECTION

For (n,2n) reaction, the newer data were measured by Frehaut[11] and Veeser[12] in the energy range from 7.9 to 14.8 MeV and 14.7 to 20 MeV, respectively. For (n,3n) reaction, new data were measured by Veeser[12] in the energy range from 14.7 to 20 MeV. Based on these new data, the evaluated data were greatly improved (Fig. 2).

4 INELASTIC SCATTERING CROSS SECTION

The cross sections of inelastic scattering to 20 discrete levels were calculated with MUP2 code, and they were normalized to the experimental data of Lister[13] and Guenther[14] in the energy range below 3.5 MeV (Fig. 3).

5 OTHER REACTIONS

For other reactions, there are also some new measured data : Begum[15] for angular distribution of elastic scattering (Fig. 4), Pai[16] for nonelastic and Qaim[17] for (n,p) and (n,n′p) reactions. The theoretical curves calculated by using MUP2 code were normalized to Qaim′s data at 14.7 MeV.

6 THEORETICAL CALCULATION

The data for tungsten were calculated in the energy range from 1 keV to 20 MeV with program AUJP[2] based on optical model and the program MUP2 based on optical model, H–F theory with width fluctuation correction and the unified theatment of exciton model and evaporation model. The comparison between calculated and measured data is given in the Table 2..

Table 2 The comparison between calculated and measured data

(MeV)	σ_{tot}			$\sigma_{n,n}$			σ_{non}		
	theo.	eval.	* x %	theo.	eval.	* x %	theo.	eval.	* x %
1.8	7.022	7.001	0.3	4.687	4.361	7.47	2.335	2.64	11.53
2.2	6.968	7.103	1.3	4.537	4.433	2.36	2.431	2.67	8.97
2.6	6.865	7.115	3.5	4.38	4.445	1.46	2.485	2.67	6.93
3.0	6.723	7.001	3.97	4.213	4.351	3.18	2.510	2.65	5.26
3.6	6.469	6.746	4.1	3.845	4.136	4.6	2.524	2.61	3.307
4.0	6.291	6.491	3.07	3.760	3.901	3.6	2.531	3.59	2.28
4.92	5.903	6.011	1.8	3.346	3.463	3.36	2.556	2.548	0.318
6.599	5.348	5.345	0.06	2.788	2.823	1.24	2.550	2.522	1.53
7.452	5.170	5.154	0.32	2.627	2.645	0.69	2.554	2.509	1.38
8.56	5.045	5.055	0.2	2.523	2.569	1.78	2.521	2.486	1.42
10.0	5.023	5.099	1.49	2.524	2.634	4.16	2.498	2.465	1.36
12.0	5.143	5.215	1.38	2.676	2.772	3.45	2.466	2.443	0.96
14.1	5.039	5.354	0.85	2.892	2.955	2.19	2.417	2.399	0.75
16.0	5.408	5.423	0.27	3.05	3.063	0.41	2.358	2.36	0.1
18.0	5.467	5.382	1.57	3.158	3.062	3.14	2.309	2.32	0.49
20.0	5.521	5.303	4.12	3.23	3.023	6.86	2.291	2.28	0.49

* $x = |\text{theo.} - \text{eval.}| / \text{eval.} \times 100$

The main parameters used are as follows :

(1) Optical potentical parameters (MeV or fm) :

$A_r = A_{so} = 0.322$ $\quad V_0 = 47.655$

$A_s = A_v = 0.681$ $\quad V_1 = -0.237$

$X_r = X_{so} = 1.307$ $\quad V_2 = 0.011$

$X_s = X_v = 1.265$ $\quad V_3 = -24.0$

$X_c = 1.25$ $\quad V_4 = 0.0$

$U_0 = -0.187$ $\quad W_0 = 8.806$

$U_1 = 0.032$ $\quad W_1 = -0.111$

$V_{so} = 6.2$ $\quad W_2 = 0.0$

(2) Level density parameters, they are given in Table 3.

Table 3 Level density parameters *

^{182}W				^{183}W			
P(z)	P(n)	S(z)	S(n)	P(z)	P(n)	S(z)	S(n)
0.69	0.0	−7.3	6.94	0.69	0.75	−7.3	6.55
0.0	0.75	−7.24	6.96	0.0	0.0	−7.24	6.94
0.68	0.0	−7.45	7.15	0.68	0.75	−7.45	6.96
0.0	0.5	−7.9	7.35	0.0	0.0	−7.9	7.15
0.68	0.0	−8.13	7.4	0.68	0.5	−8.13	7.35
^{184}W				^{186}W			
P(z)	P(n)	S(z)	S(n)	P(z)	P(n)	S(z)	S(n)
0.69	0.0	−7.3	6.72	0.69	0.0	−7.30	6.69
0.0	0.75	−7.24	6.55	0.0	0.86	−7.24	6.49
0.68	0.0	−7.45	6.94	0.68	0.0	−7.45	6.72
0.0	0.75	−7.9	6.96	0.0	0.75	−7.9	6.55
0.68	0.0	−8.13	7.15	0.68	0.0	−8.13	6.94

* The level density formula of Ref. [18] was used.

7 CONCLUDING REMARK

This evaluation is for CENDL-2 and based on CENDL-1[1]. Because the new experimental data are available in recent years, the evaluated data have been considerably improved, especially for cross sections of (n,2n), (n,3n), (n,γ) reactions and inelastic scattering to some discrete levels.

The authors wish to thank Profs. Liang Qichang and Liu Tingjin for their much help with this work. We also thank Dr. Cai Chonghai for his help in the calculation.

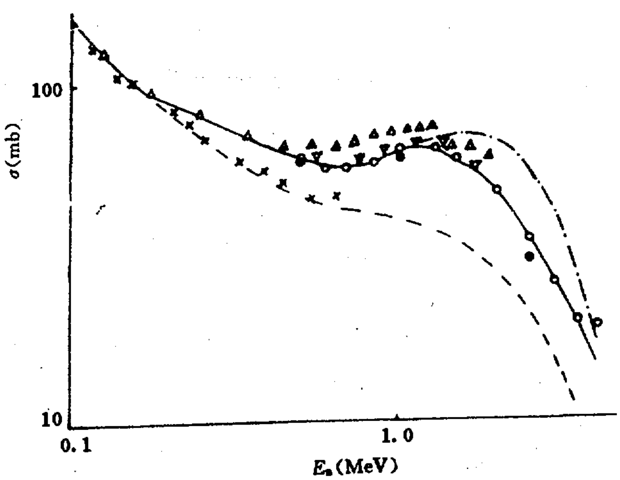

Fig. 1 Evaluated capture cross section

▽ Xiang Zhengyu (1986); △ Mackl in (1983); ○ Poenttz (1982); • Joly (1980); × Fricke (1970); ——— This work; —•— Theo. calculation; - - - CENDL-1 (1978)

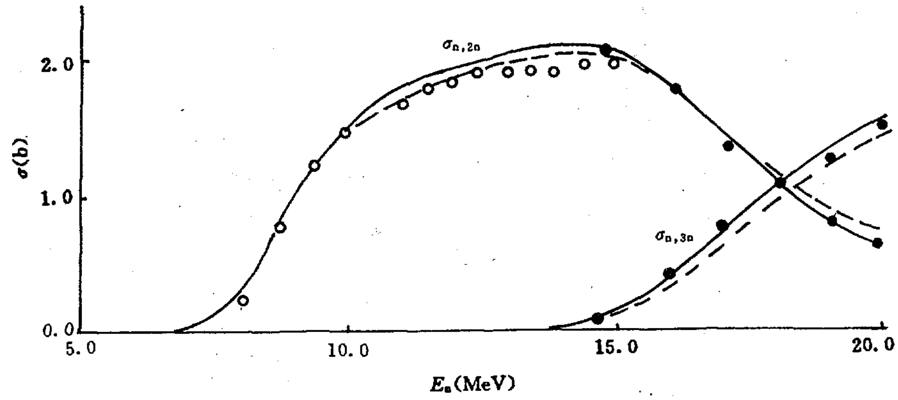

Fig. 2 Evaluated (n,2n) and (n,3n) cross section

○ Frehaut (1980); • Veeser (1981); --- ENDF / B-6; —— This work

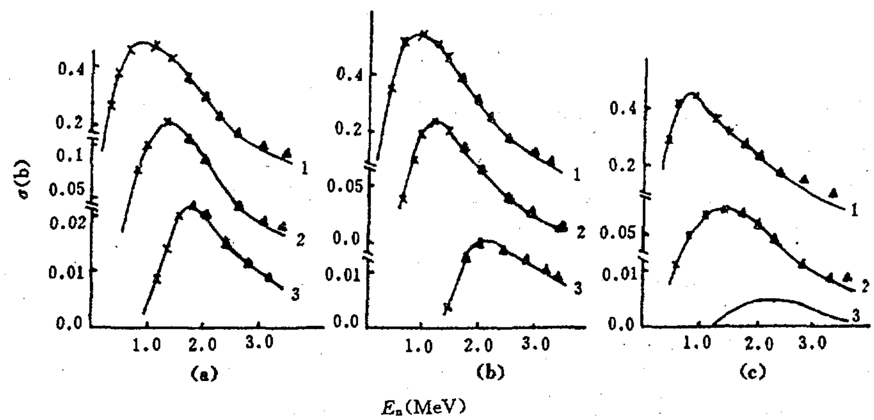

Fig. 3 Evaluated inelastic excitation cross sections

× Lister (1967); △ Guenther (1982); —— This work

a: 1. 0.1001 MeV (2^+)	b: 1. 0.1112 MeV (2^+)	c: 1. 0.1223 MeV (2^+)
2. 0.3294 MeV (4^+)	2. 0.3641 MeV (4^+)	2. 0.3965 MeV (4^+)
3. 0.6805 MeV (6^+)	3. 0.7483 MeV (6^+)	3. 0.8085 MeV (6^+)
^{182}W	^{184}W	^{186}W

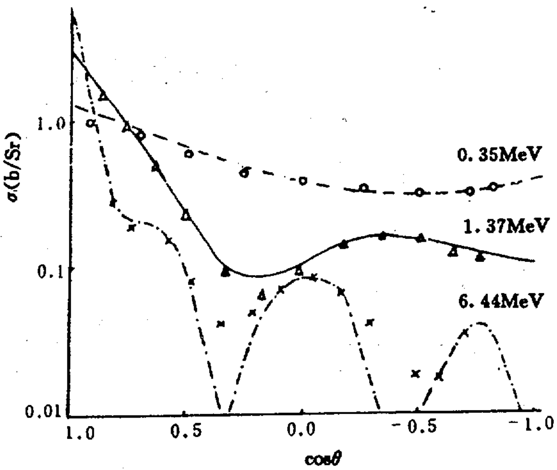

Fig. 4 The evaluated angular distributions for elastic scattering

○ Smith (1960); ▲ Tsukada (1969); × Kinney (1973);

—— ; —·— ; ---- This work

REFERENCES

[1] Ma Gonggui, Chinese Evaluated Nuclear Data Library, Version 1, P. 233, CNDC–85010, (1986)

[2] Zhou Hongmo Yu Ziqiang et al., Auto–paramete adjusting optical model calculation program AUJP, inter report (1986)

[3] Yu Ziqiang Cai Chonghai et al., Theoretical calculation program MUP2 for medium and heavy nuclear, inter report (1986)

[4] GuYifan, Total cross section evaluation of nature Tungsten , inter report (1978)

[5] Xiang Zhengyu et al., High Energy Physics and Nuclear Physics, 12, 1(1988)

[6] R. L. Macklin, Nucl. Sci. & Eng., 84, 98(1983)

[7] W. P. Poenitz, ANL–83–4, 239(1982)

[8] S. Joly, CEA–R–5089 (1981)

[9] M. P. Fricke, BNL–50276, 68(1970)

[10] M. Budnar, INDC(YUG)–6 (1979)

[11] J. Frehaut, EXFOR 20416(1980)

[12] L. R. Veeser, LA–9468–PR (1982)

[13] D. Lister, Phys. Rev., 162, 1077(1967)

[14] P. T. Guenther, Phys. Rev., C26, 2433(1982)

[15] A. Begum, Nucl. Sci. and Appli. / B, 12+13 (1981)
[16] Pai, Nucl. Instru. Method, 171, 347(1980)
[17] S. M. Qaim, Nucl. Phys., A242, 317(1975) and A382, 255(1982)
[18] Su Zongdi et al., A new set of level density parameters for Fermi Gas model, inter report (1984)

NEUTRON DATA EVALUATION OF ^{197}Au

Yuan Hanrong Wang Shunuan Yan Shiwei Liu Tong

(CHINESE NUCLEAR DATA CENTER, IAE)

GENERAL DISCRIPTION

The evaluation of all neutron data of ^{197}Au above the resonance region has been carried out on the basis of experimental measured data and theoretical calculations, and joined with the ENDF / B–6 resolved resonance region evaluation to compose the complete set of evaluated data for CENDL–2. It includes the neutron data for files 1~5 in ENDF / B–4 format in the neutron energy region from 10^{-5} eV to 20 MeV .

The experimental data available up to 1990 are collected, reviewed and fitted separately in accordance with the distinct reaction channels. Some of them are renormalized using the new standard and reference data. In the light of experimental data the optical potential parameters are adjusted and the theoretical calculation is performed. Then, on the basis of the comparisons of the calculated data with the measured data some of the calculated data are replaced by the experimental fitted data. Finally, a unified adjustment of the adopted data (including the calculated and fitted data) is carried out and the evaluated data are obtained. .

1 THEORETICAL CALCULATION

The data for files 3 ~ 5, in the neutron energy region from 5 keV to 20 MeV have been calculated with an automatically adjusted optical potential parameter code AUJP[1] and a unified theoretical calculation code for medium–heavy nuclei MUP–2N[2]. The AUJP code, as the term suggests, is used in searching for automatically a set of optimum neutron spherical optical potential parameters. In MUP−2N code the optical model is used to calculate the neutron transmission coefficients and total, elastic, nonelastic cross sections and elastic scattering angular distributions. The width fluctuation corrected Hauser−Feshbach (WHF) formula and a unified pre−equilibrium statistical theory based on exciton model and evaporation model (PE) have been used to calculate the quantities as those of (n,γ), (n,n′) (for leaving in isolated and continuous states of the residual nucleus respectively), (n,2n),(n,3n), (n,x), (n,nx) (x being p, d, t, ^{3}He, ^{4}He) cross sections, angular distributions of (n,2n), (n,3n), (n,n′x) reactions and (n,n′) reaction for leaving in isolated and continuous states, secondary neutron energy spectra of (n,2n), (n,3n), (n,n′x) reactions and (n,n′) reaction for leaving in the continuous state of the residual nucleus. All charged particle optical model parameters are taken from Refs. [3, 4] and readjusted slightly for reproducing the experimental data for each reactions. Besides, the formation and emission of the composite particles based on Fermi gas model are also considered in MUP−2N code. More details on data calculation and its calculated results are given in Ref. [5].

In general, the agreements between the measured and calculated data are satisfactory. However, in the energy region from 18 to 20 MeV the calculated (n,2n) cross section is higher than the experimental data by about 0.5 b, and (n,3n) cross section is lower than experimental data by about 0.5 b. The reason for this seems that in the evaluation of (n,3n) cross section the neutron optical potential parameters used are the same as those of incident neutron on ^{197}Au obtained by AUJP code, which give rather small inverse cross section for the third neutron emission. The discrepancy remained in reaction cross sections in high energy region may be improved also by taking into account the direct reaction mechanism .

2 DATA EVALUATION AND UNIFIED ADJUSTMENT

2.1. Neutron Resonance Parameters

In consideration of that no more data for neutron resonance parameters available after the evaluation for ENDF / B−6, the ENDF / B−6 resonance region evaluation is adopted for CENDL−2.

2.2 Smooth Neutron Cross Sections

Total cross section. Experimental fitted data are used. There are 16 experimental data sets available. Among them 9 data sets are selected and used for fitting. They are the experimental data given by Poenitz (83)[6], Poenitz (81)[7], Foster (71)[8], Whalen (66)[9], Seth (65)[10], Day (65)[11], Peterson (60)[12], Bratenahl(58)[13], and Conner (58)[14]. The fitted data closely approximate the theoretical results.

Elastic scattering cross section. Difference of total cross section and nonelastic cross sections is used. The evaluated data closely approximate the theoretical results and in agreement with the measured data [15~21].

Nonelastic cross section. Sum of all reaction cross sections, except elastic scattering, is used. The evaluated data are in good agreement with the experimental data [16, 18, 22~27].

Inelastic scattering cross section. Sum of all inelastic cross sections for discrete levels and continuous states is used. The evaluated data are in good agreement with the experimental data [28~30].

(n,2n) cross section. Experimental fitted data are used. There are more than 30 experimental data sets available for this reaction cross section. Twenty of them [31~50] are accepted in this evaluation for fitting. All the data accepted were published in seventies and eighties. Some of the data accepted are renormalized using the decay schemes given by Browne (86)[51].

(n,3n) cross section. Experimental fitted data are used. The experimental data from Refs. [44, 45] are used for fitting.

Inelastic scattering cross section to levels and inelastic scattering continuum cross section. The data from theoretical calculation are used.

(n,γ) cross section.The ENDF / B–6 data are adopted. As we know, this is a standard cross section for thermal and 200 keV ~ 2.5 MeV neutrons. Adopting the common standard cross section data is appropriate. Furthermore, the ENDF / B–6 data for (n,γ) cross section of ^{197}Au are quite good in agreement with the measured data even in the higher energy region [52~61].

(n,p) cross section. The experimental data from Refs. [62 ,63] are used for fitting.

(n, α) cross section. The data from theoretical calculation are used. They closely approximate experimental data [62~64].

(n,d), (n,t), (n, ^{3}He) cross section. The data from theoretical calculations are used.

(n,n$'\alpha$), (n.n$'$p), (n,n$'$d), (n,n$'$t) cross section . The data from theoretical calculations are used .

Figs. 1~ 9 show the comparisons of the evaluated and measured data for total, elastic scattering, nonelastic scattering, inelastic scattering, (n,2n), (n,3n), (n,γ), (n,p), and (n,α) cross sectins of ^{197}Au respectively. Figs. 10~ 13 show the evaluated data for (n,n$'\alpha$), (n,n$'$p), (n,n$'$d) and (n,n$'$t) cross sections of ^{197}Au respectively and Fig. 14 shows the evaluated neutron cross sections of ^{197}Au as a whole.

2.3 Neutron Angular Distributions

Legendre coefficients for elastic scattering, (n,2n), (n,3n), (n,n′α), (n,n′p), (n,n′d), (n,n′t) reactions and inelastic scattering for discrete levels and continuous states are obtained from MUP–2N calculation. By way of example, Figs. 15~ 19 show the comparisons of the evaluated and measured data for elastic scattering angular distributions of ^{197}Au for 0.5, 1.0, 2.5, 7.0 and 14.6 MeV respectively. The measured data shown in the figures are those of Allen (56)[18], Day (65)[65], Walt (54)[17], Etemad (73)[20] and Hansen (85)[66].

2.4 Neutron Energy Distributions

Tabulated neutron energy distributions for (n,2n), (n,3n), (n,n′α), (n,n′p), (n,n′d), (n,n′t) reactions and inelastic scattering to continuous state are obtained from MUP–2N calculation.

3 CONCLUSION

From the figures given above we can see that the present evaluated data are, in general, in good agreement with the measured data and most of them are in good agreement with the ENDF / B–6 data. The main difference between present evaluated data and ENDF / B–6 data is that the ENDF / B–6 data for (n,2n) cross section are higher systematically than present data by about 10% above 16 MeV. It should be noted that the theoretical calculated data for (n,2n) cross section are used in ENDF / B–6 while the experimental fitted data are used in present evaluation.

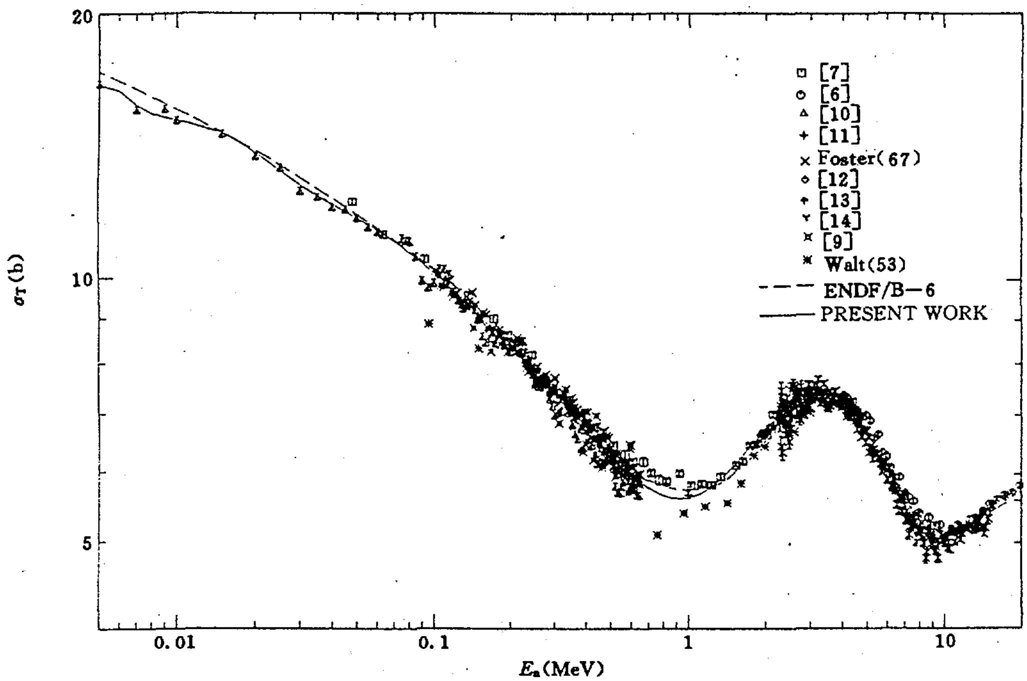

Fig. 1 Comparison of evaluated and measured data for total cross section of ^{197}Au

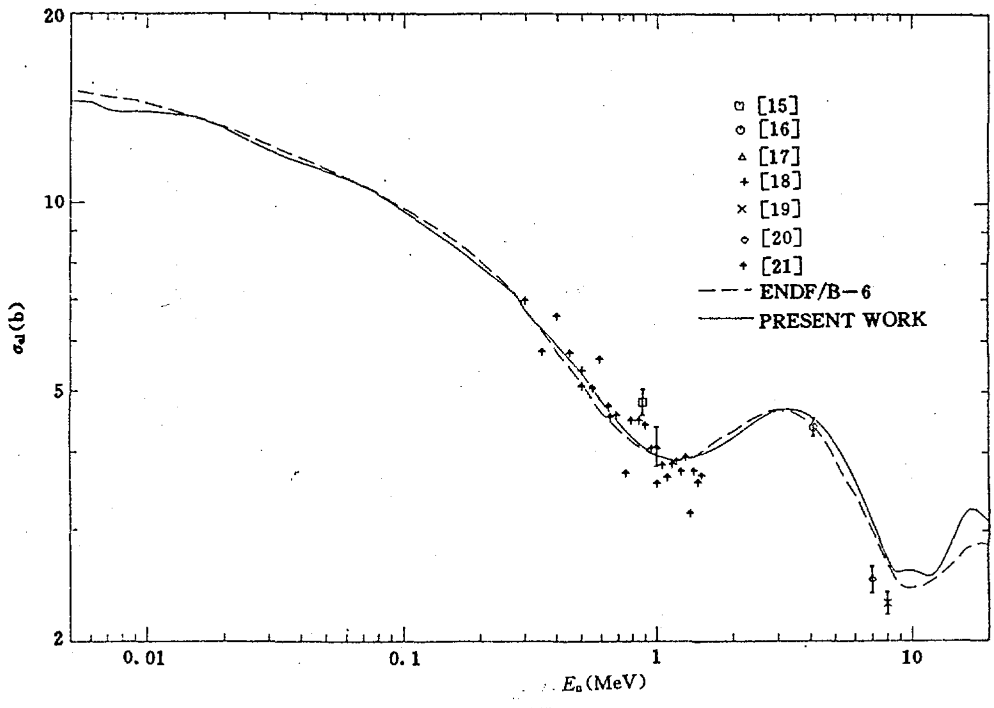

Fig. 2 Comparison of evaluated and measured data for elastic scattering cross section of ^{197}Au

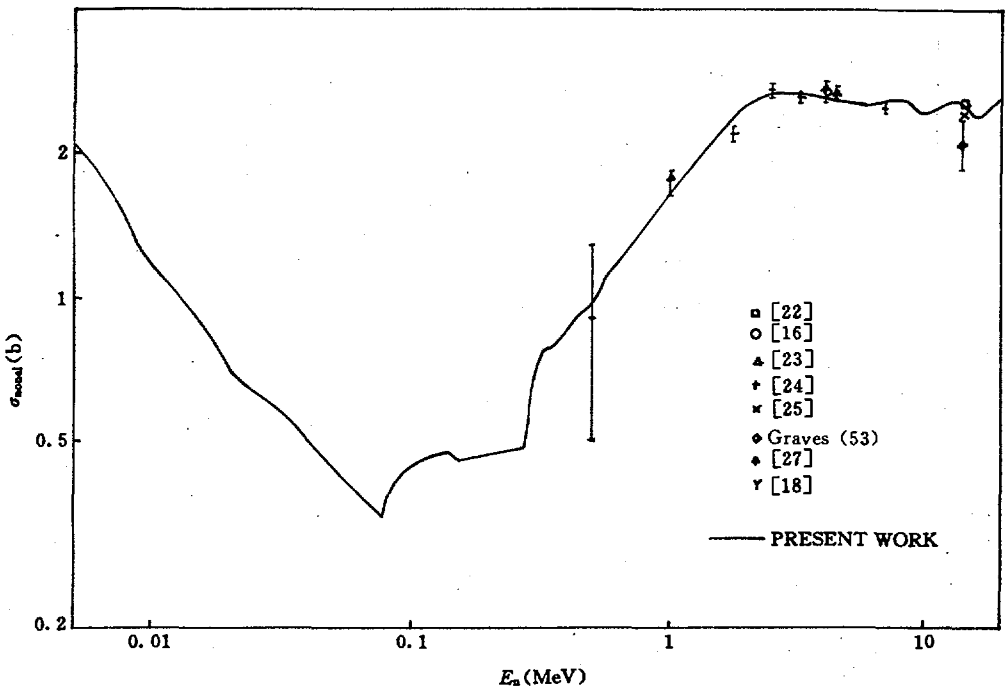

Fig. 3 Comparison of evaluated and measured data for nonelastic cross section of ^{197}Au

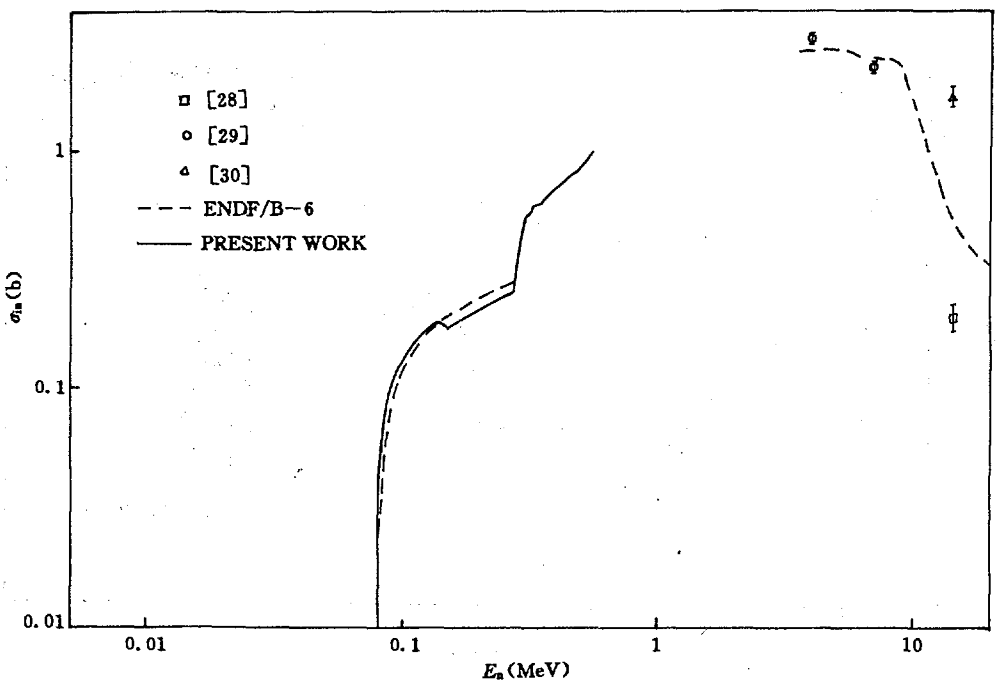

Fig. 4 Comparison of evaluated and measured data for inelastic scattering cross section of ^{197}Au

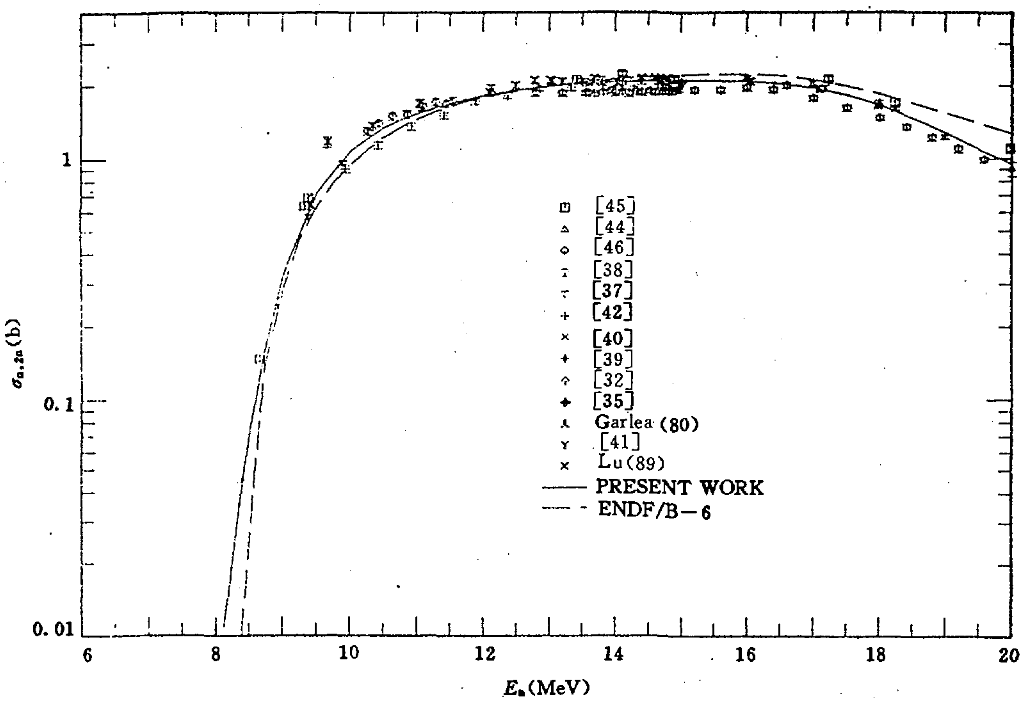

Fig. 5 Comparison of evaluated and measured data for (n,2n) cross section of ^{197}Au

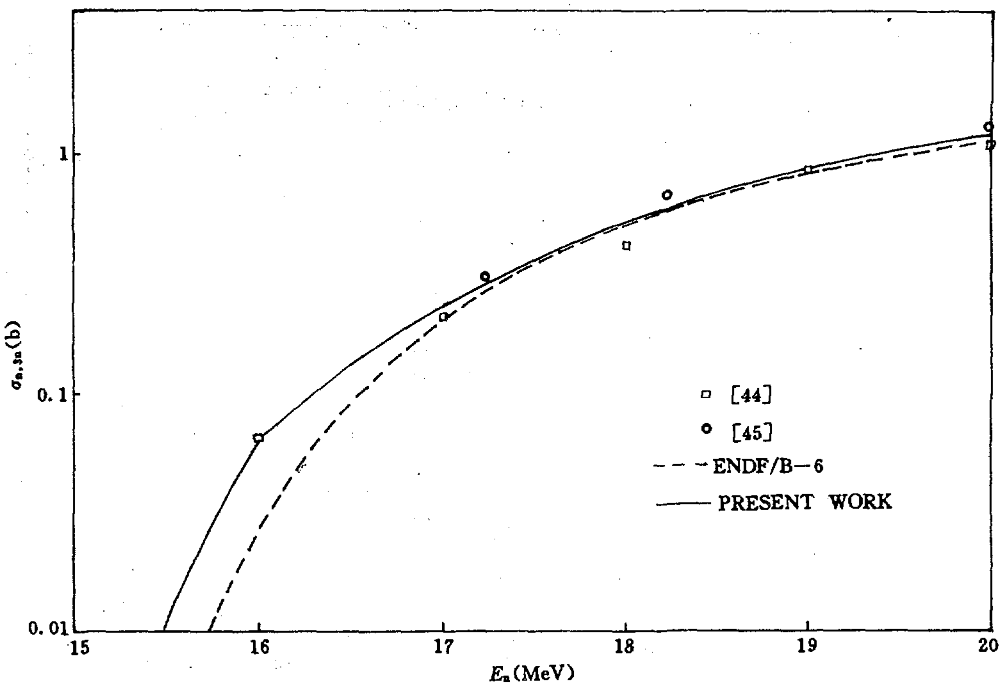

Fig. 6 Comparison of evaluated and measured data for (n,3n) cross section of ^{197}Au

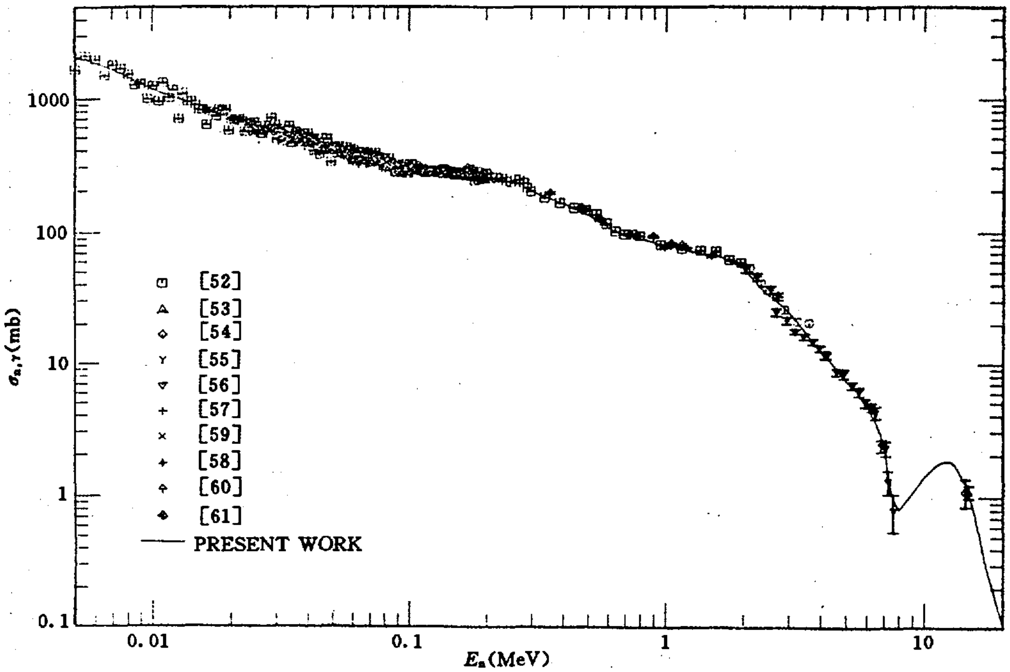

Fig. 7 Comparison of evaluated and measured data for (n,γ) cross section of ^{197}Au

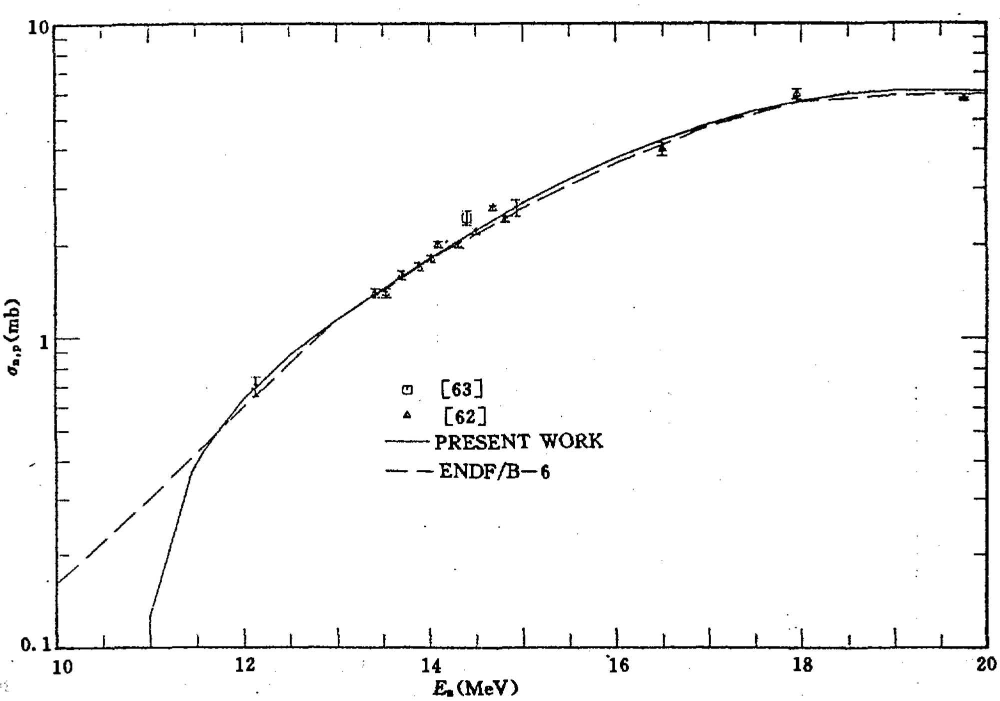

Fig. 8 Comparison of evaluated and measured data for (n,p) cross section of ^{197}Au

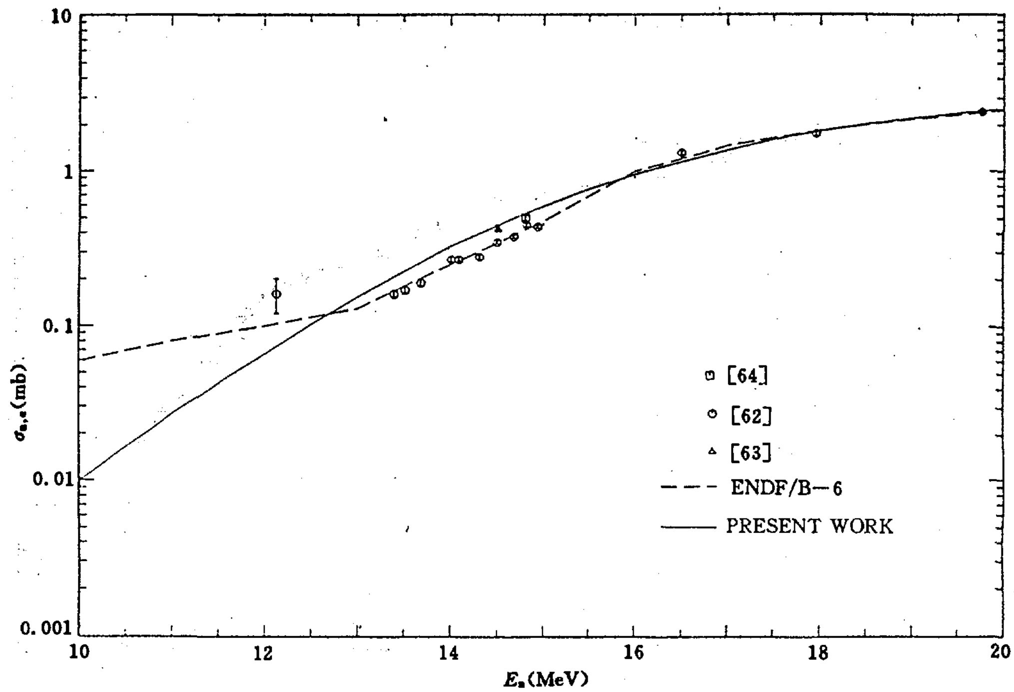

Fig. 9 Comparison of evaluated and measured data for (n,α) cross section of ^{197}Au

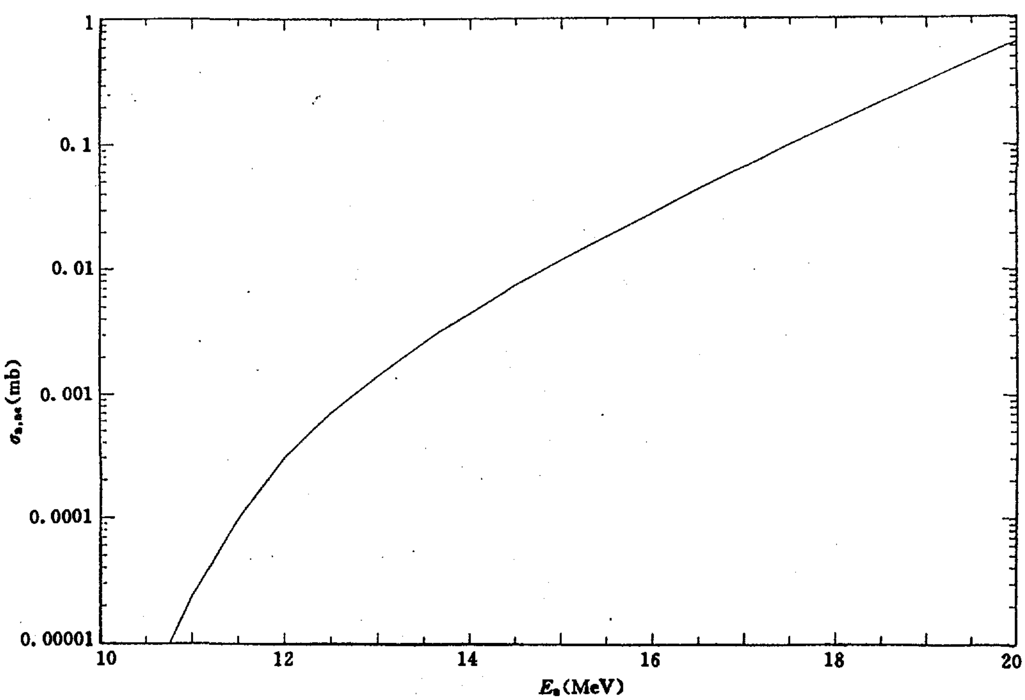

Fig. 10 Evaluated data for (n,n′α) cross section of ^{197}Au

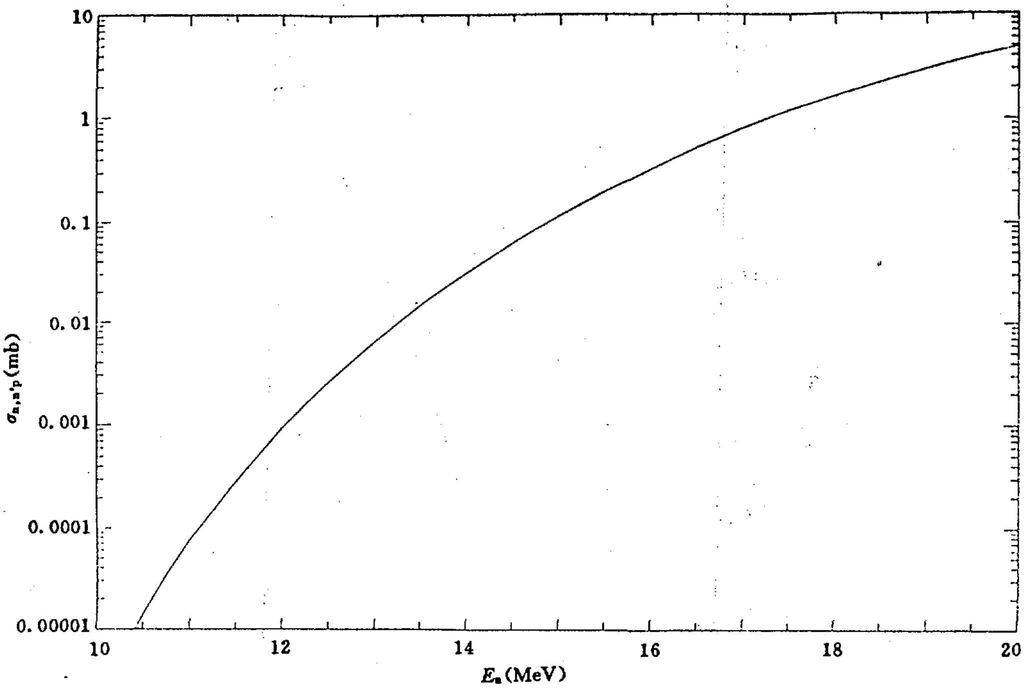

Fig. 11 Evaluated data for (n,n′p) cross section of ^{197}Au

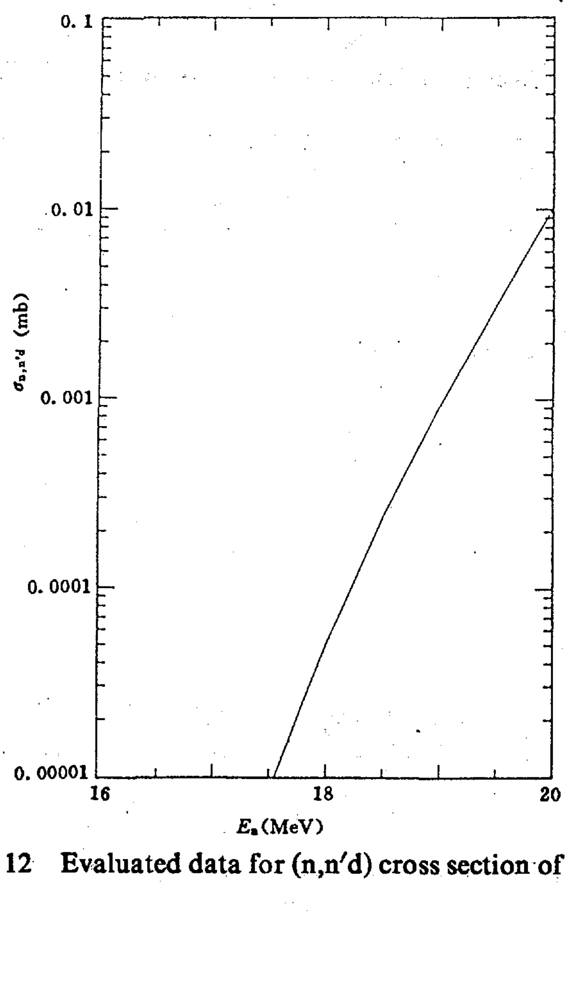

Fig. 12 Evaluated data for (n,n′d) cross section of ^{197}Au

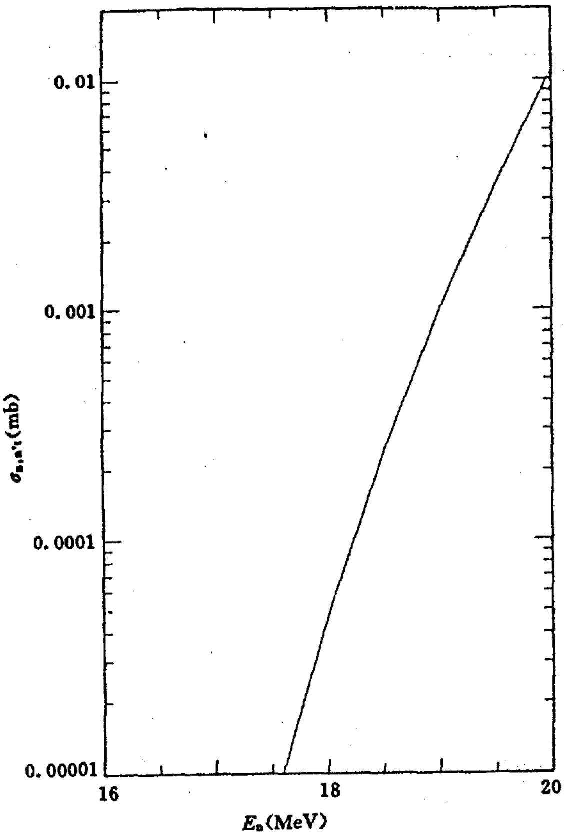

Fig. 13 Evaluated data for (n,n′t) cross section of ^{197}Au

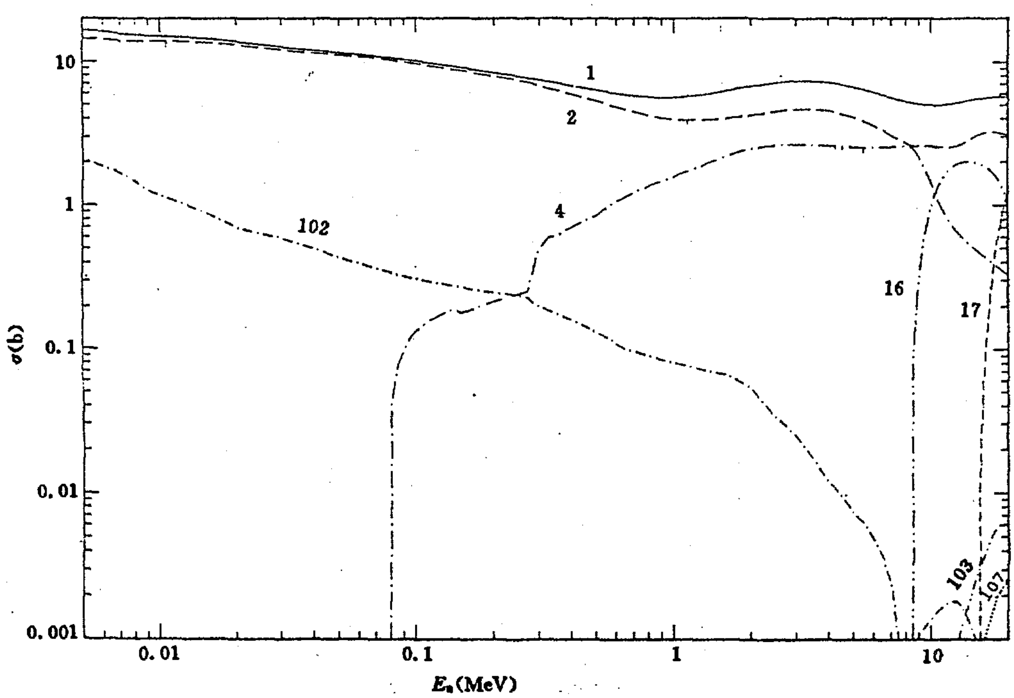

Fig. 14 Evaluated neutron cross section of ^{197}Au

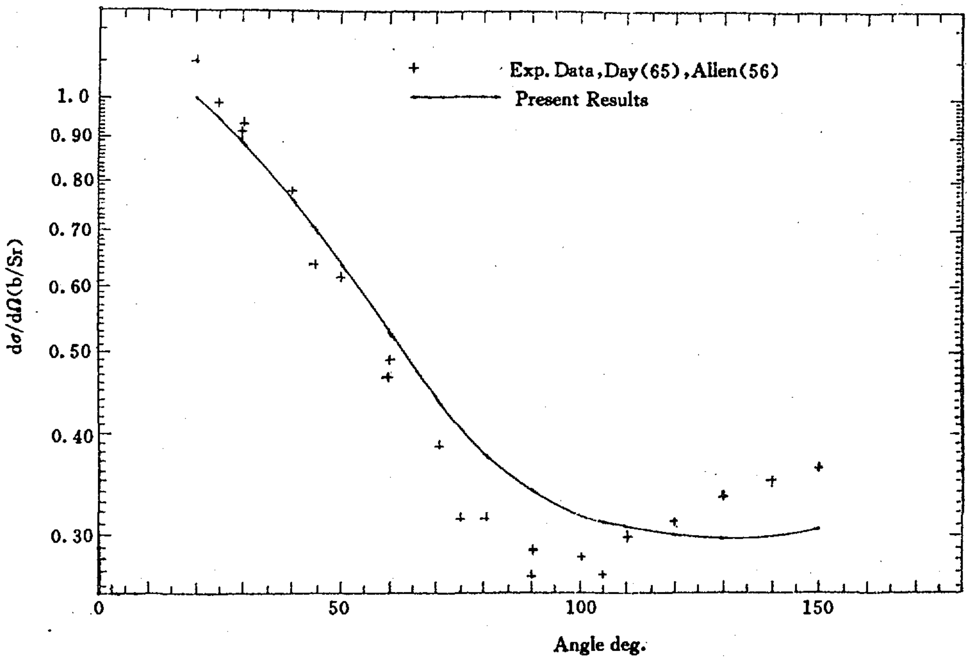

Fig. 15 Elastic scattering angular distribution of ^{197}Au for 0.5 MeV neutrons

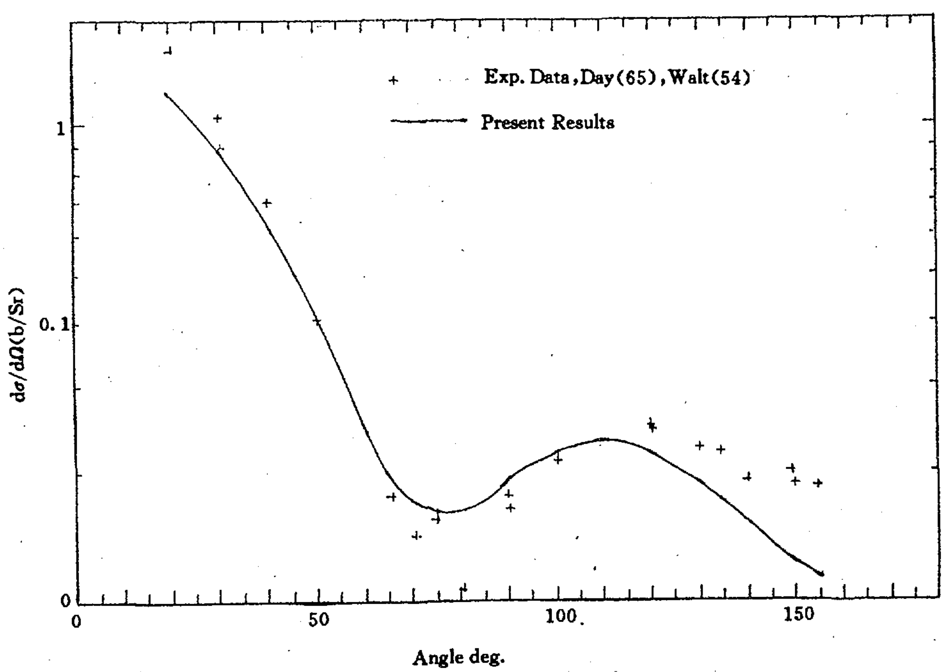

Fig. 16 Elastic scattering angular distribution of ^{197}Au for 1.0 MeV neutrons

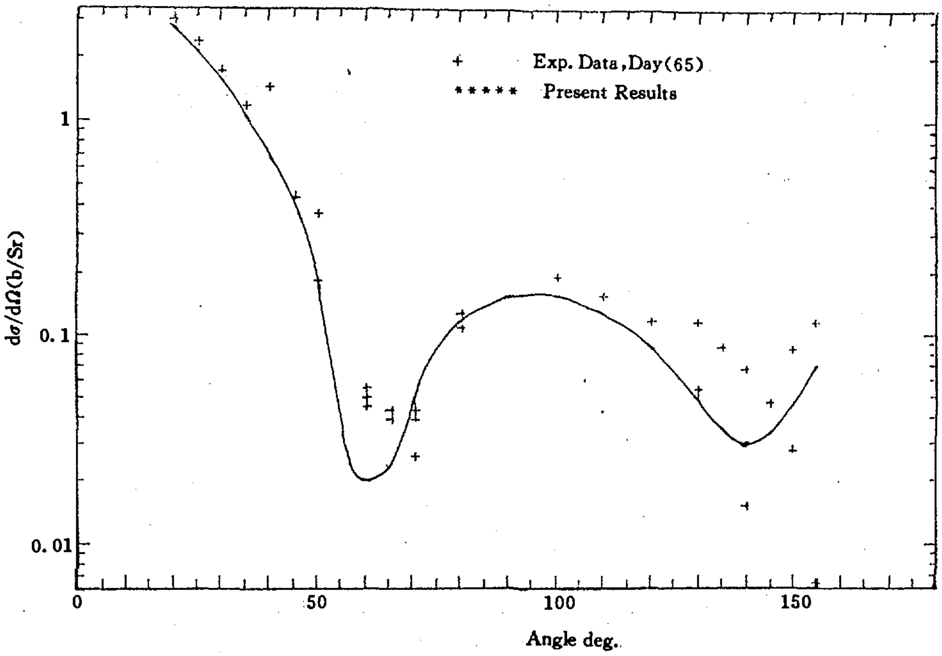

Fig. 17 Elastic scattering angular distribution of ^{197}Au for 2.5 MeV neutrons

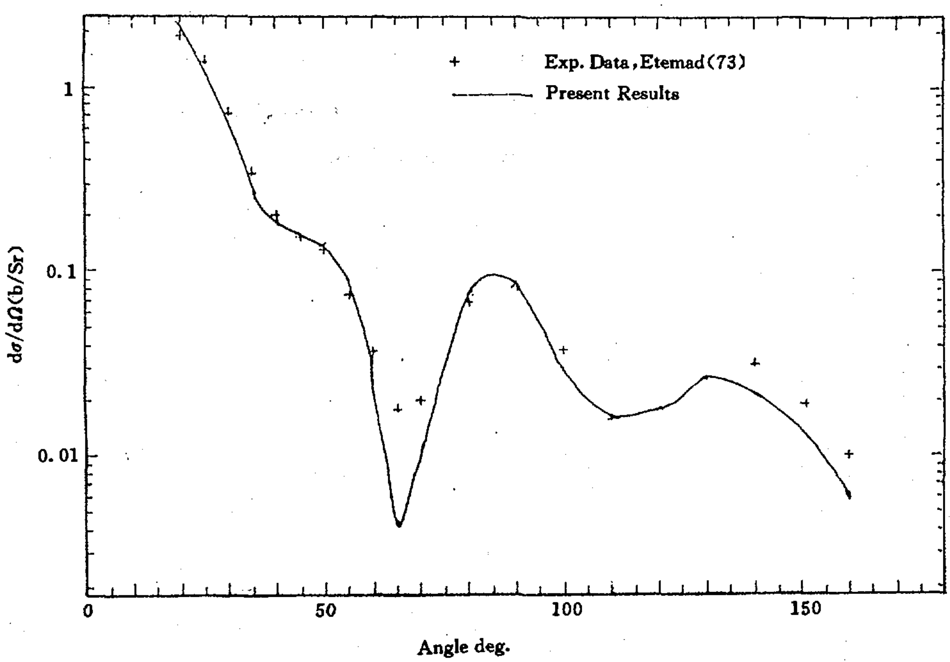

Fig. 18 Elastic scattering angular distribution of ^{197}Au for 7.0 MeV neutrons

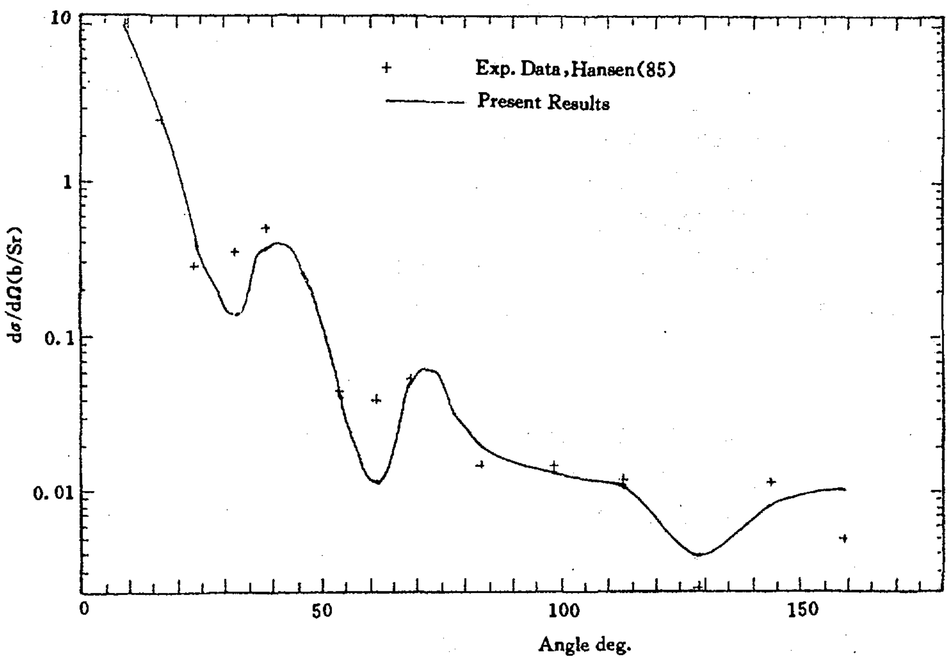

Fig. 19 Elastic scattering angular distribution of ^{197}Au for 14.6 MeV neutrons

REFERENCES

[1] Cai Conghai et al., AUJP code, CNDC Program Library, CNDC0012, 1989

[2] Zhou Hongmo et al., MUP–2N code, CNDC Program Library, CNDC0014, 1989

[3] F. D. Bechitte et al., Phys. Rev., 182, 1190(1969)

[4] C. M. Perey et al., Atomic Data and Nuclear Data Tables, 17, 1(1976)

[5] Wang Shunuan et al., Comm. Nucl. Data Prog. 5, 22(1991)

[6] W. P. Poenitz et al., ANL–NDM–80, 1983

[7] W. P. Poenitz et al., Nucl. Sci. Eng., 78, 333(1981)

[8] D. G. Foster et al., Phys. Rev., C3, 576(1971)

[9] J. F. Whalen et al., ANL–7210, 16, 1966

[10] K. K. Seth et al., Phys. Lett., 16, 306(1965)

[11] R. B. Day, EXFOR 12191002, 1965

[12] J. M. Peterson et al., Phys. Rev., 120, 521(1960)

[13] A. Bratenahl et al., Phys. Rev., 110, 927(1958)

[14] J. P. Conner, Phys. Rev., 109, 1268(1958)

[15] S. A. Cox et al., ANL–7935, 1972

[16] M. Walt et al., Phys. Rev., 98, 677(1955)

[17] M. Walt et al., Phys. Rev., 93, 1062(1954)

[18] R. C. Allen et al., Phys. Rev., 104, 731(1956)

[19] B. Holmqvist et al., AE–430, 1970

[20] M. A. Etemad, AE–482, 1973

[21] J. A. M. De Villiers et al., Z. Physik, 183, 323(1965)

[22] D. D. Phillps et al., Phys. Rev., 88, 600(1952)

[23] J. R. Beyster et al., Phys. Rev., 98, 1216(1955)

[24] J. R. Beyster et al., Phys. Rev., 104, 1319(1956)

[25] M. H. MacGregor et al., Phys. Rev., 108, 726(1957)

[26] E. R. Graves et al., Phys. Rev., 89, 343(1957)

[27] E. R. Graves et al., et al., Phys. Rev., 97, 1205(1955)

[28] M. H. MacGregor, Proc. Int. Congress on Nucl. Physics, Nucl. Interactions at Low Energies and Nucl. Structure, Paris, 7～12 July, 1958, p. 609

[29] D. B. Thomson, Phys. Rev., 129, 1649(1963)

[30] T. Akiyoshi et al., J. Nucl. Sci. Technology, 11, 523(1974)

[31] Zhao Wenrong et al., INDC(CRP)–16, 1989

[32] Y. Ikeda et al., JAERI–1312, 1988

[33] K. Kobayashi et al., Proc. Int. Conf. on Nucl. Data for Sci. Tech., Mito, 30 May～3 June, 1988, p. 261

[34] L. R. Greenwood, DOE–ER–0046–21, 15, 1985

[35] M. Herman et al., EXFOR 30803004, 1984

[36] I. Garlea et al., Rev. Roum. Phys., 29, 421(1984)
[37] S. Daroczy et al., Proc. 6th All Union Conf. on Neutron Physics, Kiev, 2~6 Oct. 1983, 3, 191, 1983
[38] A. Reggoug et al., MOH−5, 14, 1982
[39] J. Csikai, Proc. Int. Conf. on Nucl. Data for Sci. Techn., Antwerp, 6~10 Sept. 1982, p. 414, 1982
[40] T. B. Ryves et al., J. Phys. / G, 7, 115(1981)
[41] J. Laurec et al., CEA−R−5109, 1981
[42] J. Frehaut et al., Proc. 10~50 MeV Conf. BNL−NCS−51245, 399, 1980
[43] P. Andersson et al., LUNF−D6−3021, 1978
[44] L. R. Veeser et al., Phys. Rev., C16, 1792(1977)
[45] B. P. Bayhurst et al., Phys. Rev., C12, 451(1975)
[46] A. Paulsen et al., Atomkernenergie / Kerntechnik, 26, 34(1975)
[47] D. R. Nethaway, Nucl. Phys. / A, 190, 635(1972)
[48] S. M. Qaim, Nucl. Phys. / A, 185, 614(1972)
[49] A. K. Hankla et al., Nucl. Phys. / A, 180, 157(1972)
[50] G. N. Maslov et al., YK−9, 50, 1972
[51] E. Browne et al., Table of Radioactive Isotopes, John Wiley and Sons, Inc., 1986
[52] R. L. Macklin et al., Nucl. Sci. Eng., 79, 265(1981)
[53] G. Magnusson et al., Physica Scripta, 21, 21(1980)
[54] T. B. Ryves et al., J. Phys. / G, 7, 115(1981)
[55] H. A. Husain et al., Int. J. Radiation Appl. Instr. / A 34, 731(1983)
[56] P. Andersson et al., Nucl. Phys. / A, 443, 404(1985)
[57] W. Ratynski et al., Phys Rev., C37, 595(1988)
[58] Chen Yin et al., Chinese Nucl. Phys., 3, 52(1981)
[59] Zhu Shengyun et al., Chinese Nucl. Phys., 6, 23(1984)
[60] A. N. Davletshi et al., Atomnaja Energiji, 58, 183(1985)
[61] V. L. Demekhin et al., Proc. 36th All Union Conf. on Nucl. Spectr. & Nucl. Structure, Kharkov, 15~18 April 1986, p. 94, 1986
[62] B. P. Bayhurst et al., J. Inorg. Nucl. Chem., 23, 173(1961)
[63] R. F. Coleman et al., Proc. Phys. Soc., 73, 215(1959)
[64] D. W. Kneff et al., Nucl. Sci. Eng., 92, 491(1986)
[65] R. B. Day, EXFOR 12191003, 1965
[66] L. F. Hansen, Proc. Int. Conf. on Nucl. Data For Basic & Applied Science, Santa Fe, 13~17 May 1985, 1, 83, 1985

EVALUATION OF NEUTRON NUCLEAR DATA FOR NATURAL LEAD

Zou Yiming　Ma Gonggui　Wang Shiming

(INSTITUTE OF NUCLEAR SCIENCE AND TECHNOLOGY, SICHUAN UNIVERSITY, CHENGDU)

ABSTRACT

Complete neutron nuclear data for natural lead were evaluated based on both experimental data measured up to December 1985 and theoretical data calculated with program MUP2[1]. The experimental data evaluation is mainly based on CENDL-1[2], except (n,2n) cross section, for which there are newly measured data available. The data, in the neutron energy from 10^{-5} eV to 20 MeV, contain cross sections, angular distributions and energy spectra of secondary neutrons.

INTRODUCTION

The element lead has four naturally occurring isotopes. They are $^{204,206,207,208}Pb$. The fractional abundances of these isotopes are given in Table 1. The contribution from ^{204}Pb is neclected in the theoretical calculation. In such cases the effective fractional abundances are given in parentheses in Table 1.

Table 1　Fractional abundence of lead isotopes

Isotope	^{204}Pb	^{206}Pb	^{207}Pb	^{208}Pb
Abundence	0.0124	0.236	0.226	0.523
	(0.0) *	(0.24) *	(0.23) *	(0.53) *

* Effective abundances used in this calculation

Some reactions with charged-particle emission, strongly inhibited by the Coulomb barrier,are neglected for their cross section are quite small.

The recommended data are based on both experimental data and calculated data with MUP2. The measured data, available up to December 1985, were used as much as possible, but the calculated data were adopted for some reactions and energy regions due to the lack of experimental ones.

The complete data, in the energy region from 10^{-5} eV to 20 MeV, contain neutron cross sections, angular distributions and energy spectra of secondary neutrons.

1 THEORETICAL CALCULATION AND PARAMETERS CONCERNED

The data for lead were calculated with program MUP2, including optical model, H–F statistical and pre–equilibrium evaporation model.

Energy levels of the lead isotopes were taken from Table of Isotopes (7th Edition)[4] . In Tables 2~4 the energy Levels of $^{206, 207, 208}$Pb are listed respectively, which were used in the calculation.

Table 2 Energy levels of ^{206}Pb

Level	Energy (MeV)	Spin Parity	Level	Energy (MeV)	Spin Parity
1	0.0	0.0^+	9	1.9977	4.0^+
2	0.8031	2.0^+	10	2.1490	2.0^+
3	1.1650	0.0^+	11	2.2002	7.0^-
4	1.3406	3.0^+	12	2.3843	6.0^-
5	1.4670	2.0^+	13	2.4240	2.0^+
6	1.6841	4.0^+	14	2.6479	3.0^-
7	1.7030	1.0^+	15	3.0165	5.0^-
8	1.7840	2.0^+	16	3.1220	3.0^+

Table 3 Energy levels of ^{207}Pb

Level	Energy (MeV)	Spin Parity	Level	Energy (MeV)	Spin Parity
1	0.0	$1/2^-$	7	2.6624	$7/2^+$
2	0.5697	$5/2^-$	8	2.7260	$9/2^+$
3	0.8977	$3/2^-$	9	3.18002	$11/2^+$
4	1.6333	$13/2^-$	10	3.2000	$5/2^+$
5	2.3399	$7/2^-$	11	3.2230	$11/2^+$
6	2.6244	$5/2^+$			

Table 4 Energy levels of ^{208}Pb

Level	Energy (MeV)	Spin Parity	Level	Energy (MeV)	Spin Parity
1	0.0	0.0^+	8	3.9609	4.0^-
2	2.6146	3.0^-	9	3.9957	6.0^-
3	3.1977	5.0^-	10	4.1252	4.0^-
4	3.4750	4.0^-	11	4.1803	5.0^-
5	3.7085	5.0^-	12	4.2962	5.0^-
6	3.9199	6.0^-	13	4.3584	4.0^-
7	3.9464	5.0^-	14	4.3829	6.0^-

Level density parameters of the lead isotopes were taken from Su Zongdi[5]. The level density formulas are defined as

$$a = \{ 0.00880 [S(z) + S(n) + QB] \} A$$

$$V = 1.4 + 263 / A$$

were

$$QB = \begin{cases} 0.142 & \text{spherical nucleus} \\ 0.12 & \text{deformed nucleus} \end{cases}$$

$S(z) + S(n)$ are shell correct

The optical model parameters used for the program AUJP[5] are as follows:

Real well depth V	46.945 − 0.232 E MeV
Imaginary well depth W	3.805 + 0.4151 E MeV
Spin–orbit well depth V_{so}	6.0 MeV
Real well radius X_y	1.25 fm
Imaginary well radius X_s	1.24 fm
Spin–orbit well radius X_{so}	1.24 fm
Real well diffuseness A_t	0.64 fm
Imaginary well diffuseness A_s	0.48 fm
Spin–orbit well diffuseness A_{so}	0.64 fm

The theory giant dipole resonances parameters are given in Table 5.

Table 5 The iant dipole resonance parameters

For ^{206}Pb

S_{ao} (mb)	0.111	0.650	0.481	0.541	0.541	0.645	0.541	0.481
G_m (MeV)	3.96	3.94	3.96	4.61	4.61	3.94	4.61	3.96
G_g (MeV)	13.56	13.63	13.56	13.72	13.72	13.63	13.72	13.56

For ^{207}Pb

S_{ao} (mb)	0.25	0.7	0.18	0.541	0.541	0.481	0.541	0.645
G_m (MeV)	3.94	3.94	3.94	4.61	4.61	3.96	4.61	3.94
G_g (MeV)	13.63	13.63	13.63	13.72	13.72	13.56	13.72	13.63

For ^{208}Pb

S_{ao} (mb)	0.881	0.7	0.481	0.541	0.541	0.645	0.541	0.481
G_m (MeV)	3.96	3.94	3.96	4.61	4.61	3.94	4.61	3.96
G_g (MeV)	13.56	13.63	13.56	13.72	13.72	13.63	13.72	13.56

The calculated data are compar ed with measured ones, given in Figs.1 ~ 6, showing a good agreement between them.

2 RECOMMENDED NEUTRON CROSS SECTIONS

2.1 Total Cross Sections

Below 227.7 eV the total cross sections were obtained by drawing a straight line through the cross sections at thermal energy point and at 227.7 eV on log–log scale, and the thermal neutron cross section was taken from BNL–325[7]. From 227.7 eV to 4.5 keV, the data were taken from Seth[8]. In the energy region 4.5 keV to 20 MeV,the recommended data, which with agree CENDL–1[2], are based on Seth[8] and Newson[9] from 4.5 to 50 keV;Bilpuch[10] from 50 to 360 keV; Wilenzick[11] from 360 keV to 0.47 MeV; Schwartz[12] from 0.47 to 5 MeV and Splin fit of Schwartz[12] Bowen[13] and Peterson[14] data from 5 to 20 MeV.

2.2 Elastic Scattering Cross Sections

The recommended elastic scattering cross section was obtained by subtracting the nonelastic cross section from the total cross section in the entire energy range.

2.3 Nonelastic Cross Sections

Nonelasti c cross section was got by summing all calculated (n,x),(n,2n), (n,3n) cross sections and the experimentally recommended capture cross section. The recommended nonelastic cross sections is in agreement with available experimental data[15~20], because the capture cross section is very small in the energy range (see Fig. 1).

2.4 Inelastic Cross Sections

Inelastic cross sections were taken from the calculation. Inelastic excitations of levels below 3.1 MeV were treated as discrete levels. Levels above 3.1 MeV were considered as continuum. Comparisons of calculations with experimental data[21~25] were made and the agreement generally is well (Fig.2~4). There are 16 excited states in ^{206}Pb, 11 in ^{207}Pb, 12 in ^{208}Pb, all of them were merged into 36 levels for natural lead.

2.5 (n,2n) and (n,3n) Cross Sections

The (n,2n) and (n,3n) cross sections were taken from the calculation. The recommended (n,2n) cross sections are well consistent with the recent measurement of Frehaut[3] from 7 to 15 MeV. The agreement is also well with the ^{204}Pb data[26, 27], from 15 to 20 MeV.

2.6 Capture Cross Sections

Capture cross section of neutron at energy point 0.0253 eVwas taken at 171 mb for natural lead[7]. From 10^{-5} eV to 2 keV the cross sections were extented by $1/V$ dependence. As recommended capture cross sections, from 2 keV~1 MeV, the avarege cross sections of data of Allen[28] and Diven[29] were taken, and from 2.7 to 15 MeV, the data of ^{208}Pb[30~32] were taken. In the energy ranges of 1~ 2.7 MeV and 15~ 20 MeV, linear interpolation and extrapolations were made in log–log scale. Our recommendation agree with a new measurement[33] at 14.1 MeV.

2.7 (n,p) Cross Sections

The (n,p) cross section was taken from the calculation.

3 ANGULAR DISTRIBUTION OF SECONDARY NEUTRONS

The angular distributions of secondary neutrons from elastic scattering and inelastic scattering to discrete levels are given with Legendre coefficients in the center–of–mass system. The angular distributions of secondary neutrons for (n,′ continuum), (n,2n)and (n,3n), reactions are assumed isotropic.

The angular distributions of elastically scattered neutrons were taken from the calculation.The following experimental data were used to adjust the optical model parameters: Smith[34] and Walt[35] at 1 MeV; Walt[36] Gorlov[37] and Okhuysen[38] at 4 MeV; Buccino[39] and Hill[40, 41] at 5 MeV; Etemad[42], Holmgvist[43] and Ferrer[44] at 7, 8 and 11 MeV; Coon[45], Kmmerdiener[46] and Yuasa[47] at 14 MeV; Coon[45], Anderson[48] and Guzhovskii[49] at 14.6 MeV. Comparisons between the calculation and the experimental data are given in Fig. 5, showing a good agreement between them.

4 ENERGY SPECTRUM OF SECONDARY NEUTRONS

The energy spectrum of secondary neutrons from (n,n′ continuum),(n,2n) and (n,3n) reactions were taken from the theoretical calculations.

5 COMPARISONS

The comparisons between this evaluation (CENDL–2), ENDF / B–6 and JENDL–3 were made. They are in agreement with each other and the available experimental data, except the following differences :

(1) Nonelastic cross section of JENDL–3 appears somewhat higher (see Fig. 1).

(2) (n,γ) cross section of CENDL–2 appears somewhat low above 1 MeV.

(3) The evaluations of (n,2n), (n,n′) and (n,3n) have somewthat differences (see Fig. 6).

ACKNOWLEDGMENTS

We are very grateful to Profs. Cai Dunjiu et al. of the CNDC for their useful help. And to Cai Chonghai for his help in the calculation.

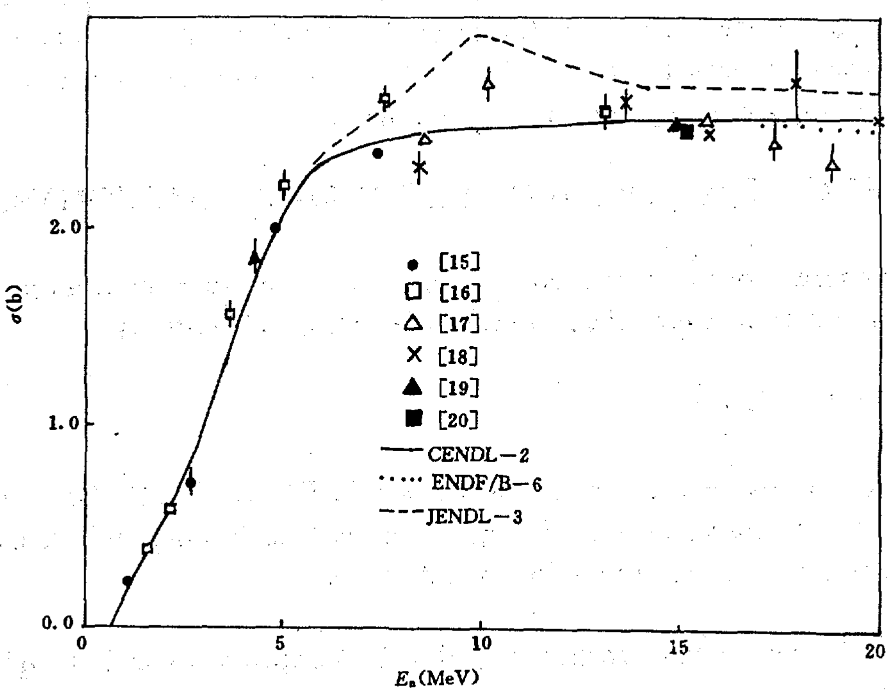

Fig. 1 Comparison of the nonelastic cross sections between CENDL−2, ENDF / B−6 and JENDL−3 for natural lead

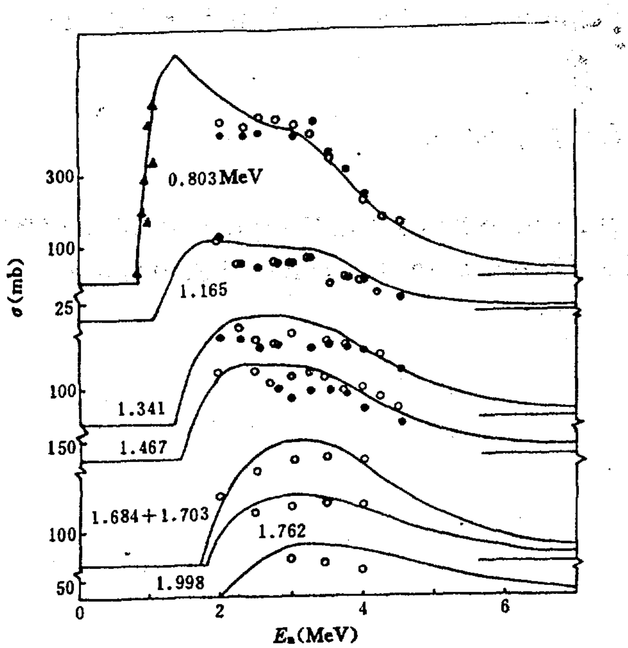

Fig. 2 Comparison of calculation with experimental for the inelastic scattering to concrete levels cross sections

^{206}Pb ▲ Konobeevskii (73); ○ Crenberg (67); • Almen−Ramstrom (75)

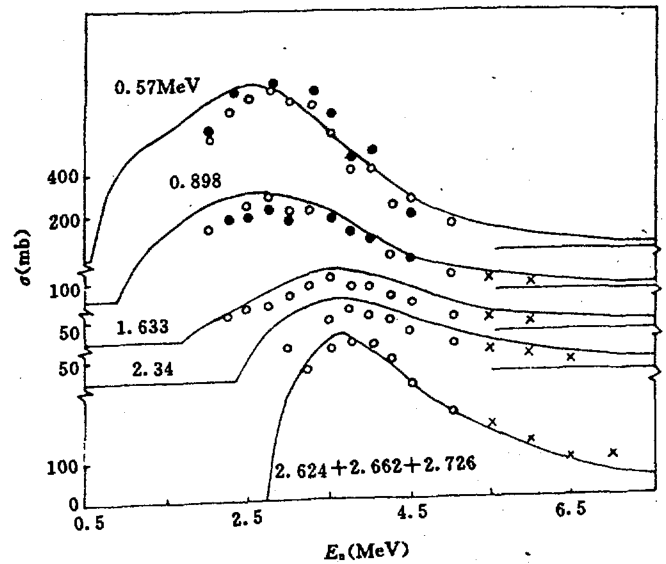

Fig. 3 Comparison of calculation with experiment for the cross sections of inelastic scattering to concrete levels

^{207}Pb • Almen–Ramstrom (75); ○ Crenberg (67); × Kinney (74)

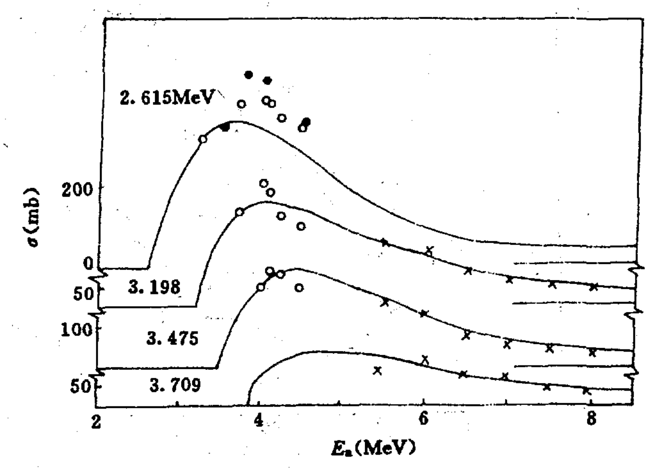

Fig. 4 Comparison of calculation with experiment for the cross sections of inelastic scattering to concrete levels

^{208}Pb • Almen–Ramstrom (75); ○ Crenberg (67); × Kinney (74)

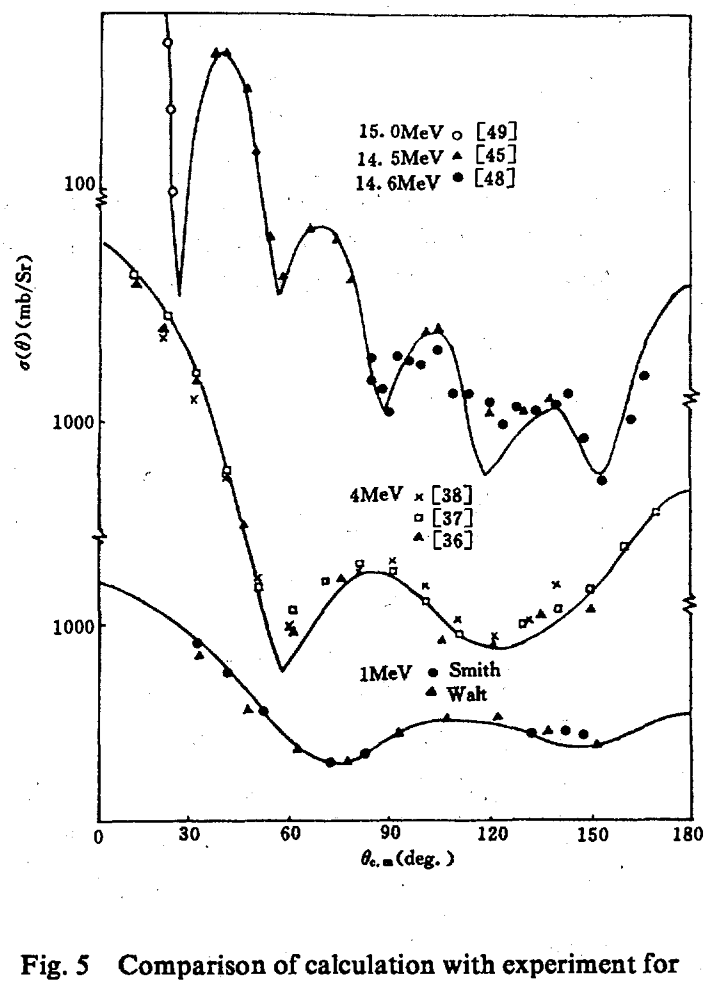

Fig. 5 Comparison of calculation with experiment for the angular distributions of elastic scattering

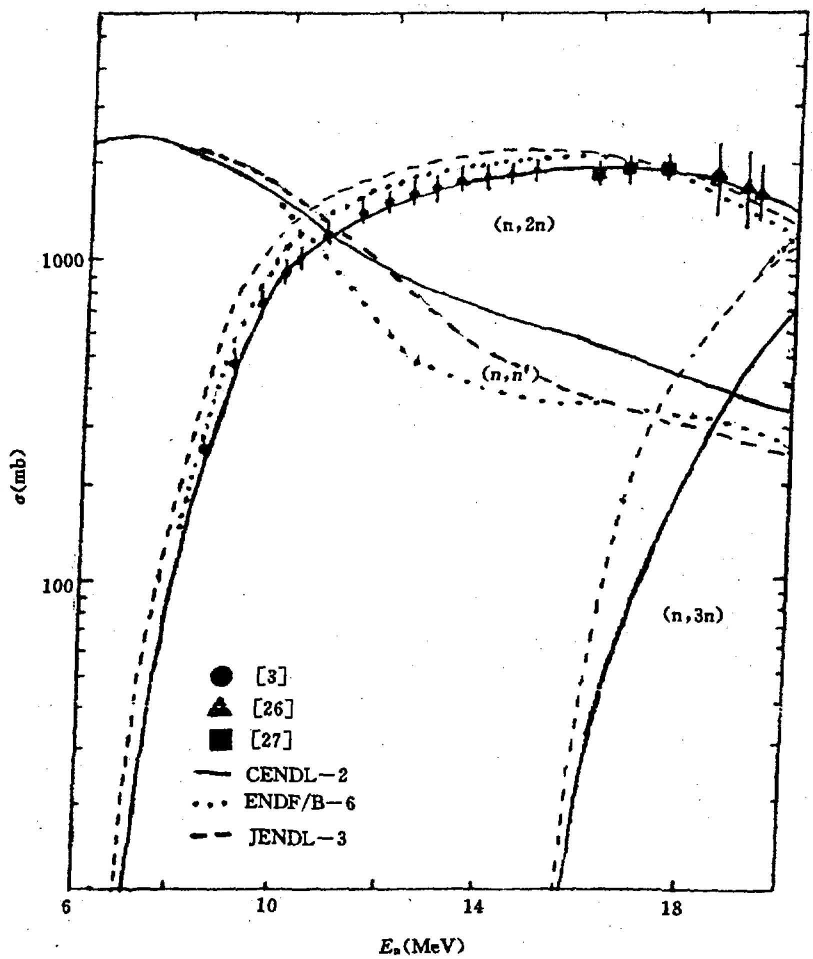

Fig. 6 Comparison of the (n,n′), (n,2n) and (n,3n) cross sections between CENDL−2, ENDF / B−6 and JENDL−3 for natural lead

REFERENCES

[1] Yu Ziqiang CaiChonghai et al., Theoretical calculation program MUP2for medium andheavy neclear, inter report (1986)

[2] Cao Jianhua et al., evaluation of neutron data for naturallead, "Chinese Evaluated Nuclear Data Library, Version-1", 245(1986) (in Chinese)

[3] J. Frehaut et al., EXFOR 20416043 (1980)

[4] C. M. Lederer and V. S. Shirley "Table of Isotopes" (7th Edition) (1978)

[5] Su Zongdi et al., A New Set of Level Density Parameters for Fermi Gas Model, Chinese Jour. of Nuclear Physics, Vol. 8, No. 3, 199(1986) (in Chinese)

[6] Zhou Hongmo et al., Auto-adjusting parameter optical model program AUJP, inter report (1978)

[7] S. F. Mughabghab, BNL-325 4th Edition (1984)

[8] K. K. Seth, Phys. Rev., 110, 692(1958)

[9] H. W. Newson, Phys. Rev., 102, 1580(1956)

[10] E. G. Bilpuch, Ann. of Phys., 14, 387(1961)

[11] R. M. Wilenzick, Phys. Rev., 121, 1150(1961)

[12] R. B. Schwartz, NBS-138 (1974)

[13] P. H. Bowen, Nucl. Phys., 22, 640(1961)

[14] J. M. Peterson, Phys. Rev., 120, 521(1960)

[15] J. R. Beyster, Phys. Rev., 98, 1216(1955)

[16] H. L. Taylor, Phys. Rev., 100, 174(1955)

[17] T. W. Bonner, Phys. Rev., 113, 1088(1956)

[18] U G. Degtyarev, Atomnay Energiya, 11, 397(1961)

[19] Lu Zuyin, Atom. Ener. Scie. and Tech., (6), 479(1964) (in Chinese)

[20] Pal Bharati, Nucl. Int. Moth., 171, 347(1980)

[21] E. Almen-Ramstrom, AE-503 (1975)

[22] L. Cranberg, Phys. Rev., 159, 969(1967)

[23] E. S. Konobeevskii, EXFOR 40215005 (1973)

[24] W. E. Kinney, ORNL-4909 (1974)

[25] J. H. Towel, Nucl. Phys., 44, 256(1963)

[26] P. Decowski, Nucl. Phys., A204, 121(1973)

[27] F. J. Vaughn, EXFOR 11223002 (1963)

[28] B. J. Allen et al., Phys. Rev. C8, 1504(1973)

[29] B. C. Diven et al., Phys. Rev., 120, 556(1960)

[30] A. I. Leipunski et al., 58GENEVA, 15, 50(1958)

[31] I. Bergqvst et al., Nucl. Phys. A191, 641(1972)

[32] D. Drke et al., Phys. Letters, B36, 557(1971)

[33] M. Budnar et al., EXFOR 30532054 (1979)

[34] A. B. Smith et al., EANDC–US–62 (1965)
[35] M. Walt et al., Phys. Rev., 93, 1062(1954)
[36] M. Walt et al., Phys. Rev., 98, 677(1955)
[37] G. V. Gorlov et al., EXFOR 80125022 (1964)
[38] P. L. Okhuysen et al., Phys. Rev., 166, 986(1959)
[39] S. C. Buccino et al., Zeitsch. F. Phsic, 196, 103(1966)
[40] R. W. Hill et al., Pull. Am. Phys. Soc., 1, 174(F1) (1956)
[41] R. W. Hill et al., Phys. Rev., 109, 2105(1958)
[42] M. A. Etemad et al., AE–482 (1973)
[43] B. Holmgvist et al., AE–430 (1971)
[44] J. C. Ferrer et al., Nucl. Phys. A275, 325(1977)
[45] J. H. Coon et al., Phys. Rev., 111, 250(1958)
[46] J. I. Kmmerdiener et al., UCRL–5123 (1972)
[47] K. Yuasa et al., J. Phys. Soc. Japan, 13, 1248(1958)
[48] J. D. Anderson et al., Phys. Rev., 110, 160(1958)
[49] B. Ya. Guzhovskii et al., Atomnaya Energiya, 11, 395(1961)

EVALUATION OF NEUTRON NUCLEAR DATA OF ^{238}U

Tang Guoyou Bao Shanglian Cao Wentian

(IHIP, PEKING UNIVERSITY)

Cai Chonghai

(PHYSICS DEPARTMENT, NANKAI UNIVERSITY)

Cai Dunjiu Shen Qingbiao Yu Baosheng

(CHINESE NUCLEAR DATA CENTER ,IAE)

INTRODUCTION

^{238}U is an important nuclide in the fuel circle of the fast reactor. Since

1950s, some new experimental data have been published. After the development of the white light neutron source in 1970s, the measured data were made great progress with more accuracy. However, up to now the systematical differences among these data are still too large to meet the requirement of the nuclear power developments. Therefore the reevaluation is necessary. Our evaluation is a development of the CENDL−1.During the reevalution, all the relatively measured data (to ^{235}U or to ^{197}Au) were renormalized to ENDF / B−6 data file. For theoretical calculation the code of FUP1 was used, where the parameters of the optical model were taken from Shen Qingbiao [60]. The recommended experimental data and the theoretical calculated data were adjusted and let $\sigma_{tot} = \sigma_{el} + \sigma_{non}$. The resonance parameters in the energy below 10 keV were taken from ENDF / B−6. All the data in the energy range 10^{-5} eV to 20 MeV were recommended as the data file of ^{238}U for CENDL−2.

1 THE EVALUATION OF THE EXPERIMENTAL DATA

1.1 The Total Cross Section

For the total cross section, 11 sets of data [1~11] have been used in the evaluation. Among them the newest data were measured by W. P. Poenitz et al.[1] in 1981.

1.2 The Cross Section of (n,f) reaction

During the evaluation more than 60 sets of data have been collected and 18 sets [12~29] of them were used. Among them, about 70% new data were renewed compared with ENDF / B−5.

1.3 The Capture Cross Section

For capture cross section 49 sets of data were collected in the energy range from 0.02 to 20 MeV, about 50% data were renewed compared with ENDF / B−5.

1.4 The Cross Section of (n,2n) and (n,3n) Reactions

The evaluation of the cross sections of (n,2n) and (n,3n) reaction was mainly contributed by Prof. Cai Dunjiu. For (n,2n) data total 11 sets of data [46~56], for (n,3n) data 3 sets of data [53, 54, 57] were used in our evaluation in the energy range from threshold to 20 MeV. Based on these data, about 87% data were renewed compared to ENDF / B−5.

1.5 The Elastic and Inelastic Cross Sections

For (n,n′) cross section, the 75 exciting function measured by 7 laboratories have been collected.

The angle integrated data for (n,n′) reaction were measured below 0.7 MeV and the uncertainties were large.

All (n,n′) data are taken from theoretically calculated results and the experimental data are only used as the references for the calculation. After the calculation we found that our calculated data were consistent very well with the new measured data by M. Baba at neutron energy 2.0, 4.25 MeV [59], which were got from double differential cross section measurements.

Data for σ(n,n) are much similar to σ(n,n′) and treated at the same way.

2 THE THEORETICAL CALCULATION

2.1 Optical Model

Because the changes of σ_t, σ_{non} and elastic angular distribution $\sigma_{n,n}$ (θ) is not very large, the parameters of the optical model for ^{238}U used in the calculation were directly taken from Shen Qingbiao published in 1979 [60].

2.2 The Fission Parameters

The fission parameters include energy level density a, pair correlation δ, fission barrier width $\hbar w$, equivalent fission barrier height V_{pf} and the energy level density parameters at saddle states P_{k1}, P_{k2}. These parameters were adjusted by automatically adjusting parameter program ASFP [61]. In the adjusting, the parameters were got by the model fitting method. Below 3 MeV, WHF theory was used. Above 3 MeV, PE theory was employed. Because there are 3 fission processes included in the energy range up to 20 MeV, the measured data of ^{238}U and concerned isotopes were used as input data. The parameters used in the evaluation are listed as follows :

	1st fission	2nd fission	3rd fission	4th fission
V_{pf}	5.56216	6.172940	6.031904	6.1700
P_{K1}	1.78804	2.17144	1.762614	2.17000
P_{K2}	0.04863	0.030130	0.202768	0.030130
δ	0.50391	0.90301	0.57768	1.160501
$\hbar w$	0.537078	0.7951	0.652	0.7951
a	29.644577	28.887375	29.526947	28.682846

3 DISCUSSION AND CONCLUSION

In the evaluation, the recommended data in neutron energy range from 0.02 MeV to 20 MeV are summarized as follows:

3.1 For the reaction cross sections of total, (n,f), (n,γ), (n,2n), (n,3n), the measured data were used and the fitted data by polynomials were recommended.

3.2 For the reaction cross sections of (n,n′), the theoretically calculated data were recommended.

3.3 Nonelastic cross sections are got by adding all cross sections of nonelastic scattering channels, and elastic scattering was obtained by subtracting nonelastic cross section from total cross section.

3.4 The elastic scattering angular distribution and all energy and angular distributions of the second neutrons were calculated.

The comparison of this work with ENDF / B–6 and JENDL–3 are shown in Figs. 1 ~ 6.

ACKNOWLEDGMENTS

Much thanks for Chinese Nuclear Data Center, from which we got some technical support by authors.

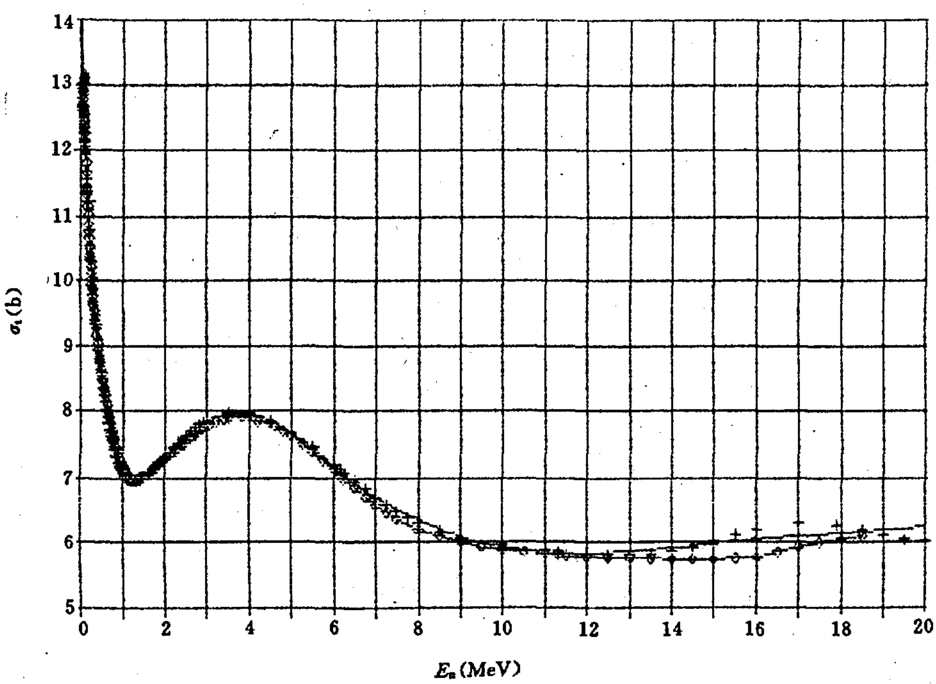

Fig. 1 ^{238}U total cross section

---- ENDF / B–6 ◇ JENDL–3 + This work

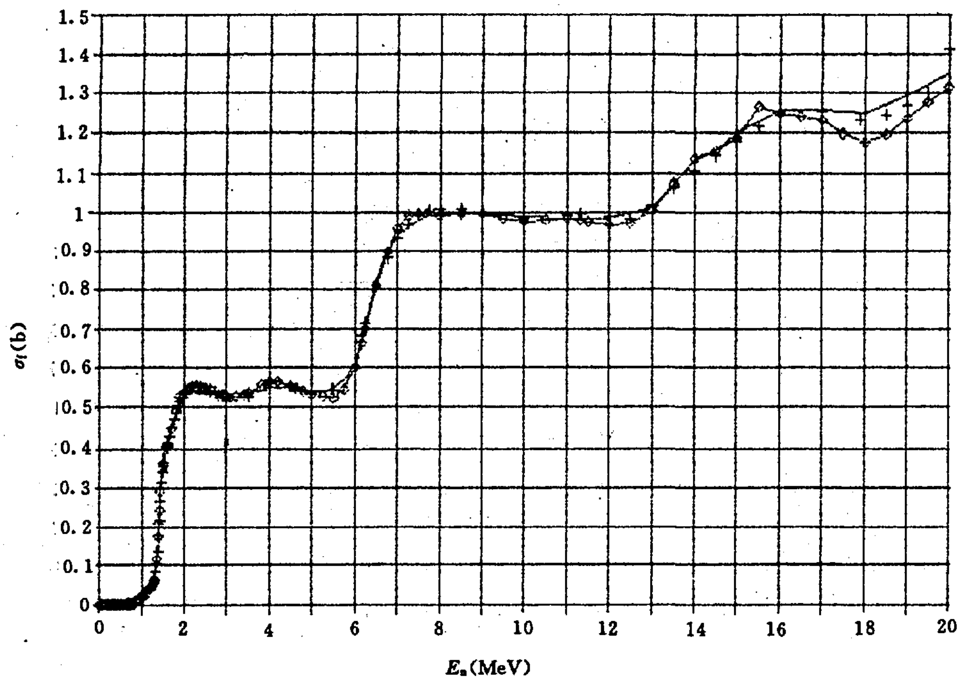

Fig. 2 ^{238}U (n,f) cross section

---- ENDF / B–6 ◇ JENDL–3 + This work

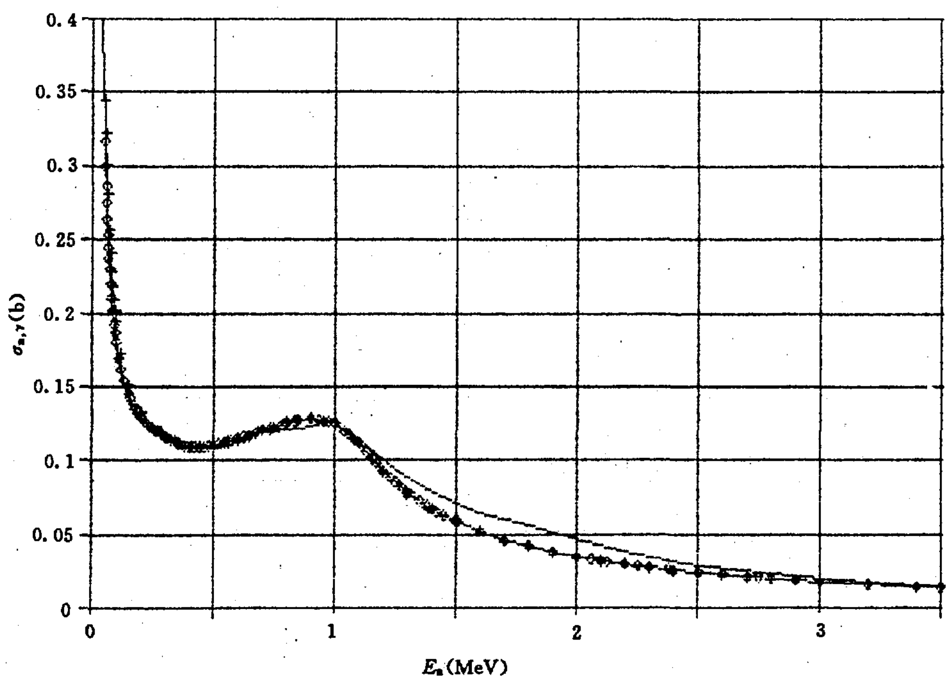

Fig. 3 ^{238}U (n,γ) cross section

---- ENDF / B–6 ◇ JENDL–3 + This work

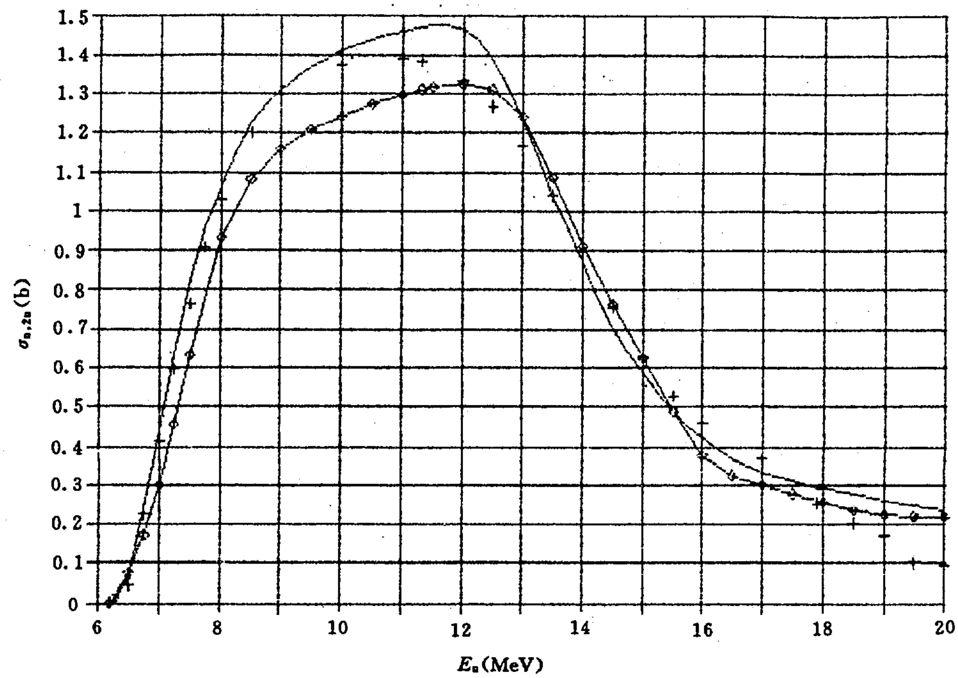

Fig. 4 ^{238}U (n,2n) cross section

---- ENDF / B-6 ◇ JENDL-3 + This work

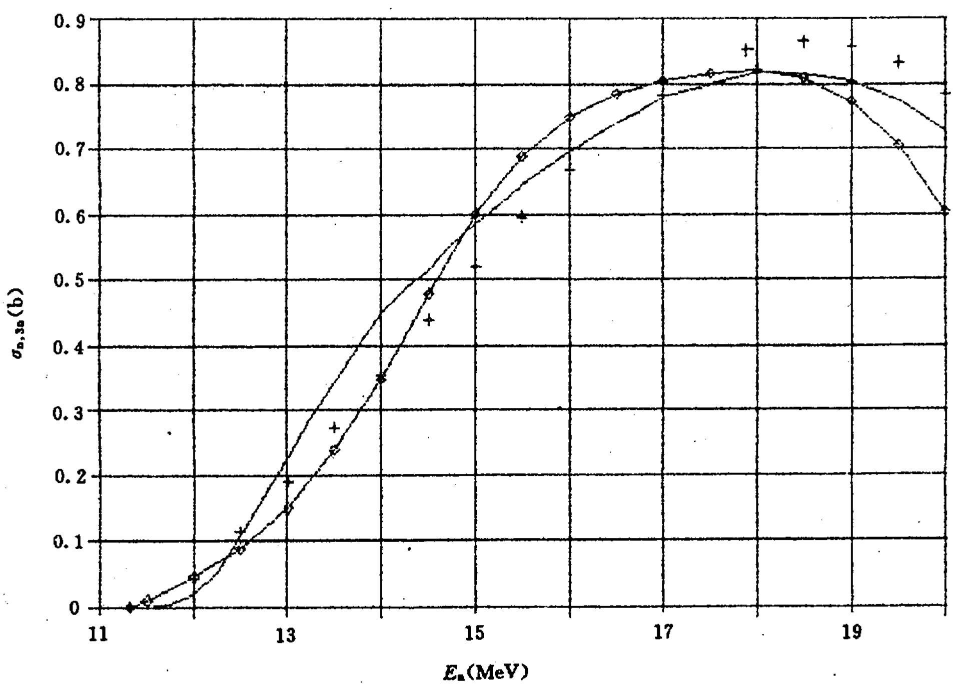

Fig. 5 ^{238}U (n,3n) cross section

---- ENDF / B-6 ◇ JENDL-3 + This work

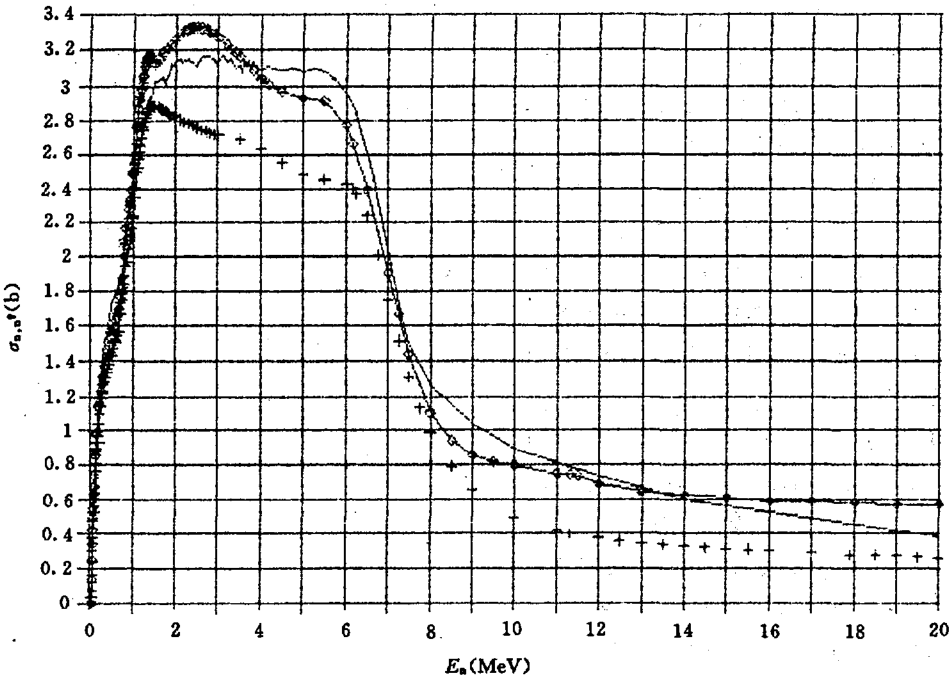

Fig. 6 ^{238}U (n,n′) cross section

---- ENDF / B−6 ◇ JENDL−3 + This work

REFERENCES

[1] W. P. Poenitz, NSE, 78, 333(1981)
[2] J. F. Whalen, ANL−7710, 9(1971)
[3] S. H. Hayes, NSE 50, 243(1973)
[4] R. B. Schwartz, NSE 54, 322(1974)
[5] J. Cabe, CEA−R−4524, (1973)
[6] M. Baba, EANDC (J)−30, 66(1973)
[7] J. Vaignier, CEA−R−3503, (1968)
[8] V. N. Kononov, 73 Kiev, 2, 199(1974)
[9] R. Batchelor, NP. 65, 326(1965)
[10] A. B. Bratenahl, PR., 110, 927(1958)
[11] D. G. Foster, PRIC, 39, 576(1971)
[12] F. C. Difilippo, NSE, 68, 43(1978)
[13] J. W. Behrens, NSE, 63, 250(1977)
[14] J. W. Meadows, W. MEADOWS, (1975); NSE, 58, 255(1975)
[15] R. E. Slovacek, NSE, 62, 455(1977)

[16] M. S. Coats, 75WASH, GB7(1975)
[17] S. Cierjacks, 76ANL, 94(1976)
[18] C. Nordborg, 76ANL, 128(1976)
[19] M. Cance, 76ANL, 141(1976)
[20] P. E. Vorotnokov, YFI–20, 9(1975)
[21] B. I. Fursov, AE, 43(3), 181(1977)
[22] Kh. D. Androsenko, 83 Kiev, 2, 153(1983)
[23] A. A. Goverdovskij, 83 Kiev, 2, 159(1983)
[24] Wu Jingxia, CNP, 5(2), 158(1983)
[25] M. Varnagy, NIM, 196, 465(1982)
[26] M. Cance, NSE, 68(2), 197(1978)
[27] I. D. Alkhagov, YFI–22, 12(1976)
[28] R. Arlt, 79 JULICH (B15), (1979)
[29] I. Garler, RRP, 29, 421(1984)
[30] M. C. Daniels, NP / A 384, 88(1982)
[31] W. P. Poenitz, NSE, 78, 239(1981)
[32] W. P. Poenitz, 57, 300(1975)
[33] M. Lindner, NSE, 59, 381(1976)
[34] M. P. Fricke, 71KNOX, 1, 252(1971)
[35] H. O. Menlove, NSE, 33, 24(1968)
[36] K. Wasshark, NSE, 76(3), 363(1978)
[37] T. Ryves, JNE, 27, 519(1973)
[38] J. F. Barry, JNE, 18, 481(1964)
[39] R. C. Hanna, JNE, 8, 197(1959)
[40] K. Dietze, ZFK–341, (1977)
[41] A. N. Davletshin, 75Kiev, 4, 109(1976)
[42] Ju. G. Panitkin, AE, 39, (1), 17(1975)
[43] T. S. Belanova, AE, 19, 3; FEI–3, 65(1965)
[44] D. Drake, PL / B, 36, 557(1971)
[45] Huang Zheng, LBL–1118, 243(1980)
[46] J. L. Perkin, JNE, 14, 49(1961)
[47] J. H. Landrum, PR, C8, 1938(1973)
[48] Zhou Youpu, Hsj–77091, (1978)
[49] H. Karius, JP / G, 5, 5, 715(1979)
[50] H. Kornilov, ZFK–410, 68(1980)
[51] T. B. Ryves, JP / G, 6(6), 771(1980)
[52] R. Pepelnik, 85 Santa, FE, P211
[53] D. S. Mather, AWRE 047 / 69 919690
[54] L. R. Veeser, 78 Harwell, 1054(1978)

[55] J. Frehaut, Frehaut's letter of 18th June 1985
[56] R. Batchelor, NP 65, 236(1965)
[57] J. Frehaut, BNL–NCS–51245(1980)
[58] J. Q. Shao, NSE, 92, 350(1986)
[59] M. Baba, INDC(JPN)–129 / L(1990)
[60] Shen Qingbiao, Hsj–78224(1979)
[61] Cai Chonghai, Internal Report of Nankai University ASFP and FUP1(1990)

EVALUATION OF NEUTRON NUCLEAR DATA OF ^{237}Np FOR CENDL–2

Tang Guoyou Fan Jihong Cao Wentian Bao Shanglian

(INST. OF HEAVY ION PHYSICS, PEKING UNIVERSITY)

Cai Chonghai

(PHYSICS DEPARTMENT, NANKAI UNIVERSITY)

ABSTRACT

The measured data of (n,f), (n,γ) reaction for ^{237}Np have been evaluated in the energy region from 30 keV to 20 MeV. All the data of ^{237}Np for other reaction channels are theoretically calculated. The recommended experimental data and the theortically calculated data are adjusted and make $\sigma_{tot} = \sigma_{el} + \sigma_{non}$. All the data in the energy range 10^{-5} eV to 20 MeV are recommended as the data file of ^{237}Np for CENDL–2.

INTRODUCTION

^{237}Np is an important element in the fuel circle of the nuclear reactor. From the sixties to the eighties the neutron nuclear data of ^{237}Np were measured continually. Some evaluated data were also published[1~3]. After the evaluations, some new measurements came to us for reaction channels (n,f) and (n,γ). Therefore a new evaluation is necessary.

1 THE MEASURED DATA

The existed experimental data of ^{237}Np are mainly in the reaction channles (n,f) and (n,γ).

1.1 (n,f) Reaction

The data have been measured since 1947. Up to now there were more than 30 groups of data published and 10 groups were measured in the eighties. The measurements were mainly carried out relative to ^{235}U, the accuracy was in 2 ~ 5% . All relatively measured data are renormalized using ^{235}U data of ENDF / B–6 file. All the 22 recommended data groups[4~25] are listed in Table 1 and shown in Fig. 1.

Table 1

Author	Year	E_n (MeV)	Author	Year	E_n (MeV)
A. Protopopov[4]	1958	14.6	J. Alknaiov[15]	1977	14.8
B. Gokhberg[5]	1958	0.012~1.5	D. Gardy[16]	1979	0.77~0.96
S. Kalinin[6]	1958	2.5~8.3	J. Behrens [17]	1982	0.02~30
H. Schmit[7]	1959	1.64~7.63	M. Cance[18]	1982	2.47
P. White[8]	1965	0.04~14.1	J. Meadows[19]	1983	0.1~9.4
J. Perkin [9]	1965	0.024	R. Arlt[20]	1981	8.7~14.7
J. Grundl[10]	1967	1.07~8.07	M. Varnagy[21]	1982	13.5~14.8
W. Brown[11]	1970	0.1~2.8	I. Garlea[22]	1984	14.75
R. Jiacoleti[12]	1972	0.2~6.76	Wu Jingxia[23]	1984	4.0~5.5
W. Kobayaski[13]	1973	3.5~4.9	K. Kanda[24]	1985	0.51~15
S. Plattard[14]	1975	0.02~2.01	A. Goverdovsk[25]	1984	4.44~16.4

1.2 Capture reaction (n,γ)

Total 6 data groups were collected, but only 4 groups[26~29] were recommended. The standards of the relatively measured data, ^{235}U (n,f) cross sections and ^{197}Au (n,γ) cross sections, were re–normalized using new data of ENDF / B–6 file. The situations of the measured data are listed in Table 2 and the recommended data are shown in Fig. 2.

Table 2

Author	Lab.	Year	E_n (MeV)
M. Linder[26]	USALRL	1976	0.121~2.73
J. Trofimor[27]	CCPRI	1976	0.25~1.91
L. Weston[28]	USAORL	1981	0.02~0.212
A. Davletshin[29]	CCPFEI	1985	0.174~1.15

1.3 The Reaction (n,2n)

All the data were measured using activation method. The cross sections of ^{237}Np (n,2n) were calculated on the basis of the ^{236}Pu products. In order to know ^{236}Pu products the both data, the ratio of β emission and electron capture (EC), and R, the ratio of the products of ^{236}Np isomer and ^{236}Np, need to be known well. But up to now R is not well known, especially R as the function of neutron energy E is not known. Therefore all the collected data[30~35] were only used as references during the parameter adjusting of the model calculation. The comparison of the theoretical and measured data is shown in Fig. 3.

2 THEORETICAL CALCULATION

Without so many measured data, all data of other reaction channels of ^{237}Np are given by theoretical calculations.

These data were calculated using FUP1[36], in which the coupled channel optical model, F–H theory with width fluctuation (WFH) and pre–equilibrium Evaporation Model based on Excitation Model (PE) were adopted. The parameters of the optical model and fission parameters needed to be input from other calculations.

2.1 The Parameters of Optical Model

Due to there are no measured data of total cross section σ_t , nonelastic cross section σ_{non} and elastic angular distribution σ_{nn} (θ), the parameters of the optical model for ^{237}Np are got from parameter adjusting for ^{239}Pu[37].

2.2 Fission Parameters

The fission parameters include the energy level density a, pair correlation δ, fission barrier width $\hbar w$, equivalent fission barrier height V_{pf} and the energy density parameters at saddle states : P_{k1} , P_{k2}. These parameters are got from a auto parameter adjusting program ASFP[38]. In the adjusting, the parameters are got by the model fitting method. Below 3 MeV, WHF theory is used. Above 3 MeV, PE theory is employed. Because there are 3 fission proceedings included in the energy range up to 20 MeV, the measured data of ^{237}Np and its isotopes are used as input data. The parameters used in the evaluation are listed in Table 3.

Table 3 Fission parameters

	1st fission	2d fission	3d fission	4th fission
V_{pf}	5.871492	5.678481	5.514261	5.68
P_{k1}	3.109137	1.638118	1.010123	1.64
P_{k2}	0.222279	0.0546934	0.134143	0.055
δ	0.622767	1.116893	0.562664	0.756084
$\hbar w$	0.441609	0.652	0.79	0.65
a	28.488922	29.175522	28.418579	29.07745

2.3 Direct Interaction

In the high neutron energy range the direct interaction need to be considered, which is obtained from an assistant program based on coupled channel optical model by Shen Qingbiao[37].

3 THE RESULTS FROM CALCULATION AND THE DATA RECOMMENDATION

From Fig. 1 to Fig. 3, one sees that:

For σ_{nf} (E), the caloulated data are fully consistent with experimetal data in $E<14$ MeV. Above 14 MeV, the measured data by Behrens et al. are lower about 10% in maximum.

For $\sigma_{n\gamma}$ (E), the data are consistent each others in $E<1$ MeV. Above 1.2 MeV, the calculated data are higher than measured ones.

For $\sigma_{n,2n}$ (E), the data are also consistent.

Therefore our recommendation is as follows:

3.1 In 30 keV$<E<$20 MeV Region

For $\sigma_{n.f}$ (E), the fitted experimental data are recommended. For $\sigma_{n\tau}$ (E), the fitted experimental data are recommended in 30 keV$<E<$2.75 MeV; above 3 MeV the calcuated data are used and the data are smoothly connected in 3 MeV point. For all other data of reaction channels σ_t (E), $\sigma_{n,2n}$ (E), $\sigma_{n,3n}$ (E), σ_{el} (E), integrated inelastic cross section σ_{in} (E), secondary neutron spectrum and the angular distribution of the secondary neutrons, the calculated data are used. During the self consistent adjusting, following relations are kept:

$$\sigma_{non}(E)=\sigma_{nf}(E)+\sigma_{n,\gamma}(E)+\sigma_{in}(E)+\sigma_{n,2n}(E)+\sigma_{n,3n}(E)$$

$$\sigma_{el}(E)=\sigma_t(E)-\sigma_{non}(E)$$

3.2 In $E<30$ keV Region

In the energy range of 10^{-5}eV to 130 eV, resolved resonance parameters are given; In the energy range of 130 eV to 30keV, the unresolved resonaance parameters are given. All the parameters in that energy range were taken from the Westens' evaluated data[28].

All recommended data (include files 1~ 5) are stored into CENDL−2 in ENDF / B format. The data for all reaction channles are shown in Fig. 4.

4 DISCUSSION AND CONCLUSION

For σ_{nf}, the evaluation included all newly measured data [17~25] and all the relatively measured data were renormalized using ENDF / B−6 standard data.

For $\sigma_{n\gamma}$ data, the newly measured data by Weston (1981)[28] and Davletsshin (1985)[29] were included in the evaluation, therefore the fitted experimental data are recommended and might be more reliable.

The comparison of the evaluated data and JENDL−2, ENDF / B−5 is shown in Fig. 5.

ACKNOWLEDGMENTS

Much thanks for Dr. Liang Qichang, who gave us useful help during the evaluation, and for Chinese Nuclear Data Center, from which we got financial support.

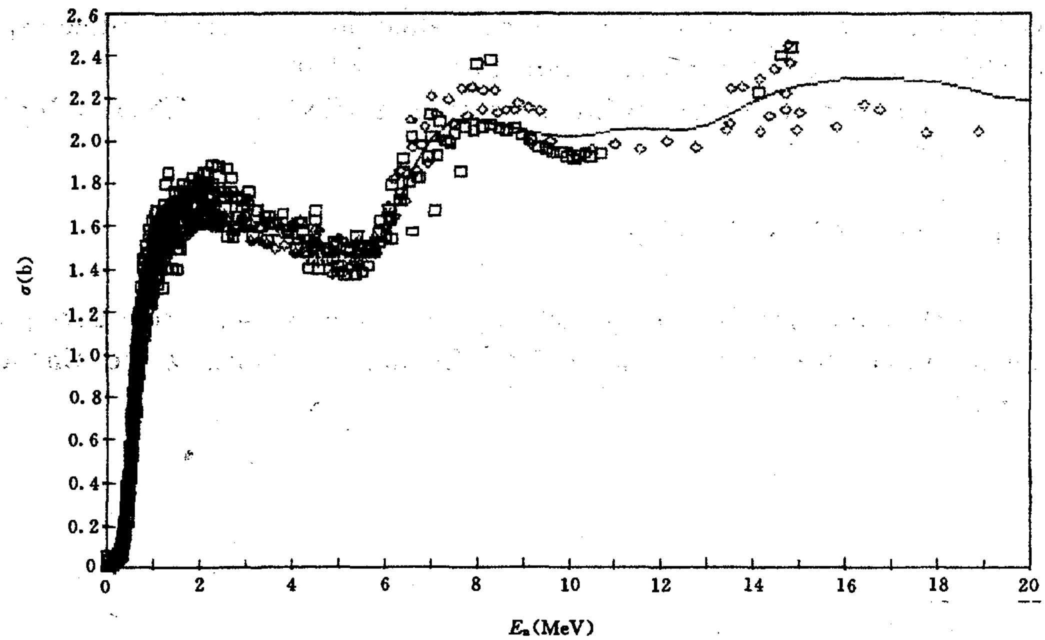

Fig. 1 $^{237}Np(n,f)$ experimental and calculated data

□ ◇ exp. data ——— calculalted data

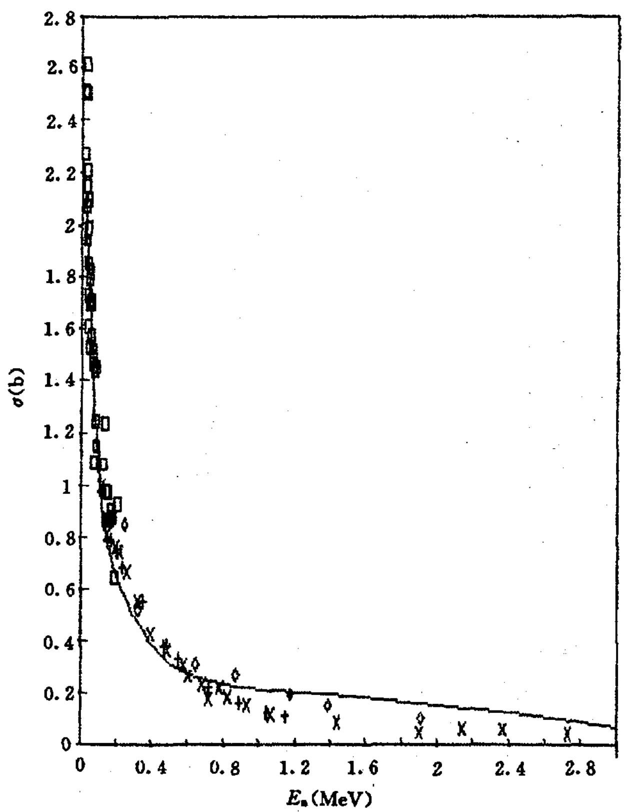

Fig. 2 $^{237}Np(n,\gamma)$ experimental and calculated data

□ + ◇ × exp. data ——— calculalted data

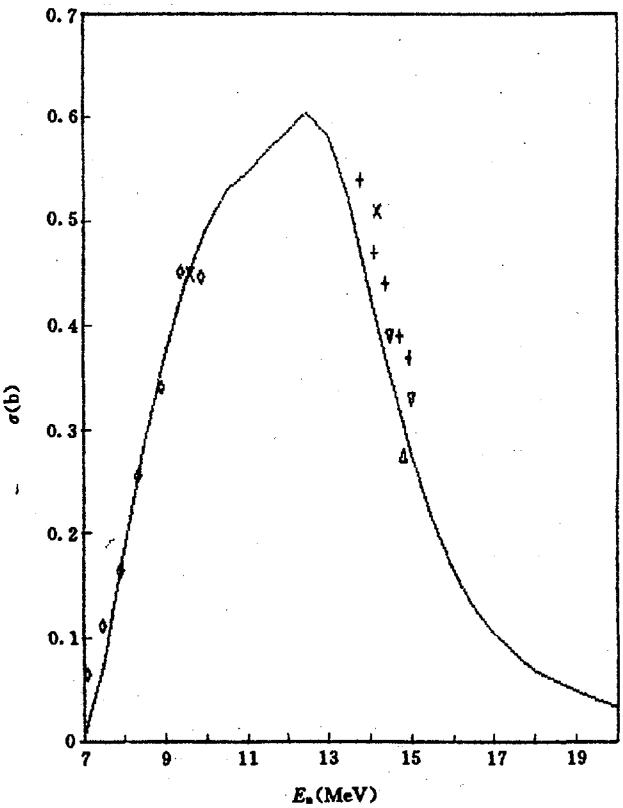

Fig. 3 $^{237}Np(n,2n)$ experimental and calculated data

+ ◇ △ × ▽ exp. data ——— calculated data

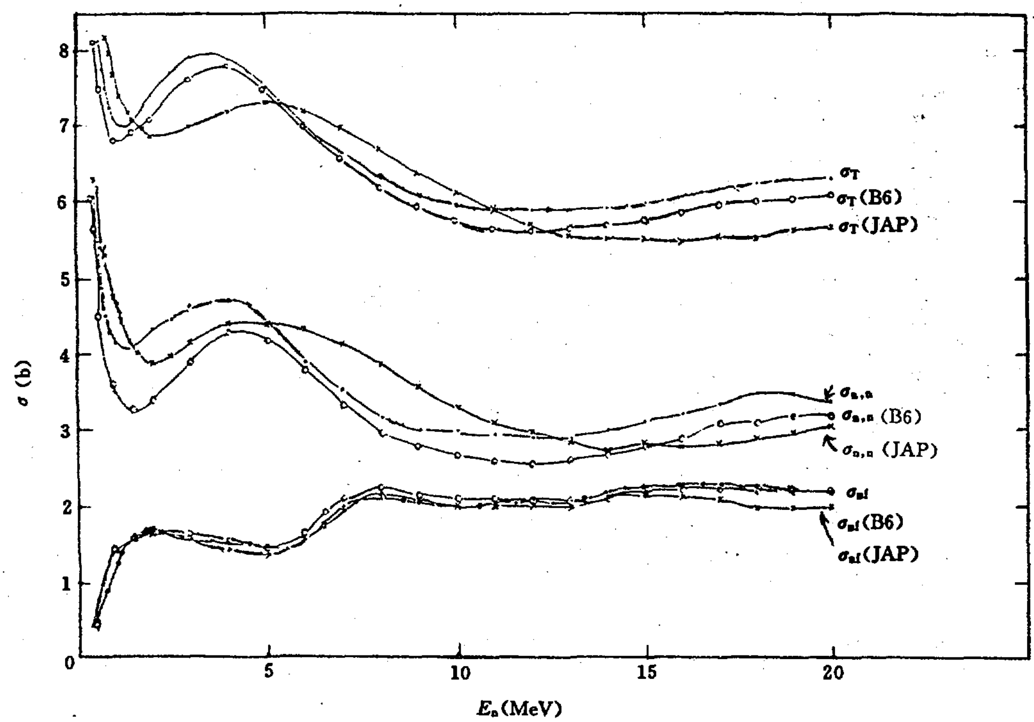

Fig. 4–A Comparison of present evaluated data with

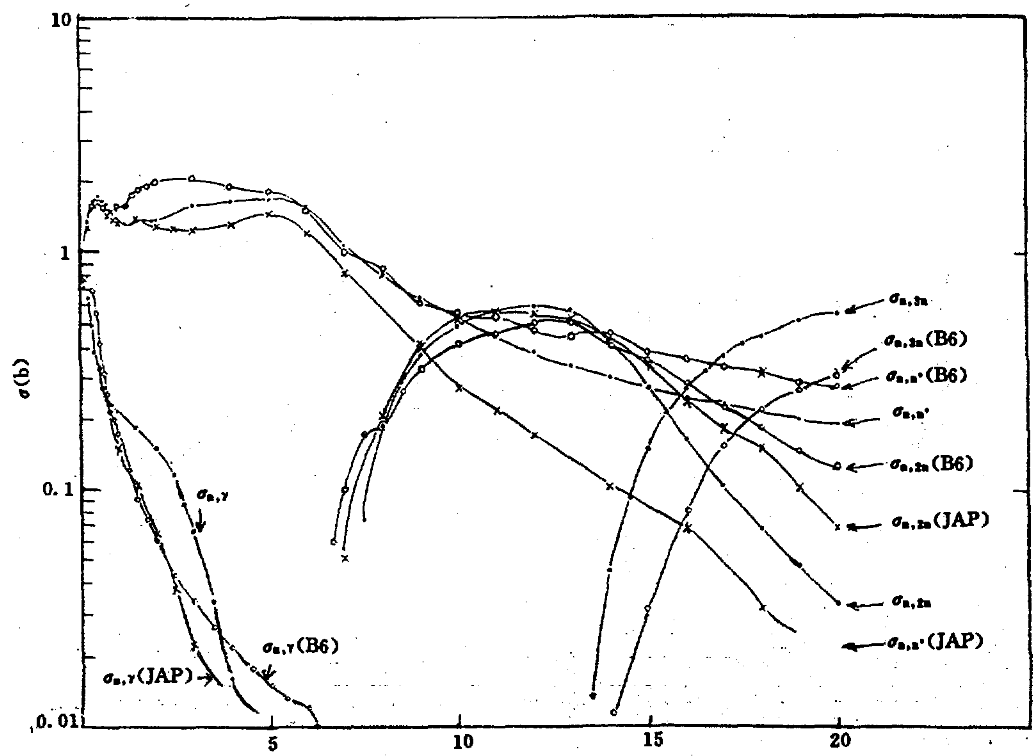

Fig. 4–B Comparison of present evaluated data with those of ENDF / B–6 and JENDL–2

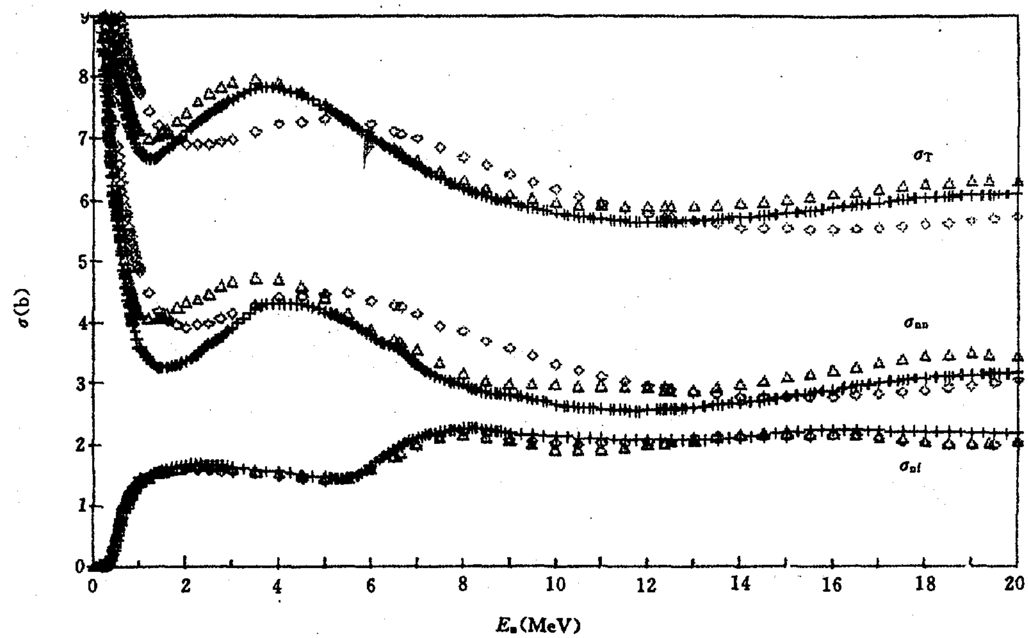

Fig. 5a Comparison of this work to other works

+ ENDF / B-6 ◇ JENDL △ This work

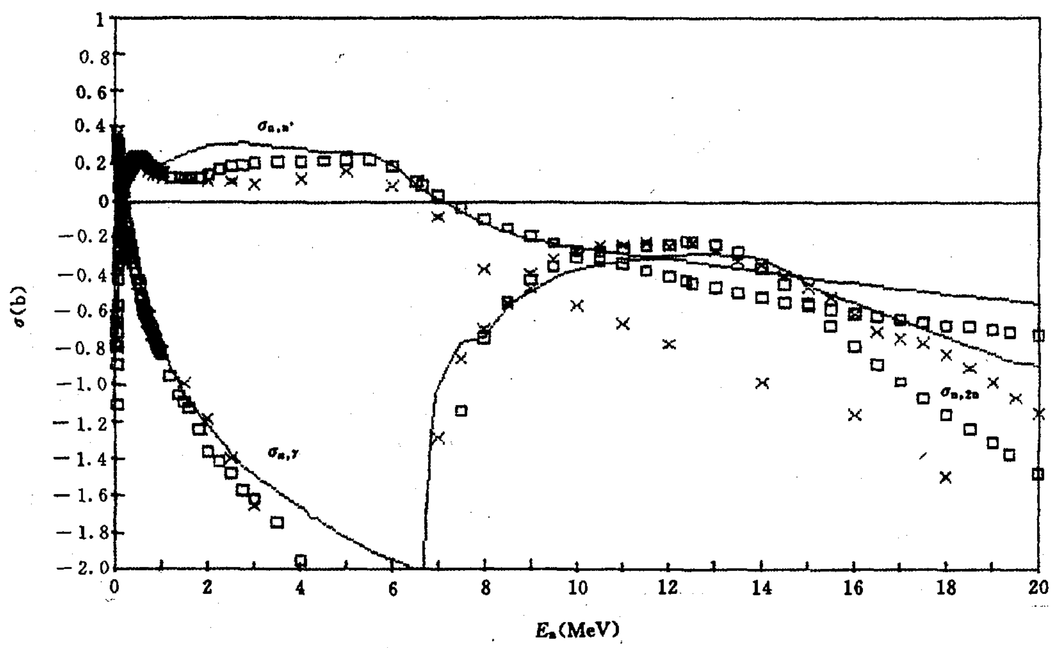

Fig. 5b Comparison of this work to other works

□ This work —— ENDF / B-6 × JENDL-2

REFERENCES

[1] USA ENDF / B–6
[2] N. Wachi et al., JAERI–M 84–103
[3] H. Derrien et al., INDC (FR)–41 / L (1989)
[4] A. E. Protopopove et al., AE 4(2) (1958)
[5] B. G. Gokhery et al., DOK 128(6), 1157(1959
[6] S. P. Kalinin et al., 58 Genva, 16, 134(2149)
[7] H. W. Schmit et al., PR 116, 1575(1959)
[8] P. H. White et al., 65 Salzurg 1 219; JNE 21, 671(1967)
[9] J. L. Perkin et al., JNE / AB, 19, 423(1965)
[10] J. A. Grundl et al., NSE. 30, 39(1976)
[11] W. K. Brown et al., NP / A 156, 609(1970)
[12] R. J. Jiacoletti et al., NSE. 48, 412(1972
[13] W. Kobayaski et al., KURRI–TR–6, 1(1973)
[14] S. Plattard et al., Plattard–7311
[15] J. D. Alknaiov et al., 77 Kiev, 3, 155
[16] D. J. Grady et al., 79 Knoxvill, 976
[17] J. W. Behrens et al., NSE 80, 393(1982)
[18] M. Cance et al., 82 Antwerp 51
[19] J. W. Meadows et al., NSE 85, 271(1983)
[20] R. Arlt et al., KE 24, 465(1984)
[21] M. Varnagy et al., NIM 196, 465(1982)
[22] I. Garlea et al., INDC (ROM) / 15 (1983)
[23] Wu Jingxia et al., CNP 6, 369(1984)
[24] K. Kanda et al., JAERI–M–85–035, 220(1985)
[25] A. A. Goverdovskij et al., AE 58(2), 271(1985); FEI–1552(1984)
[26] M. Lindner et al., NSE 59, 381(1976)
[27] Ju. N. Trofimor et al., 83 Kiev 2, 142
[28] L. Weston et al., NSE 79, 184(1981)
[29] A. N. Davletshin, 83 Kiev 2, 189
[30] J. L. Perkin et al., JNE 14, 69(1961)
[31] J. H. Landrum et al., PR / C 8, 1938(1973)
[32] K. Linere et al., PR / C 12, 1507(1975)
[33] T. Nishi et al., NEANDC(J)–421, 20(1975)
[34] J. A. Gromova et al., AE 54, 117(1983)
[35] N. V. Kornilov et al., AE 58, 117(1985)
[36] Cai Chonghai et al., Internal Report of Nankai Univ. FUP1
[37] Shen Qingbiao et al., Hsj–78224(11js)

THE SUMMARY OF EVALUATIONS OF ^{1}H, ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{14}N, ^{16}O AND Mo FOR CENDL–2

Liang Qichang

(CHINESE NUCLEAR DATA CENTER, IAE)

The evaluations[1] of neutron nuclear data of ^{1}H, ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{14}N, ^{16}O and Mo were completed by various evaluators for CENDL–1 before 1985. Due to the conditions at that time, these evaluated data sets are not complete for general purpose file, for example, the incident neutron energy range are only from 1 keV to 20 MeV, and in most cases, the angular and energy distributions of secondary neutrons are not given, except the angular distribution of elastic scattering neutron.

In order to meet the requirement of the nuclear engineering, nuclear science and technology, and to prepare the CENDL–2, the complete evaluated neutron nuclear data for the nuclides mentioned above are needed, so the re–evaluation or extensively revision of neutron nuclear data of these nuclides are expected.

In the general, the main purpose of the re–evaluation of these nuclides is to improve and update the earlier evaluations, such as to extend the incident neutron energy to thermal energy region, supplement the data type (MF1–MF5) of evaluations and newly experimental data, and adopt the improved theoretical model calculation results. Unfortunately, due to many reasons, the previous evaluators could not undertake the re–evaluation of these nuclides; on the other hand, no improved method of theoretical model calculation for the light nuclides has been developed and available in CNDC and its network since 1985. In these cases, the re–evaluation of these nuclides were only based on the earlier evaluations contained in CENDL–1, and supplemented with the existing foreign libraries, such as ENDF / B–6, JENDL–3 and BROND. The cross sections taken from different libraries were adjusted to ensure the continuall connection at 1 keV and consistent in physics.

All the re–evaluation data sets were checked by using the ENDF Utility Codes and then accepted and stored in CENDL–2.

These evaluations should be further perfect if the improved theoretical model method for calculating the data of light nuclides would be available in

CNDC.

REFERENCE

[1] CNDC, Chinese Evaluated Nuclear Data Library, Version–1 (CENDL–1), 1986 (in Chinese)

CINDA INDEX

Nuclide	Quantity	Energy (eV) Min.	Max.	Lab	Type	Documentation Ref.	Vol.	Page	Date
^{1}H	Evaluation	1.0–5	2.0+7	AEP	Eval	Jour CNDP	6	298	Dec 91
^{2}H	Evaluation	1.0–5	2.0+7	AEP	Eval	Jour CNDP	6	7	Dec 91
^{3}H	Evaluation	1.0–5	2.0+7	〃	Eval	Jour CNDP	6	14	Dec 91
^{3}He	Evaluation	1.0–5	2.0+7	〃	Eval	Jour CNDP	6	22	Dec 91
^{4}He	Evaluation	1.0–5	2.0+7	〃	Eval	Jour CNDP	6	298	Dec 91
^{6}Li	〃	1.0–5	2.0+7	〃	Eval	Jour CNDP	6	298	Dec 91
^{7}Li	〃	1.0–5	2.0+7	〃	Eval	Jour CNDP	6	298	Dec 91
^{9}Be	〃	1.0–5	2.0+7	〃	Eval	Jour CNDP	6	298	Dec 91
^{10}B	〃	〃		TSI	Eval	Jour CNDP	6	24	Dec 91
^{11}B	〃	〃		TSI	Eval	Jour CNDP	6	25	Dec 91
^{14}N	〃	〃		AEP	Eval	Jour CNDP	6	298	Dec 91
^{16}O	〃	〃		AEP	Eval	Jour CNDP	6	298	Dec 91
^{19}F	〃	〃		AEP	Eval	Jour CNDP	6	26	Dec 91
Mg	〃	〃		SIU	Eval	Jour CNDP	6	30	Dec 91
Al	〃	〃		AEP	Eval	Jour CNDP	6	36	Dec 91
Si	〃	〃		BJG	Eval	Jour CNDP	6	42	Dec 91
S	〃	〃		NAN	Eval	Jour CNDP	6	47	Dec 91
K	〃	〃		NAN	Eval	Jour CNDP	6	53	Dec 91
Ti	〃	〃		LNZ	Eval	Jour CNDP	6	64	Dec 91
V	〃	〃		SIU	Eval	Jour CNDP	6	77	Dec 91
Cr	〃	〃		SIU	Eval	Jour CNDP	6	94	Dec 91
Fe	〃	〃		AEP	Eval	Jour CNDP	6	108	Dec 91
Ni	〃	〃		SIU	〃	Jour CNDP	6	127	Dec 91
Cu	〃	〃		SIU	〃	Jour CNDP	6	142	Dec 91
Zr	〃	〃		SIU	〃	Jour CNDP	6	158	Dec 91
Nb	〃	〃		SIU	〃	Jour CNDP	6	173	Dec 91
Mo	〃	〃		AEP	〃	Jour CNDP	6	298	Dec 91
Ag	〃	〃		FUD	〃	Jour CNDP	6	187	Dec 91
^{107}Ag	〃	〃		AEP	〃	Jour CNDP	6	194	Dec 91
^{109}Ag	〃	〃		AEP	〃	Jour CNDP	6	194	Dec 91
Sn	〃	〃		LNZ	〃	Jour CNDP	6	210	Dec 91
Sb	〃	〃		LNZ	〃	Jour CNDP	6	220	Dec 91
^{181}Ta	〃	〃		LNZ	〃	Jour CNDP	6	230	Dec 91
W	〃	〃		SIU	〃	Jour CNDP	6	242	Dec 91
^{197}Au	〃	〃		AEP	〃	Jour CNDP	6	249	Dec 91
Pb	〃	〃		SIU	〃	Jour CNDP	6	268	Dec 91
^{238}U	〃	〃		BJG	〃	Jour CNDP	6	279	Dec 91
^{237}Np	〃	〃		BJG	〃	Jour CNDP	6	287	Dec 91

Author, Comments
Liang Qichang, FOR CENDL–2
Zhuang Youxiang+, FOR CENDL–2
Zhuang Youxiang, FOR CENDL–2
Zhao Zhixiang, FOR CENDL–2
Liang Qichang, FOR CENDL–2
Liang Qichang, FOR CENDL–2
Liang Qichang, FOR CENDL–2
Liang Qichang, FOR CENDL–2
Chen Qiankun+, CENDL–2
Qi Huiquan, FOR CENDL–2
Liang Qichang, FOR CENDL–2
Liang Qichang, FOR CENDL–2
Zhao Zhixiang+, FOR CENDL–2 and ENDF / B–6
Tang Guoyou+, CENDL–2
Liu Jicai+, FOR CENDL–2
Tang Guoyou+, FOR CENDL–2
Shi Yi+, FOR CENDL–2
Han Min+, FOR CENDL–2
Yao Lishan, FOR CENDL–2
Zou Yiming+, FOR CENDL–2
Ma Gonggui+, FOR CENDL–2
Liu Tingjin+, FOR CENDL–2
Ma Gonggui+, FOR CENDL–2
Zou Yiming+, FOR CENDL–2
Zou Yiming+, FOR CENDL–2
Ma Gonggui+, FOR CENDL–2
Liang Qichang, FOR CENDL–2
Wang Yansen+, FOR CENDL–2
Liu Tingjin+, FOR JENDL–3 AND CENDL–2
Liu Tingjin+, FOR JENDL–3 AND CENDL–2
Yao Lishan, FOR CENDL–2
Yao Lishan, FOR CENDL–2
Yao Lishan, FOR CENDL–2
Ma Gonggui+, FOR CENDL–2
Yuan Hanrong+, FOR CENDL–2
Zou Yiming+, FOR CENDL–2
Tang Guoyou+, FOR CENDL–2
Tang Guoyou+, FOR CENDL–2

核数据进展通讯
原子能出版社出版
(北京 2108 信箱)
中国核数据中心激光照排
北京市海淀区三环快速印刷厂印刷
☆
开本 787×1092 1/16 · 印张 21 · 字数 300 千字
1992 年 4 月北京第一版 · 1992 年 4 月北京第一次印刷
ISBN 7-5022-0646-9
TL · 385

COMMUNICATION
OF
NUCLEAR DATA
PROGRESS

No. 6 (1991)

ISBN 7-5022-0646-9
TL · 385