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EDITORIAL NOTE

This is the seventh issue of *Communication of Nuclear Data Progress* (CNDP), in which the nuclear data progress in China during the last year is carried. It includes nuclear data measurement, theoretical model calculation, evaluation, library, systematics research, processing and news, as well as atomic and molecular data; in detail, 14 MeV neutron activation cross section, nuclear decay data, inelastic angular distribution, integral prompt spontaneous fission neutron spectrum and α spectrum measurements of reaction $^{40}Ca(n,\alpha)$; programs UNF — for fast neutron data calculation of structural materials, APCOM and APOM — for searching optimal charged particle and neutron optical potential parameters respectively, p + ^{63}Cu reaction calculation in energy region 3~ 55 MeV; evaluation of $^{197}Au(n,2n)^{196}Au$ cross section, progress on nuclear structure and decay data evaluation for A–chain and so on; a database on ion–atom collision processes, and evaluation of trapping and desorption data; systematics calculation of nuclear data for radiation damage assessment and related safety aspects, and systematics of (n,t) and (n,^{3}He) reaction cross sections at 14 MeV, construction of covariance matrix for experimental data, spline fit for multi–sets of correlative data etc..

For the limited experience and knowledge, there might be some shortcomings and errors, welcome to make comments about them.

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I EXPERIMENTAL MEASUREMENT

RECENT PROGRESS ON 14 MeV NEUTRON ACTIVATION CROSS SECTION MEASUREMENTS

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The activation cross section data of 14 MeV neutrons are important for development of fusion power reactors. The activation cross sections leading to the production of long-lived radionuclides especially attract the human attention, for they effect a series of problems, such as re-applying the old structure meterial of a fusion reactor, reducing its radiation background and disposing the nuclear waste, etc.. So a Coordinated Research Program was organized by the IAEA to measure some activation cross sections leading to the production of long-lived radionuclides in 1988. Since June, 1990 we have measured some activation cross sections for the generations of long-lived radionuclides and obtained useful results at the Intense Neutron Generator of Lanzhou University. The results obtained are given in Table 1[1].

* The paper is writen by Yuan Junqian

Table 1 Values of activation cross sections for the generations of long-lived radionuclides

Neutron energy (MeV)	Cross section (mb) $^{151}Eu(n,2n)^{150m}Eu$	$^{153}Eu(n,2n)^{152}Eu$	$^{159}Tb(n,2n)^{158}Tb$
13.54 ± 0.05	1227 ± 47	1469 ± 117	
13.72 ± 0.06	1238 ± 48	1467 ± 113	2077 ± 277
14.35 ± 0.09	1165 ± 44	1502 ± 118	2144 ± 112
14.60 ± 0.11	1168 ± 44	1496 ± 118	1909 ± 85
14.80 ± 0.11	1170 ± 44	1596 ± 118	1922 ± 89

Neutron energy (MeV)	Cross section (mb) $^{109}Ag(n,2n)^{108m}Ag$
13.64 ± 0.05	223 ± 7
13.79 ± 0.06	223 ± 18
14.03 ± 0.07	227 ± 20
14.33 ± 0.09	224 ± 8
14.60 ± 0.11	232 ± 8
14.80 ± 0.11	236 ± 7

Some activation cross sections for the rare nuclear reactions and interesting reactions were also measured. The results obtained are given in Tables 2 and 3 respectively.

Table 2 Values of activation cross sections for some rare nuclear reactions[21]

Reaction	Neutron energy (MeV)	Cross section
	13.6 ± 0.1	414 ± 38 mb
	13.8 ± 0.1	445 ± 41 mb
	13.9 ± 0.1	455 ± 43 mb
$^{58}Ni(n,x)^{57}Co$	14.1 ± 0.1	487 ± 46 mb
	14.3 ± 0.1	521 ± 50 mb
	14.6 ± 0.1	541 ± 53 mb
$^{92}Mo(n,x)^{91m}Nb$	14.7 ± 0.2	64 ± 6 mb
$^{106}Cd(n,x)^{105}Ag$	14.7 ± 0.1	256 ± 83 mb
$^{54}Fe(n,t)^{52m,g}Mn$	14.7 ± 0.1	80 ± 8 μb
$^{58}Ni(n,t)^{56}Co$	14.5 ± 0.2	92 ± 26 μb
$^{51}V(n,n'\alpha)^{47}Sc$	14.5 ± 0.2	105 ± 15 μb
$^{92}Mo(n,n'\alpha)^{88}Zr$	14.5 ± 0.2	124 ± 38 μb

Table 3 Values of activation cross sections for the interesting reactions[3,4]

Neutron	Cross section (mb)		
energy (MeV)	$^{50}Ti(n,\alpha)^{47}Ca$	$^{46}Ti(n,p)^{46}Sc$	$^{48}Ti(n,p)^{48}Sc$
13.50	6.6 ± 0.5	306 ± 15	61.3 ± 2.8
13.84	7.4 ± 0.5	286 ± 14	62.4 ± 2.7
14.18	8.0 ± 0.5	299 ± 13	64.4 ± 2.7
14.38	8.9 ± 0.5	306 ± 13	65.7 ± 2.7
14.67	9.6 ± 0.5	294 ± 12	63.5 ± 2.6
14.81	9.5 ± 0.6	305 ± 12	65.5 ± 2.6

Neutron	Cross section (mb)	
energy (MeV)	$^{58}Ni(n,2n)^{57}Ni$	$^{58}Ni(n,p)^{58mg}Co$
13.64	13.0 ± 0.5	442 ± 16
13.79	16.9 ± 0.6	434 ± 16
14.00	22.8 ± 0.8	403 ± 13
14.21	26.6 ± 0.8	367 ± 11
14.43	30.5 ± 0.9	328 ± 0.9
14.62	34.2 ± 1.0	318 ± 8

Neutron	Cross section (mb)			
energy (MeV)	$^{98}Mo(n,\alpha)^{95}Zr$	$^{95}Mo(n,p)^{95m}Nb$	$^{95}Mo(n,p)^{95g}Nb$	$^{181}Ta(n,p)^{181}Hf$
13.5 ± 0.05	5.3 ± 0.4	6.5 ± 1.0	34.5 ± 1.7	2.47 ± 0.12
13.66 ± 0.05	5.5 ± 0.5	6.7 ± 1.0	34.6 ± 1.7	2.63 ± 0.12
14.29 ± 0.07	5.3 ± 0.4	7.0 ± 1.0	35.2 ± 1.8	3.40 ± 0.14
14.37 ± 0.07	5.4 ± 0.3	7.1 ± 1.1	35.0 ± 1.8	3.42 ± 0.14
14.70 ± 0.11	5.5 ± 0.3	7.3 ± 1.2	35.5 ± 1.8	3.63 ± 0.15
14.80 ± 0.11	5.6 ± 0.3	7.5 ± 1.2	36.5 ± 1.9	3.71 ± 0.15

A few papers on the reactions as stated above have been published and are to be published (see Refs.). In this paper the measurements of activation cross sections for $^{209}Bi(n,2n)^{208}Bi$, $^{179}Hf(n,2n)^{178m2}Hf$ and $^{108}Cd(n,p)^{108m}Ag$ reactions which have not been published yet are described in detail.

The samples of 20 mm diameter were pressed by the powder of HfO_2 and the metal powder of Bi with natural isotopic composition and were packed in nylon gluey tape to protect the powder from losing after weighing. The sample disc of Cd with 30 mm in diameter and 0.8 mm in thickness was made by natural metal foil. The samples in question were sandwiched between two niobium

foils to evaluate the neutron fluence on the samples. The sample of HfO_2 was wrapped in 0.5 mm thickness Cd foil to reduce the activities of $^{178m2}Hf$ from $^{177}Hf(n,\gamma)^{178m2}Hf$ reaction induced by thermal neutrons.

Irradiations were carried out by neutron source of $T(d,n)^4He$ reaction at the Intense Neutron Generator of Lanzhou University.

The distance of the samples from target is about 8 mm . The irradiation lasted up to 12 h. with neutron intensity of about $1\sim3\times10^{12}$ n / 4π.s. The cooling time of the sample was 360 d.

The radioactivity of the reaction products was assayed by γ–ray spectroscopy using a CH8403 coaxial HPGe detector made in China in conjunction with a EG & G ORTEC 7450 Multichannel Analyzer. The efficiency of the detector was calibrated by using the standard γ source, SRM4275, made in U. S. A.[5]. The relative photopeak detection efficiency of the detector was known within an error of ± 1.5%. The decay data used in the present work were listed in Table 4 and taken from literature[6]. In the measurement of γ activities, some corrections were made for the effect of neutron fluence fluctuation and γ–ray self absorption in the sample, the coincidence sum effect in the investigated nuclide and the counting geometry, etc..

The results of measurement are also given in Table 4. The values of reference cross sections used in calculation of the results were taken from literature[7]. Since the samples were quite near target the correction was not made for contribution of low energy neutron (n,γ) reaction to the $^{179}Hf(n,2n)^{178}Hf$ reaction.

Table 4 Data and measured cross sections

Reaction	E_0 (MeV)	C. S. (mb)	Ab. (%)	$T_{1/2}$ (y)	E_r (keV)	I_r (%)
$^{179}Hf(n,2n)^{178m2}Hf$	14.8	6.04 ± 0.32	13.629	31	495	68.9
$^{209}Bi(n,2n)^{208}Bi$	14.6	2194 ± 166	100	3.68×10^5	2614	99.79
$^{108}Cd(n,p)^{108m}Ag$	14.6	12 ± 3	0.88	418	434	90.5

The major uncertainties of the measured results include the reference cross section, the counting statistics, the relative efficiencies of the detector, the weight of the sample, self absorption of γ–ray, and the coincidence sum effects of cascade γ–ray.

We thank professsor Lu Hanlin for much help to our work.

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PROGRESS ON NUCLEAR DECAY DATA MEASUREMENT AT NUCLEAR PHYSICS LABORATORY, JILIN UNIVERSITY

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Last year nuclear decay data of three nuclides were measured. These nuclides are ^{152}Eu, ^{99}Mo and ^{182}Ta. The γ-rays emitted in the decays of ^{152}Eu, ^{99}Mo and ^{182}Ta have been re-investigated. As the results of these studies many discrepancies in the literatures have been clarified and some errors were corrected.

Our result of ^{182}Ta decay shows that the five new levels reported in the latest study are not related to the decay of ^{182}Ta. The Referee's report of Z. Phys. Germany, on our paper of ^{182}Ta indicated that in this work the γ spectroscopy of the ^{182}Ta β-decay has been improved and essentially shown that the five new levels proposed in Ref. [1] are not existent. It solves therefore a problem, which was raised already in the recent $A = 182$ compilation (R. B. Firestone, Nu-

clear Data Sheets, Vol. 54, 307 (1988)).

PROGRESS ON NUCLEAR DATA MEASUREMENT IN PEKING UNIVERSITY IN 1991

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1 DEVELOPMENT OF EQUIPMENTS

1.1 4.5 MV Single End Van de Graaff Accelerator

The machine in the year has got some progress as following :

1) In order to solve the problem why the high voltage is not possible to be high enough a new accelerator tube has been mounted to the machine and the result confirmed that the main problem is the shielding for secondary electron. Therefore, a new high voltage tube bought from Oxford University will be mounted to the machine before May, 1992.

2) The vacuum condition has been improved from two sides : a light leak position was found in focus system of the head part; the oil defusing pump was replaced by a molecular pump to reduce the oil contamination.

3) The experimental measurement of $^{40}Ca(n,\alpha)$ reaction was carried out for total 200 hours at high voltage about 2 MeV with D(d,n) neutron source at beam intensity about 6 μA (ion source of D_2^+ was used) with the machine in 1991. Because the PIG ion source used at this moments is not suitable for light ions, a high frequency source will be mounted to the machine to increase the beam intensity up to 50 μA in 1992.

4) The pulse punch system in head has been tested and the problem for the system has been found up to end of 1991. The system is expected to be ready in 1992.

1.2 EN-18 Tandem Accelerator

The tandem accelerator already ran for total 2500 hours in 1991. The most beam time of the accelerator was for testing of AMS (Accelerator Mass Spectroscopy) line, with which ^{14}C can be well separated and ^{10}Be will be tested for next step.

The minor beam time of the machine was for ion beam analysis technique, which are the Heavy Ion Back Scattering Analysis (HIBSA) and Elastic Recoil Detection Analysis (ERDA). The result of HIBSA shows that the energy resolution of HIBSA is much better as compared to alpha RBS. The sample used was a film of high temperature super conductor material of YBCUO on Ti background. ^{12}C was used as incident particle. Using ERDA technique, light elements O, N and H in semiconductor material were analyzed simultaneously and the concentration changing roles were investigated under different temperature. Using the same method the process of formation of $CoSi_2$ crystal in Co / Si system was reached at temperature about 850 °C.

Some of beam time of the machine was used to measure the stopping power at energy range about 0.4 MeV / amu. Some new methods for the measurement were developed, such as the ERHD (Elastic Recoil Hydrogen Detection) method, with which the hydrogen recoil peaks on surface and between the layers were measured. Because the thickness was well determined and the energy difference was known by the measurement, from which the stopping power was determined.

2 WORKS RECENTLY COMPLETED AND IN PROGRESS

2.1 Measurement of $^{7}Li(n,n')$ (478 keV) Inclastic Angular Distribution

The measurement was done at neutron energy 14.9 MeV via the method of shape analysis of Doppler shifted γ-ray spectra in 5 laboratory angles[1]. This work was cooperated with the Low Energy Nuclear Physics Institute, Beijing Normal University. The data were also calculated by using the code DUCK4, which was slightly modified in order to meet the parameter auto-research on Optical Model. The calculation was carried out in energy range 8 to 20 MeV in step 2 MeV[2].

2.2 The Measurement of the Integral Prompt Spontaneous Fission Neutron Spectrum

This is a relative measurement of ^{248}Cm to ^{252}Cf, which was cooperated with Dr. M. V. Blinov, V. G. Hhloping Radium Institute, Leningrad, USSR.

The primary results show that the neutron spectrum in the energy range below 500 keV has a extra component compared with Maxwell distribution at t = 1.38 MeV[3].

2.3 The Double Differential Cross Section Measurement of Carbon

The measurement was carried out at 14.9 MeV neutron energy, which is coopeated with the Low Energy Nuclear Institute of Beijing Normal University. This measurement was also a preparation for further measurement at our 4.5 MeV Van de Graaff accelerator at our institute for other elements. The Van de Graaff was designed by ourselves and produced in Shanghai, China. Now it is just time before normal running.

2.4 The Measurement of the (n,p), (n,α) Reaction

The reactions of (n,p), (n,α) are very impotant both for theoretical research on research of nuclear reaction mechanism and nuclear structure and for applications of nuclear data measurement. Therefore a international cooperation program between Joint Nuclear Research Center of Peking University, Tsinghua University, Beijing Normal University (PTNNC), which located in Institute of Heavy Ion Physics, Peking University and the Joint Institute of Nuclear Research (JINR), Dubna, Russian Republic is going on. The detector is a quadruple grided ion chamber made by JINR, the sample of CaF_2 was made in PTNNC and the sample of ^{64}Zn was made by JINR. The experiment was carried out by using 4.5 MeV Van de Graaff Machine at high voltage of 2 MV of D_2^+ beam at beam curent of 6～8 μA in Institute of Heavy Ion Physics, Peking University. The two dimensional picture is shown in Fig. 1.

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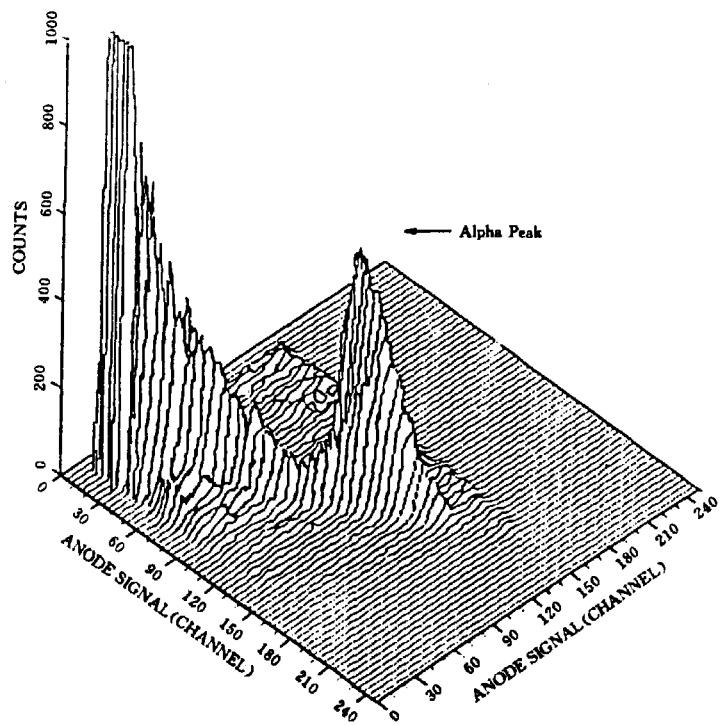

Fig. 1a Two dimensional picture of anode and cathode signal from gridcd ion chamber for reaction $^{40}Ca(n,\alpha)$

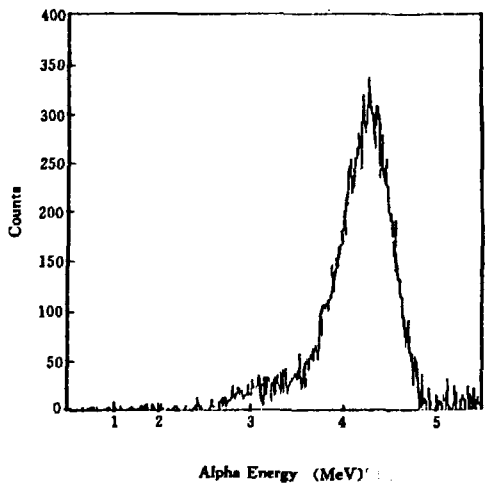

Fig. 1b α spectrum for reaction $^{40}Ca(n,\alpha)^{37}Ar$ at $E_n = 4.0$ MeV

II THEORETICAL CALCULATION

UNF PROGRAM OF FAST NEUTRON DATA CALCULATION FOR STRUCTURAL MATERIALS

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ABSTRACT

The master equation theory of precompound and compound nuclear reaction has been generalized to the inclusion of the conservation of angular momentum and parity. Based on this improved semi-classical theory the code UNF has been developed as an evaluation tool of the calculations of nucleon induced reaction cross sections and double differential cross sections. For structural materials at incident neutron energies below 20 MeV, it is demonstrated that the constructed model contains the Hauser-Feshbach, Weisskopf-Ewing as well as the exciton models as limiting cases. The unified treatment of pre-equilibrium processes includes a number of interesting features, such as: the exciton state densities with the exact Pauli exclusion correction which are renormalized to the back-shifted Fermi-gas formula; the introduction of formation factors of composite particle in calculations of pick-up type composite particle emission and the double differential cross sections (D.D.X.) for all kinds of particles in terms of the leading particle model.

INTRODUCTION

In recent years pre-equilibrium nuclear reaction theories have been developed with great successful for the description of the double differential cross

sections based on the exciton model. This success was mainly due to introducing a leading particle into the generalized exciton model[1] and application of the pick–up mechanism for composite particle emissions[2, 3]. For the purpose to calculate the complete set of fast neutron data, a new semi–classical model of multi–step nuclear reaction processes has been proposed, in which the discrete level effect in multi–particle emissions was included as well as the pre–equilibrium phenomenon combining with the parity conservation and angular momentum conservation.

In section 2 the basic formulation of the semi–classical theory of multi–step reaction processes are given. Section 3 is devoted to the description of the double differential cross sections and some related contents. The functions of UNF code are given in section 4. Some calculated results with UNF code are shown in the last section. The calculation for n + ^{56}Fe shows that the semi–classical model can rather nicely reproduce the experimental data of the total neutron spectra and the double differential cross sections. The calculated results of the spectra for (n,α), (n,d) and (n,t) indicate that the pick–up mechanism plays an important role in the pre–equilibrium composite particle emissions.

With the increasing of incident energies the components of the pick–up picture increase obviously. In particular to the composite particle with large binding energies, like d, t and ^{3}He, the pick–up components are always the dominant parts. Therefore, the pick–up mechanism must be taken into account in the composite particle emission processes, which has been included in UNF code.

To keep the energy conservation the recoil nucleus effects are also taken into account.

1 BASIC FORMULATION OF SEMI–CLASSICAL THEORY

The Hauser–Feshbach model is successful in the equilibrium reaction processes, but the pre–equilibrium effects are exclusive. The exciton model is a useful tool to describe the pre–equilibrium phenomenon but it is unable to account the parity and angular momentum conservations. For this reason, to develop a new theory that includes both the success of these two model, a semi–classical model has been proposed.

The energy spectrum formula reads

$$\frac{d\sigma}{d\varepsilon} = \sum_{J\pi} \sigma_a^{J\pi} \sum_n P^{J\pi}(n) \frac{T_b^{J\pi}(n,E,\varepsilon)}{T_t^{J\pi}(n,E)} \qquad (1)$$

where E is the excitation energy,

ε is the energy of emitted particle,

$\sigma_a^{J\pi}$ stands for the absorption cross section in $J\pi$ channel,

$T_b^{J\pi}(n,E,\varepsilon)$ is the T factor of emitted particle b with excitation energy E at n exciton state in $J\pi$ channel,

$T_t^{J\pi}(n,E)$ is the total T factor, which is given by

$$T_t^{J\pi}(n,E) = \sum_b \int T_b^{J\pi}(n,E,\varepsilon) d\varepsilon \qquad (2)$$

$P^{J\pi}(n)$ stands for the $J\pi$ channel occupation probability of n exciton state.

Obviously, if we do not consider the parity and angular momentum effects, the Eq. (1) is reduced to the exciton model, while if the pre–equilibrium effect is omitted, it is reduced to the Hauser–Feshbach model.

The approach to account the exact Pauli exclusion effect in the exciton state densities has been found [4]. For the nucleon induced nuclear reaction processes, the exciton state density was proposed as

$$\omega^{J\pi}(n,E) = P(\pi)\omega(n,E)R_n(J) \qquad (3)$$

where

$P(\pi) = \frac{1}{2}$ for parity factor,

$$R_n(J) = \frac{(2J+1)^2}{2\sqrt{2\pi}\,\sigma_n^3} \exp\left\{\frac{-(J+1/2)^2}{2\sigma_n^2}\right\}$$

$$\omega(n,E) = g\frac{(gU)^h (gU - A(p,h))^{p-1}}{p!h!(n-1)!} \qquad (4)$$

$$n = p + h.$$

$g = \frac{6a}{\pi^2}$ is the single particle level density around the Fermi surface, a is the

level density parameter.

$U=E-\Delta$, Δ is pair correction. The Pauli exclusion correction $A(p,h)$ is approximately equal to

$$A(p,h)=\frac{1}{2}p(p-1)+\frac{1}{2}h(h-1) \qquad (5)$$

To show the correctness of Eq. (4), we sum up Eq. (4) over all exciton states and rewrite

$$\omega(n,E)=e^{f(h,U)} \qquad h=2n-1$$

where

$$f(h,U)=\lg(g)+h\ \lg(gU)+h\ \lg(gU-h^2)-\lg h!-\lg(h+1)!-\lg(2h)!$$

Using Strirling formula for factorials

$$\lg h!=h\ \lg h-h+\frac{1}{2}\lg 2\pi h$$

the function $f(h,U)$ has a sharp maximum at a value h_0. We now expand $f(h,U)$ at h_0

$$f(h,U)=f(h_0,U)+\frac{1}{2}f''(h_0,U)(h-h_0)^2+\ldots \qquad (6)$$

In terms of this expression one can immediately carry out the integral over h and obtain the result for the total state density

$$\rho(E)=\sum_n \omega(n,E)$$

$$=e^{f(h_0,U)}\int e^{\frac{1}{2}f''(h_0,U)(h-h_0)^2}\,dh$$

$$=\sqrt{\frac{\pi}{|\frac{1}{2}f''(h_0,U)|}}\,e^{f(h_0,U)} \qquad (7)$$

The value of h_0 is obtained by the condition

$$f'(h_0,U)=0 \qquad (8)$$

In order to obtain an approximate solution, for high value of U, $h_0^2 >> h_0 >> 1$. The resulting equation for h_0 is

$$\frac{2r}{1-r} = \lg\frac{1-r}{4r^2} \tag{9}$$

where

$$h_0^2 = rgU$$

This equation can be solved numerically

$$r = 0.28431$$

and the two terms of f and f'' have the form

$$f(h_0,U) = \sqrt{gU}\,[4\sqrt{r} - \sqrt{r}\frac{2r}{1-r}] + \lg\frac{g}{4\pi^{\frac{3}{2}}(rgU)^{\frac{5}{4}}}$$

$$f''(h_0,U) = -\frac{4-2r+2r^2}{\sqrt{gU}\,(1-r)^2\sqrt{r}}$$

Substituting the value of r and using $g = \frac{6a}{\pi^2}$, we obtain

$$\rho(E) = \frac{1-r}{4\pi Ur\sqrt{2-r-r^2}}\,e^{2\sqrt{r}\frac{2-r}{1-r}\sqrt{\frac{6}{\pi}aU}} = C_1\frac{\sqrt{\pi}}{12U}e^{2C_2\sqrt{aU}} \tag{10}$$

$$C_1 = 1.0118$$

$$C_2 = 0.9966$$

It indicates that if summed over all exciton number, the exciton state density of Eq. (4) reproduce the Fermi gas level density of one type fermion system. In practice for two type fermion system a renormalized factor need to be introduced.

$$\eta(U) = \frac{U}{C_1 a^{1/4}(U+T)^{5/4}} \tag{11}$$

where

$$T=\frac{1}{2a}[1+\sqrt{1+4aU}].$$

The renormalized exciton state density reads

$$\omega^{R}(n,E)=\eta(U)\omega(n,E). \tag{12}$$

Thus, we get the result

$$\sum_{n}\omega^{R}(n,E)=\rho_{B-S}(E), \tag{13}$$

where $\rho_{B-S}(E)$ is the Back–Shifted Fermi gas level density [5].

The T–factor in H–F model can be rewritten into the form.

$$\begin{aligned}T_{b}^{J\pi}(E)&=\frac{1}{2\pi h}\sum_{jr}\int T_{jr}^{b}(\varepsilon)\rho(E',j'\pi')\mathrm{d}\varepsilon\\&=\frac{1}{2\pi h}\sum_{jr}\int T_{jr}^{b}(\varepsilon)\sum_{n}\omega^{R}(n,E',J'\pi')\mathrm{d}\varepsilon\\&=\sum_{n}T_{b}^{J\pi}(n,E'),\end{aligned} \tag{14}$$

where E' is the residual excitation energy.

This procedure demonstrates that the statistical treatment in H–F model can be decomposed into multi–step processes with a self–consistent fashion.

Eq. (13.) is correct only for high excitation energy. In other words, only for high exciton states the independent particle model is held. For lower exciton states, we can introduce some additional correction[6]. If the pick–up mechanism and the two type fermion effects are taken into account, the T factor needs rewriting into

$$T_{b}^{J\pi}(n,E)=\frac{1}{2\pi h}\sum_{jr}\int T_{jr}^{b}(\varepsilon)F_{b}(n,\varepsilon)Q_{b}(n)\omega^{R}(n-1,E',j'\pi')\mathrm{d}\varepsilon. \tag{15}$$

The formation factor of composite particles $F_b(n,\varepsilon)$ is given by Ref. [3].

$$F(n,\varepsilon)=1 \quad \text{for } n,\ p \text{ and eq. states}$$

$$F_{b}(n,\varepsilon)=\frac{1}{(2\pi h)^{A_b-1}}\int_{\overline{p_b}\ \text{fixed}(U,m)}^{A_b-1}\prod_{i=1}\mathrm{d}\overline{p_i}\mathrm{d}\overline{x_i}. \tag{16}$$

where A_b is the mass number of composite particle,

$\vec{p}_i, \vec{x}_i$ are the relative momenta and coordinates.

$[l,m]$ stands for the pick-up configuration ($l+m=A_b$),

l : particles above the Fermi surface,

m : particles below the Fermi surface.

From the calculations we found the fact that when the incident energy is less than 20 MeV, $l=1$ is the dominant component[7].

Another factor, combination factor, should be introduced to account for memory by the excitation system in the first stages of the reaction for the type of projectile.

If the pick-up configuration is taken into account, the combination factor reads[6]

$$Q_{\substack{b \\ [l,m]}}(n) = \left(\frac{A}{Z}\right)^{Z_b} \left(\frac{A}{N}\right)^{N_b} \begin{bmatrix} p \\ l \end{bmatrix} \begin{bmatrix} A-h \\ m \end{bmatrix} \begin{bmatrix} A_b \\ Z_b \end{bmatrix} \sum_{i=0}^{h} \begin{bmatrix} h \\ i \end{bmatrix}$$
$$\left(\frac{Z}{A}\right)^{i} \left(\frac{N}{A}\right)^{h-i} \sum_{j} \begin{bmatrix} i \\ j \end{bmatrix} \begin{bmatrix} h+1-i \\ l-j \end{bmatrix} \begin{bmatrix} Z-i \\ Z_b-j \end{bmatrix} \begin{bmatrix} N-h+i \\ N_b-l+j \end{bmatrix} \qquad (17)$$

where A, Z, N (A_b, Z_b, N_b) are the mass number, proton number and neutron number of the target (emitted particle).

As an example, the values of the combination factors are given for n + ^{56}Fe reaction in Table 1.

Table 1 List of Q factor of n + ^{56}Fe

n	(n,n)	(n,p)	(n,α)	(n,^{3}He)	(n,d)	(n,t)
3	1.4333	0.5000	0.9923	0.8122	0.9758	1.1439
5	1.2889	0.6667	1.0074	0.8800	0.9901	1.1030
7	1.2167	0.7500	1.0151	0.9140	0.9975	1.0827
9	1.1733	0.8000	1.0199	0.9345	1.0021	1.0706

One can see that with the increasing of the exciton number, all the values tend to 1.

The main contribution of the Q–factor is for n, p emissions. Since the neutron is the incident particle, then it is of advantage to neutron emissions and depresses proton emissions, especially at low exciton states.

In this theory, the exciton state occupation probability $q^{J\pi}(n,t)$ satisfies the $J\pi$ dependent master equation

$$\frac{dq^{J\pi}(n,t)}{dt} = \lambda_+^{J\pi}(n-2)q^{J\pi}(n-2,t) + \lambda_-^{J\pi}(n+2)q^{J\pi}(n+2,t) - [\lambda_+^{J\pi}(n) + \lambda_-^{J\pi}(n) + W_T^{J\pi}(n)]\, q^{J\pi}(n,t) \quad (18)$$

where the transition rates within the exciton states are given by[8]

$$\lambda_\nu^J(n) = \frac{2\pi}{h}|<M>^2|\chi_\nu^J(n)Y_\nu(n) \quad (19)$$

here $\nu = +, 0, -$

The form factor of angular momentum can be obtained in terms of the approach in F. K. K. theory[9], but spin 1 / 2 was used instead of spin 0. The life time of n exciton state in $J\pi$ channel is defined by

$$\tau^{J\pi}(n) = \int_o^\infty q^{J\pi}(n,t)dt \quad (20)$$

Then the occupation probability of n exciton state in $J\pi$ channel is obtained by

$$P^{J\pi}(n) = \tau^{J\pi}(n)W_T^{J\pi}(n) \quad (21)$$

where $W_T^{J\pi}$ stands for the total emission rate of n exciton state in $J\pi$ channel. The occupation probabilities satisfy the normalization condition

$$\sum_n p^{J\pi}(n) = 1 \quad (22)$$

2 FORMULATION OF DOUBLE DIFFERENTIAL CROSS SECTIONS

Based on the leading particle model[10], the generalized master equation is :

$$\frac{dq(n,\Omega,\varepsilon,t)}{dt} = \sum_{m} \int d\Omega' \int d\varepsilon' q(m,\Omega',\varepsilon',t) W_{m\to n}(\Omega'\varepsilon',\Omega\varepsilon)$$
$$- \{ \sum_{m} \int d\Omega' \int d\varepsilon' W_{n\to m}(\Omega'\varepsilon',\Omega\varepsilon) + W_T(n) \} \; q(n,\Omega,\varepsilon,t) \qquad (23)$$

where $q(n,\Omega,\varepsilon,t)$ is the occupation probability of the composite system at time t in exciton state n with leading particle energy ε and direction Ω, $W_{m\to n}(\varepsilon',\Omega',\varepsilon,\Omega)$ is the transition probability of the system from state (m,ε',Ω') to state (n,ε,Ω) in per unit time, $W_T(n)$ is the total emission rate of n exciton state.

The solution of Eq. (23) can be obtained in the form of a partial wave expansion

$$q(n,\Omega,\varepsilon,t) = \sum_{l} \eta_l(n,\varepsilon,t) P_l(\cos\theta) \qquad (24)$$

where P_l is the Legendre polynomial.

Introducing the partial wave life time

$$\zeta_l(n,\varepsilon) = \int_0^\infty \eta_l(n,\varepsilon,t) dt \qquad (25)$$

the double differential cross section of single particle emission is given by the following expression

$$\frac{d^2\sigma}{d\Omega d\varepsilon} = \sum_{n} \frac{d\sigma(n)}{d\varepsilon} A(n,\Omega) \qquad (26)$$

where $\frac{d\sigma(n)}{d\varepsilon}$ is the component of n exciton state in the spectrum,

$$A(n,\Omega) = \frac{1}{4\pi} \sum_{l} \frac{\xi_l(n)}{\xi_o(n)} p_l(\cos\theta) \qquad (27)$$

it satisfies

$$\int A(n,\Omega) d\Omega = 1$$

The angular distribution of emitted composite particle can be obtained by the following approach. The basic idea is that the leading particle picks up some nucleon in the compound nucleus to form a composite particle and the momentum conservation is taken into account, the normalized angular factor is introduced by[11]

$$A_{lm}(n,\Omega_b,\varepsilon_b) = 1/N_{lm}\int d\vec{p}_1 \ldots d\vec{p}_{A_b}$$
$$\delta(\vec{p}_b - \sum_{i=1}^{A_b}\vec{p}_i)\prod_{i=2}^{A_b} D_n(\vec{p}_i)\tau(n_1,\Omega_1,\varepsilon_1) \qquad (28)$$

With $|\vec{p}_1| > p_f$ *and* $|\vec{p}_i| < p_f$ for $i = 2 \ldots A_b$. For lower excitation energy $[l,n]$ in the dominant part.

$\tau(n_1,\Omega_1,\varepsilon_1)$ in Eq. (28) is the life time of the leading particle with energy ε_1 in direction Ω_1. The δ function in Eq. (28) implies the momentum conservation.

$D_n(\vec{p}_i)$ in Eq. (28) is the momentum distribution of the compound nucleus. All of the explicit formulas can be found in Ref. [11].

3 THE FUNCTION OF UNF CODE

The UNF code is developed for calculations of fast neutron data for structural materials with incident energies from 1 keV to 20 MeV, written in FORTRAN–77 on Micro–VAX–II computer. Besides elastic scattering the code may handle decay sequence up to (n,3n) reaction channel, including 14 reaction channels. The physical quantities calculated by the UNF code contain

3.1 Cross sections of total, elastic scattering, compound elastic scattering, nonelastic scattering and all reaction channels in which the discrete level emissions and continuum emission are included.

3.2 Angular distributions of elastic scattering both in C. M. system and in Lab. system.

3.3 The energy spectra of the particles emitted in all reaction channels.

3.4 Double differential cross sections of all kinds of particle emission (neutron, proton, α particle, deuteron, triton and helium–3), as well as the recoil nuclei.

3.5 Kinetic energy released from every reaction channels (KERMA factors).

3.6 γ production data (γ spectra, γ production cross section and multiplicity)

and the isomeric ratio data.

3.7 The total double differential cross sections of emitted particles from all the reaction channels.

If the direct inelastic scattering data and the direct reaction data are available from other codes, one can input the data so that the results may include the direct process effect.

3.8 The output form is in the ENDF / B–6 format.

4 RESULTS AND DISCUSSION

Using the UNF code we performed the calculation of n + ^{56}Fe at $E_n = 14.1$ MeV. The neutron production spectrum in C. M. S. is shown in Fig. 1 and the total neutron double differential cross section are shown in Fig. 2 and Fig. 3 for $\theta = 30°$, and 150°, respectively. The data of neutron production spectrum is taken from ENDF / B–6, while the data of D. D. X. are taken from Ref. [12]. The proton and α–particle production spectrum are shown in Fig. 4 and Fig. 5. The data of proton and α production spectra at $E_n = 14.5$ MeV are taken from Refs. [13] and [14]. The calculations of n+^{209}Bi have also been performed at $E_n = 14.1$ MeV and $E_n = 10$ MeV. The data are taken from Refs. [15] and [16]. The neutron production spectrum for $E_n = 14.2$ MeV and the D.D.X. of neutron at $\theta = 30°$, 90°, 150° are shown in Figs. 6~9, respectively. The D.D.X. of neutron for $E_n = 10$ MeV at $\theta = 45°$, 90°, 120° are shown in Figs. 10~12.

To keep the energy conservation for whole reaction processes, the recoil effect must be taken into account. Because the D.D.X. of all kinds of particles have been calculated, thus, one can obtain the kinetic energies released from material (KERMA factor).

The energy released in the whole reaction processes is given by

$$E_{release} = \sum_i \frac{\sigma_i}{\sigma_T} (E_L + Q_i) \tag{29}$$

where σ_i is the cross section of i–th channel,

Q_i is the Q value of the i–th channel

and $\sum_i \sigma_i = \sigma_T$ i for all channel.

For the case of n + ^{56}Fe at $E_n = 14.1$ MeV, the energies released from each reaction channel are listed in Table 2.

Table 2 List of kerma factors of n + ^{56}Fe at E_n = 14.1 MeV

	(n,γ)	(n,n)	(n,p)	(n,α)	(n,d)	(n,2n)	(n,np)	(n,nα)
γ	0.005	2.182	0.209	0.087	0.0034	0.0849	0.0039	
n		8.038				0.305	0.0284	0.0003
p			0.0235				0.0597	
α				0.131				0.0026
d					0.168			
Recoil	0.0001	0.320	0.0137	0.0130	0.0013	0.0424	0.0069	0.0003
total	0.0052	10.540	0.458	0.231	0.0215	0.4822	0.0988	0.0031

(unit: MeV)

In previous model calculation, only the exciton states in which the particle number p must be equal or great than A_b permit to emit the composite particle with mass number A_b. So the initial exciton state for particle A_b emission is given by

$$n_0 = 2A_b - 1 \tag{30}$$

When the pick-up mechanism is employed in the model, the situation will be changed. Since the leading particle can pick up nucleons from the compound nucleus. Therefore the initial exciton state of particle A_b emission is always equal to 3.

The pick-up mechanism plays an important role in the pre-equilibrium reaction processes. To show this fact the percentages of n exciton state in the continuum part of cross sections of (n,α), (n,d) and (n,t) for n+^{56}Fe are given in Table 3~ 5, respectively.

Table 3 Percentage of n exciton state in cont. part of C. S. (n,α)

E_n (MeV)	$n=3$	$n=5$	$n=7$	$n=9$	eq.
10	8.8	4.7			86.5
14.1	27.1	8.1	8.4		56.5
18	52.6	12.5	6.1	4.0	24.8

Table 4 Percentage of n exciton state in cont. part of C. S. (n,d)

E_n (MeV)	$n=3$	$n=5$	$n=7$	$n=9$	eq.
14.1	83.3	0.5			16.2
16.	95.9	2.0	0.1		2.0
18	94.4	3.8	0.3		1.5

Table 5 Percentage of n exciton state in cont. part of C. S. (n,t)

E_n (MeV)	$n=3$	$n=5$	$n=7$	$n=9$	eq.
16	94.6	0.2			5.1
18	96.7	1.6			1.7
20	95.0	3.7	0.2		1.1

The results indicate that the percentages of low exciton states increase with the increasing of incident energies while the components of equilibrium state decrease.

In the case of (n,α) reaction, with previous model calculation the exciton states $n=$ 3, 5 contribute nothing to cross section. But if the pick–up mechanism is taken into account, they may give important contribution to the cross section. In particular, at high incident energies, they become the dominant parts. This is the reason why the cross section of (n,α) is always too small to be calculated by the previous approach. As the matter of fact, the pick–up mechanism stands for the semi–direct processes, which could not be neglected in the composite particle emissions.

From Table 5 one can see that in the case of triton emission, the dominant part is $n=$ 3, which is just omitted in the previous approach that is unable to

reproduce the data.

It is easy to draw the conclusion that the semi-direct processes, e. i. the pick-up mechanism must be taken into account in composite particle emission processes.

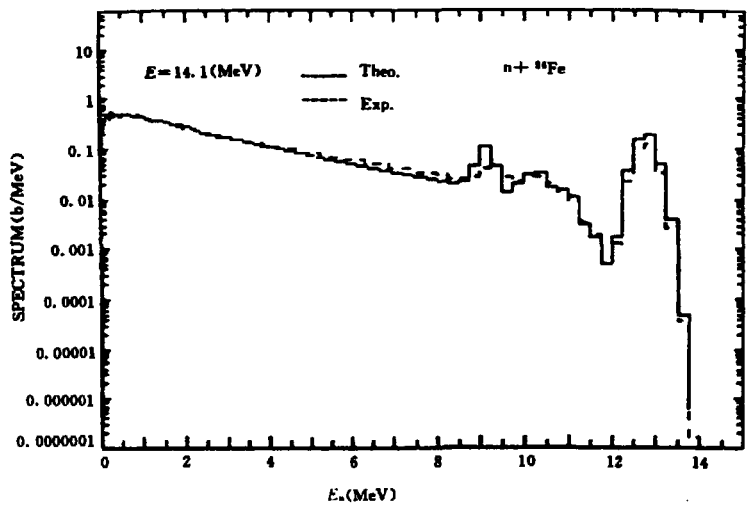

Fig. 1 Neutron production spectrum in C. M. S. for Fe

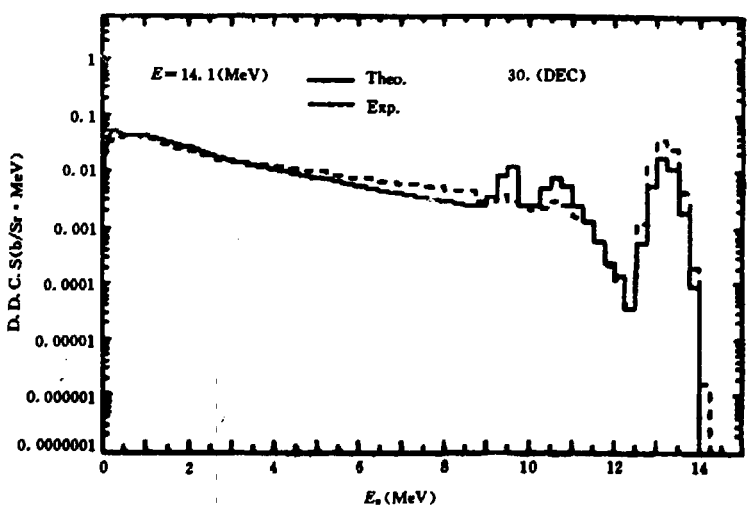

Fig. 2 Double differential neutron emission cross section at 30 deg. for Fe

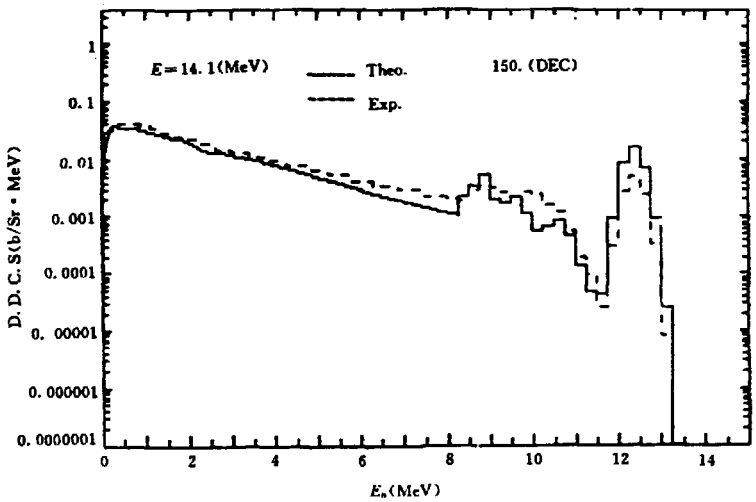

Fig. 3 Double differential neutron emission cross section at 150 deg. for Fe

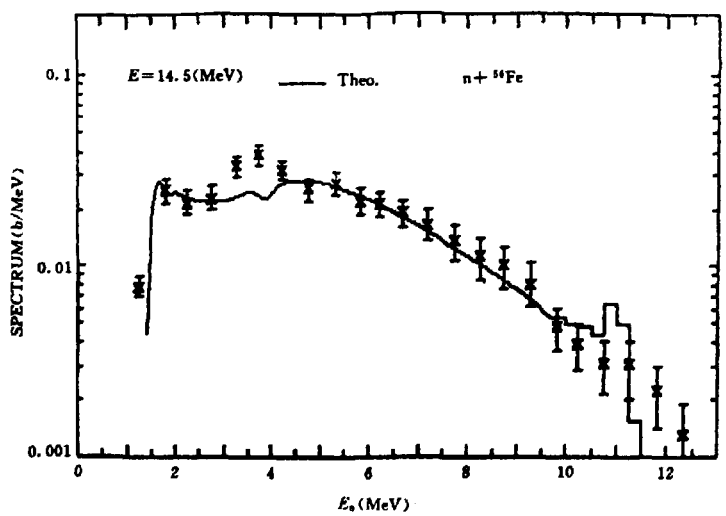

Fig. 4 Proton production spectrum in C. M. S. for Fe

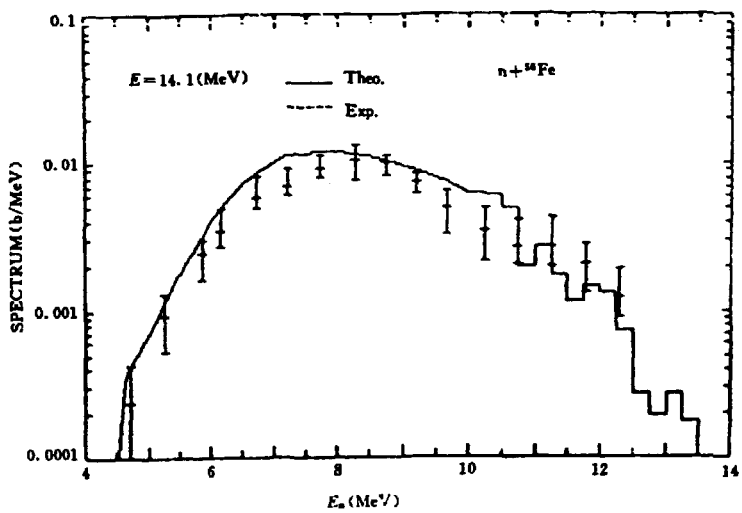

Fig. 5 Alpha production spectrum in C. M. S. for Fe

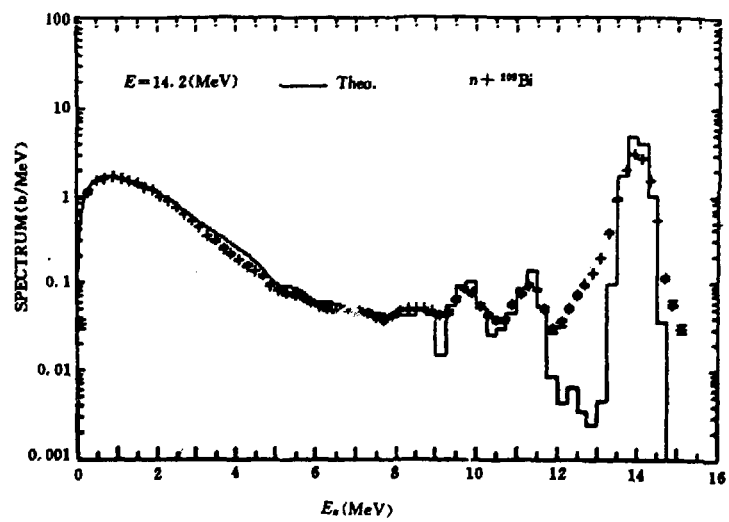

Fig. 6 Neutron production spectrum in C. M. S. for Bi

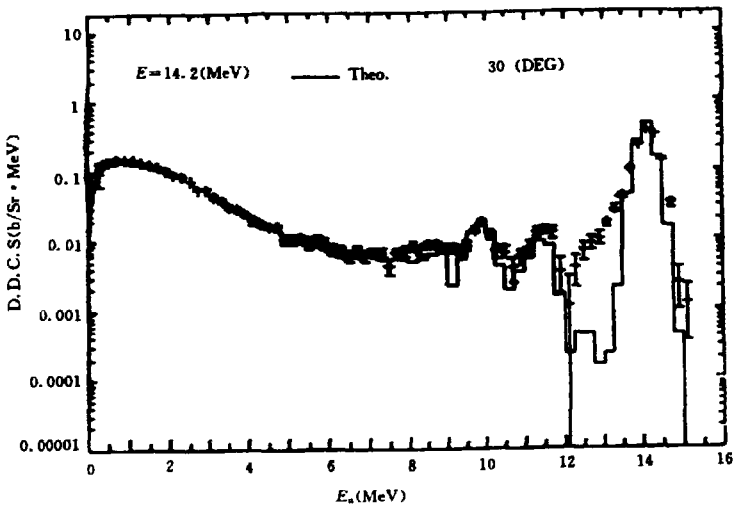

Fig. 7 Double differential neutron emission cross section at 30 deg. for Bi

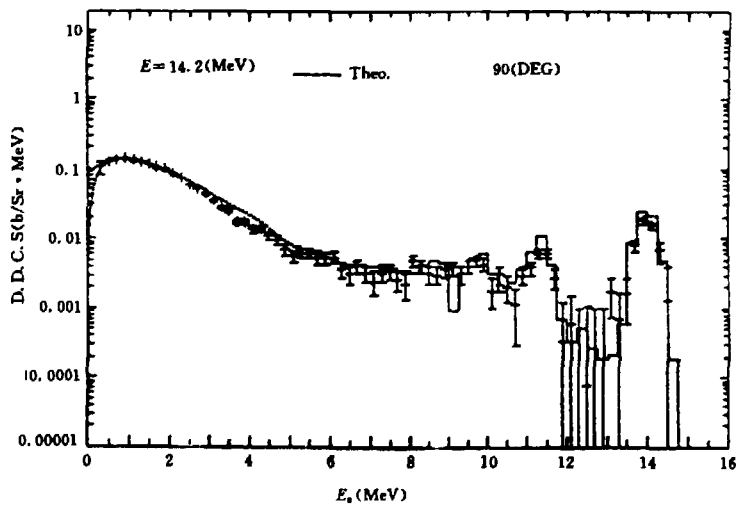

Fig. 8 Double differential neutron emission cross section at 90 deg. for Bi

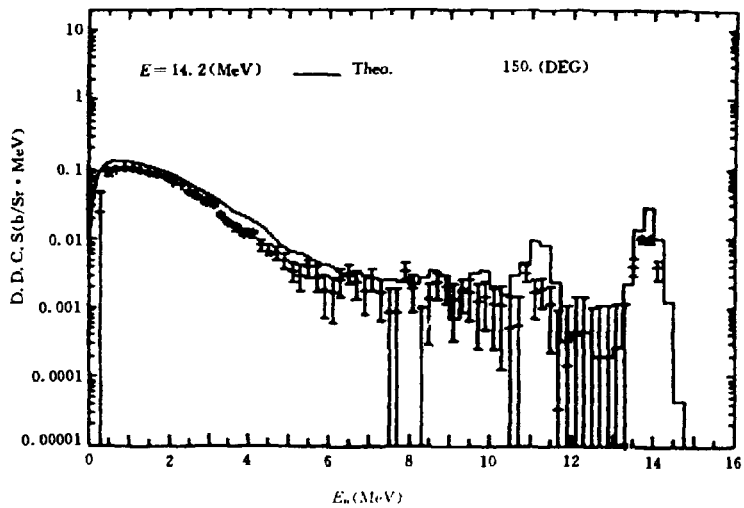

Fig. 9 Double differential neutron emission cross section at 150 deg. for Bi

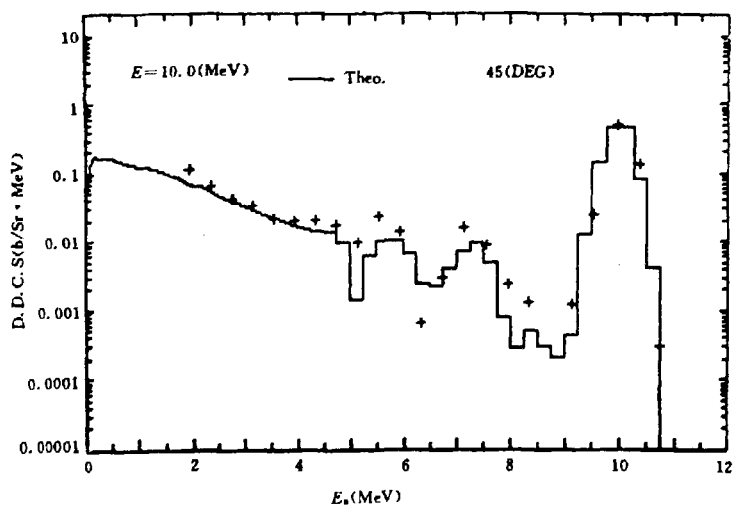

Fig. 10 Double differential neutron emission cross section at 45 deg. for Bi

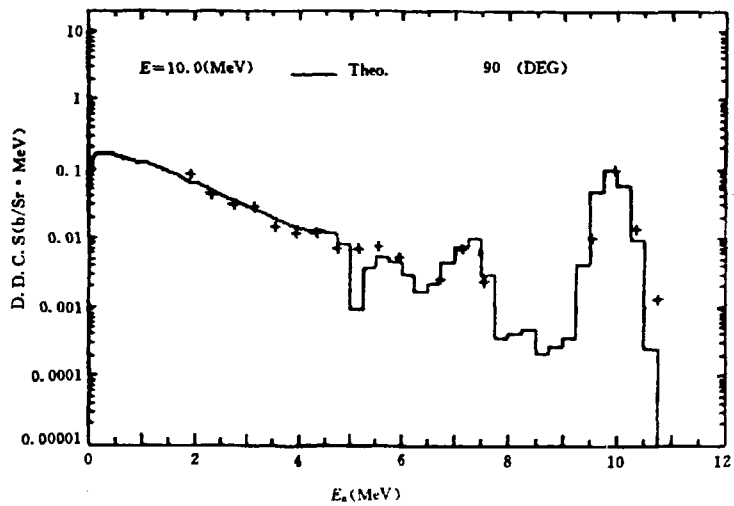

Fig. 11 Double differential neutron emission cross section at 90 deg. for Bi

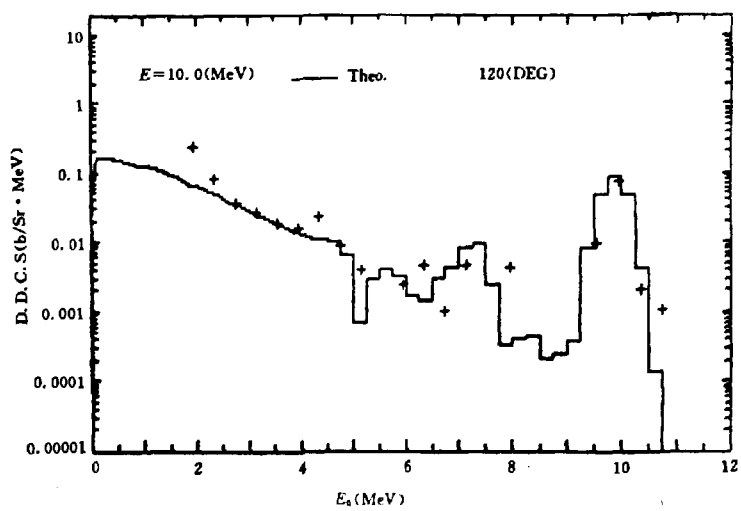

Fig. 12 Double differential neutron emission cross section at 120 deg. for Bi

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PROGRESS ON NUCLEAR DATA THEORETICAL WORK AND NUCLEAR THEORY RESEARCH AT THE THEORY GROUP OF CNDC

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In 1991, the theory group of CNDC mainly worked on the fields of nuclear data calculations, nuclear model programs and parameters, and nuclear reaction theory research which are described briefly as follows :

1 Since the Hauser–Feshbach theory is successful in the equilibrium reaction processes, the pre–equilibrium effects are exclusive. The exciton model is a useful tool to describe the pre–equilibrium phenomenon but it is unable to account the parity and angular momentum conservations. For this reason, to develop a new theory which includes both the success of these two model, a semi–classical model has been proposed. Based on this theory, a new code UNF is developed, in which the discrete level effect in multi–particle emissions was included as well as the pre–equilibrium phenomenon combining with the parity and angular momentum conservations.

With the increasing of incident energies the components of the pick–up picture increase obviously. In particular to the composite particle with large binding energies, like d, t, and ^{3}He, the pick–up components are always the dominant parts. Therefore, the pick–up mechanism must be taken into account in the composite particle emission processes, which has been included in UNF code. To keep the energy conservation the recoil nucleus effect is also taken into account.

The UNF code is used for calculations of fast neutron data for structural materials with incident energies from 1 keV to 20 MeV, written in FORTRAN–77 on Micro–VAX–II computer. Besides elastic scattering the code may handle decay sequence up to (n,3n) reaction channel, including 14 reaction channels. The physical quantities calculated by the UNF code are the fol-

lowing:

1.1 Cross sections of total, elastic scattering, compound elastic scattering, nonelastic scattering, and all reaction channels in which the discrete level emissions and continuum emission are included.

1.2 Angular distributions of elastic scattering both in C. M. system and in Lab. system.

1.3 The energy spectra of the particles emitted in all reaction channels.

1.4 Double differential cross sections for each reaction channel of all kinds of particle emission (n, p, d, t, ^{3}He, and α), as well as the recoil nuclei.

1.5 Kinetic energy released from each reaction channels (KERMA factors).

1.6 γ production data (γ spectra, γ production cross section and multiplicity) and the isomeric ratio data.

1.7 The total double differential cross sections of emitted particles from all reaction channels.

If the direct inelastic scattering data and the direct reaction data are available from other codes, one can input the data so that the results may include the direct process effect.

1.8 The output form is in the ENDF / B–6 format.

2 CMUP2 is a program for calculating complex reactions of medium–heavy nuclui with $E \lesssim 50$ MeV neutron or charged particles (p, d, t, ^{3}He, α). The adopted theories in this program are optical model, evaporation model, and pre–equilibrium emission theory. The calculated direct reaction and compound–nucleus elastic scattering results obtained with other codes can be added to the input data of the program CMUP2. Because the incident energy is higher, the pre–equilibrium mechanism and the pick–up mechanism of composite particle emission are applied in the first, second, and third emission processes. The calculated nuclear data with this program are as follows: σ_t(for neutron only), σ_{el}(for neutron only), σ_{non}, $\sigma_{cl}(0)$, one–particle and two–particle emission cross sections and energy spectra, three–particle and four–particle emission cross sections, 6 kinds of particle emission cross sections and corresponding energy spectra, 6 kinds of particle emission multiplicities, and residual nucleus yield cross sections.

3 APOM is a program for automatically searching the optimal neutron optical potential parameters in $E \lesssim 20$ MeV energy region for medium–heavy nuclei by means of the improved fastest falling method, for which each parameter step length can be adjusted respectively and automatically. The quantity χ^2 given includes the relative errors of the calculated values with the

experimental data for the total and nonelastic cross sections as well as the elastic scattering angular distributions. The optical potentials considered here are Woods–Saxon form for the real part, Woods–Saxon and derivative Woods–Saxon form for the imaginary parts corresponding to the volume and surface absorptions respectiively, and the Thomas form for the spin–orbit part. In order to improve the agreement between the theoretical and experimental values at the high energy part, the E^2 term is included in the volume absorption part. The calculations of the compound nucleus elastic scattering are within the framework of the width fluctuation corrected Hauser–Feshbach theory. This program is suitable for single element or natural nucleus. Many application practices of this program show that the searching velocity of the best parameters is fast and generally a rather successful results can be obtained.

APCOM is a program for automatically searching the optimal $E<50$ MeV charged particle optical potential parameters by means of the improved fastest falling method, for which each parameter step length can be adjusted respectively and automatically. The details are the same as that described in code APOM mentioned above. Because the emitted charged particle must overcome the Coulomb barrier, their excitation functions become observable only if the incident energy is larger than about 4 MeV. Hence, the contribution of the compound nucleus elastic scattering process could be neglected. This program allows user to fit the experimental data for 10 nuclei maximally. Thus for those elements lack of experimental data, one can obtain its optical potential parameters based on the experimental data of neighbor nuclei with this program. Many application practices of this program show that the searching velocity of the best parameters is fast and generally a rather successful results can be obtained.

4 The calculation and analysis of neutron induced reaction on ^{56}Fe in 5~ 50 MeV energy region are made. A set of neutron optical potential parameters for ^{56}Fe in energies of 5~ 50 MeV is obtained based on the available experimental data. The various calculated nuclear data are in good agreement with the experimental data in the above mentioned energy region. Therefore, the various predicted cross sections, yields, angular distributions, and emitted particle energy spectra in this energy region are reliable to some extent. The following conclusions can be obtained :

4.1 The calculated (n,xn) energy spectrum in high energy part is mainly contributed by direct inelastic scattering of discrete energy levels. For (n,n′) cross section, the contribution from the direct reaction already approaches to that from the statistical theory at $E_n = 20$ MeV. When $E_n > 30$ MeV, the main con-

tribution to (n,n′) cross section comes from the direct reaction.

4.2 For single–particle emission cross section, the main contribution of the statistical theory comes from the equilibrium process as $E_n < 10$ MeV, whereas more than 90% of contribution comes from the pre–equilibrium process at $E_n = 20$ MeV, and nearly the whole contribution comes from the pre–equilibrium process as $E_n > 25$ MeV.

4.3 The contribution of the pre–equilibrium process to the second particle emission can be neglected for $E_n < 20$ MeV and the contribution of the pre–equilibrium process to the third particle emission can be neglected for $E_n < 50$ MeV.

5 The calculation and analysis of proton induced reaction on ^{89}Y in $E < 40$ MeV energy region are made. A set of proton optical potential parameters for $E < 40$ MeV is obtained based on the available experimental data of ^{89}Y and neighbour nucleus ^{90}Zr. The calculated nuclear data for some channels, for which there exist better measured data, are in good agreement with the experimental data. Therefore, the various predicted cross sections, yields, angular distributions, and emitted particle energy spectra in this energy region are reliable to some extent. The calculated radioisotope yield cross sections show that what energy region is better for specific radioisotope production in certain nuclear reaction. The following conclusions are obtained :

5.1 For single–particle emission cross section, the main contribution of the statistical theory comes from the equilibrium process as $E_p < 10$ MeV, whereas the main cotribution comes from the pre–equilibrium process as $E_p > 30$ MeV.

5.2 The cotribution of the pre–equilibrium process to the secondary particle emission can be neglected as $E_p < 35$ MeV and the contribution of the pre–equilibrium process to the third particle emission can be neglected in the whole energy region mentioned above.

The calculation of reaction p+^{63}Cu in $E < 40$ MeV energy region has been performed and the calculated results are in good agreement with the experimental data.

6 The medium energy proton nonelastic or reaction and neutron total cross sections are the most important and basic ones. Nowadays, large amounts of medium energy experimental data for both of them have been accumulated. Based on the Letaw and Pearlstein systematic formulae and considering as many experimental data as possible, new systematic formulae for medium energy ($E < 1000$ MeV) proton nonelastic and neutron total cross sections, which are in pretty good agreement with experiments for $A = 12 \sim 238$ nuclei, were

obtained. They are universal and can be used in medium energy nuclear data evaluation.

7 Sensitivity of nuclear level density parameters is studied. A series of calculations is performed on n+^{197}Au (E_n = 5 keV~ 20 MeV) for cross section and spectrum to examine the sensitivity of three sets of level density parameters based on the same Gilbert–Cameron Fermi gas model.

From the calculated results comparison of the three sets level density parameters, it is certain that there are really some differences among the calculated results for the three sets parameters; furthermore, from the comparison of (n,n′) and (n,2n) cross sections it seems that the Su–Zhuang's parameters are rather slightly better than the others from the point of view of the tendency approaching to the experimental data.

In order to obtain a definite conclusion of the evaluation of level density parameters, the calculations of reaction cross sections and spectra for more nuclides should be carried out and the systematic analysis even for specific or regional nuclides for extracting the level density information should also be done.

8 The neutron total cross section for interaction with nuclei in the mass region of A = 40~ 60 fluctuates quite violently for energies less than about 5 MeV, rendering precise optical analysis increasingly difficult. Nevertheless, our analyses have shown that optical potentials, which fit the higher energy data very accurately, tend to give that total cross sections at low energies are clearly greater than the mean value of the fluctuating experimental data. And it has become clear that the depth of the real potential shows a non–linear behaviour around the Fermi surface, this is often referred to as the Fermi surface anomaly. Precision analyses have also shown that it is no longer adequate to assume that the radius of the real potential is independent of neutron energy.

In order to remove the anomaly at low energies for the total cross section, we have made use of the optical model including the dispersion relations to analyse the neutron total cross sections and the available data on the elastic scattering by ^{40}Ca, ^{51}V, ^{56}Fe, and ^{59}Co etc.. It is found that it is indeed less than the one given by the global optical potential and in general accord with the experimental data. A set of the optical potential parameters using the dispersion optical model for this mass region has been obtained.

9 The non–equilibrium nuclear reaction entropy for both closing and opening system is studied based on the nonlinear single particle occupation number

equation. The relations between transport coefficents and nuclear temperature parameter are obtained in terms of the equation. For closing system, we solve the equation with analytical, relaxation ansatz and numerical methods, respectively. The evaluations of entropy in all the cases are calculated. For opening system, the single particle occupation number equation is established and its numerical solution are given, the evaluations of entropy and occupation number distribution with different emission rates are also calculated and compared each other.

10 A unified model of nuclear reaction has been presented through renormalization for the wave function generated by optical model potential. The obtained formulae of the nuclear reaction cross section make it possible to calculate the cross sections of the discrete levels and the isomeric states of the residual nuclei. Calculations have been made to the reactions ^{59}Co(n,2n) and ^{93}Nb(n,2n) by using this model. The calculated results are in good agreement with the experimental data.

11 A coupled model of particle emission and fission with considering coupled single particle motion and collective deformed motion inside excited nucleus near the deformed ground state is described in a stochastic framework. The influence of nuclear collective deformed fluctuation on the double differential cross section and spectrum of emitted particles is studied in detail in the early time regime prior to fission events especially for middle heavy nuclei with very high fission barrier by solving a coupled master equation and Fokker–Planck equation.

The effect of the nuclear collective deformed fluctuation on statistical model can be used for some middle heavy nuclei data calculation in the energy range from 3 MeV to 40 MeV on needs for some applications. By using a statistical model including equilibrium and pre–equilibrium mechanism with the considering of the influence of the nuclear collective deformed fluctuations, not only a better fitting with cross sections but also a reasonable shape of spectrum in high energy tail and lower energy range could be obtained. More theoretical and experimental investigations are necessary to obtain more detailed results on the shape of emitted particle spectrum especially in lower and higher energy range. It has been clearly recognized that it is a very interested subject in studying the coupled model of particle emission and fission. How to consider the coupling between single particle motion and collective deformed motion degrees of freedom after a incident particle absorbing is still an interested open problem.

12 The relativistic microscopic optical potential, Schrodinger equivalent potential and mean free paths of nucleon at finite temperature in nuclear matter and finite nuclei are studied based on Walecka's model and thermo-field dynamics. We let only the Hartree-Fock self-energy of nucleon represent the real part of microscopic optical potential and the fourth order of meson exchange diagrams, i.e. the core polarization represent the imaginary part of microscopic optical potential in nuclear matter. The microscopic optical potential of finite nuclei is obtained by means of the local density approximation.

The contribution of the fourth order exchange diagrams is first studied to the imaginary part of nucleon self-energy, the relativistic microscopic optical potential and the Schrodinger equivalent potential of the relativistic microscopic optical potential based on Walecka's meson-nucleon model. An effective lagrangian including nucleon, σ- and ω-mesons, which is required to produce the nuclear matter saturation properties, has been introduced in nuclear matter.

13 So far the study of intermittency in particle production in high energy hadronic interactions and heavy ion collisions is based on the flat average distribution of the produced particles. But the real experimental data show that the average distribution is unflat, more likely, it has a Gaussian-like shape. In order to take this effect into account, the weighted distribution in particle production is proposed. The probabilities of the weighted distribution are supposed to be $a_1\ p_1,\ a_2\ p_2,\ \cdots\ a_M\ p_M$. $a_1, a_2, \cdots a_M$ are weight factors which are determined and calculated by the averaged distribution, $p_1, p_2, \cdots p_M$ are probability factors. With the weighted distribution, the $\ln < Fi > \sim -\ln\delta y$ drawings show a double-slope structure which is consistent to the experimental predictions. The first slope is mainly produced by the unflat average distribution, while the second one is produced by the random cascade process.

In the previous work, it has been improved that the average distribution of particles produced in AA colissions doesn't have $\ln < Fi >$ depend on $-\ln\delta y$ in small δy reigion, i.e. no intermittency is produced by the average distribution of the produced particles in small δy region. In the followed work, the random cascade process is applied in the particle production. The average distribution is treated as the weight factors and coupled with the random cascade distribution to form the weighted random cascade distribution. The new distribution possesses a double-slope structure in $\ln < Fi > \sim \ln\delta y$ drawings. This behavior is consistent to the analysis of experimental data.

APCOM — A CODE FOR SEARCHING OPTIMAL CHARGED PARTICLE OPTICAL POTENTIAL PARAMETERS IN $E \lesssim 50$ MeV ENERGY REGION

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APCOM is a program for automatically searching the optimal charged particle optical potential parameters in $E \lesssim 50$ MeV energy region by means of the fastest falling method[1]. The projectile p, d, t, ^{3}He, and α are allowed in this program.

The charged particle optical potential $V(r)$ is defined as Woods–Saxon form[2]:

$$V(r) = V_C(r) - Vf_r(r) - iW_V f_V(r) + 4ia_S W_S \frac{df_S(r)}{dr} + \lambda_\pi^2 \frac{2V_{SO}}{r} \frac{df_{SO}(r)}{dr} (\vec{s} \cdot \vec{l}), \tag{1}$$

where

$$V_C(r) = \begin{cases} zZe^2 / r & \text{if } r \geqslant R_C \\ zZe^2(3 - r^2 / R_C^2) / 2R_C & \text{if } r \leqslant R_C \end{cases} \tag{2}$$

$$V = V_0 + V_1 E + V_2 E^2 + V_3 (N - Z) / A + V_4 Z / A^{1/3} \tag{3}$$

$$W_S = W_{S0} + W_{S1} E + W_{S2} (N - Z) / A \tag{4}$$

$$W_V = W_{V0} + W_{V1} E + W_{V2} E^2 \tag{5}$$

$$f_i(r) = \frac{1}{1 + \exp[(r - r_i) / a_i]} \qquad i = r,\ S,\ V,\ SO \tag{6}$$

$$R_i = r_i A^{1/3} \qquad i = r,\ S,\ V,\ SO,\ C \tag{7}$$

$$a_i = a_{i0} + a_{i1}(N-Z)/A \qquad i = S,\ V \tag{8}$$

E is the incident neutron energy in laboratory system. z is the charge number of the projectile. λ_π is the Compton wavelength of pion, $\lambda_\pi^2 = 2.0$ fm^2. The 15 parameters: V_0, V_1, V_2, W_{S0}, W_{S1}, W_{V0}, W_{V1}, W_{V2}, r_r, r_S, r_V, r_C, a_r, a_{S0}, and a_{V0} can be adjusted. The maximum number of energy points is 30 in this program.

The adjustment of the optical potential parameters is performed automatically with computer to minimize a quantity called χ^2, which represents the deviation of the calculated nuclear data from the experimental values. The χ^2 is defined as follows:

$$\chi^2 = \frac{1}{W_{ne} + W_{el}} [W_{ne}\chi^2_{\sigma_{ne}} + W_{el}\chi^2_{\sigma_{el}(\theta)}] \tag{9}$$

where

$$\chi^2_{\sigma_{ne}} = \frac{1}{N_{ne}} \sum_{j=1}^{N_{ne}} \left[\frac{\sigma^T_{ne}(j) - \sigma^E_{ne}(j)}{\Delta\sigma^E_{ne}(j)}\right]^2 \tag{10}$$

$$\chi^2_{\sigma_{el}(\theta)} = \frac{1}{N_{el}} \sum_{j=1}^{N_{el}} \frac{1}{n_j} \sum_{i=1}^{n_j} \left[\frac{\sigma^T_{el}(\theta_{j\,i}) - \sigma^E_{el}(\theta_{j\,i})}{\Delta\sigma^E_{el}(\theta_{j\,i})}\right]^2 \tag{11}$$

The superscripts T and E represent the theoretical and experimental values, respectively. The values of N_{ne} and N_{el} are the numbers of energy points of the experimental data, corresponding to σ_{ne} and $\sigma_{el}(\theta)$, respectively. Where n_j is the number of angles of the experimental differential cross section corresponding to the j'th energy point, and $\theta_{j\,i}$ is the angle value of the i'th angle for the j'th energy point. W_{ne} and W_{el} are weight factors.

We regard χ^2 as the function of the adjustable parameters. In order to search for the minimum of the χ^2, the adjusted parameters are constantly changing along the direction in which the χ^2 decreases fastest. In this program the fastest falling method is improved, for which each parameter step length can be adjusted respectively and automaticaliy. Because the emitted charged particle must overcome the Coulomb barrier, their excitation curves become observable only if the incident energy is larger than about 4 MeV. Therefore, the contribu-

tion of the compound nucleus elastic scattering process may be neglected. This program allows user to fit the experimental data for 10 nuclei maximally. Thus for those elements lack of experimental data, one can obtain its optical potential parameters based on the experimental data of neighbor nuclei with this program.

Many application practices for this program show that the searching velocity of the best parameters is fast and generally a rather successful results can be obtained with this program.

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APOM — A CODE FOR SEARCHING OPTIMAL NEUTRON OPTICAL POTENTIAL PARAMETERS

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The optical model is one of the most important theories in nuclear data calculations. In addition, the Hauser–Feshbach theory and the evaporation model, describing the compound nucleus process, as well as the exciton model, describing the pre–equilibrium emission process, all depend on the transmission coefficient T_{lj} or the compound nucleus formation cross section σ_a which should be also calculated by optical model. The calculated results of optical model are mainly decided by its parameters. Thus choosing and adjusting the optical potential parameters are the crucial steps in nuclear data calculations.

APOM is a program developed from program AUJP[1] for automatically searching the optimal neutron optical potential parameters in $E<20$ MeV en-

ergy region for medium–heavy nuclei by means of the fastest falling method[2] instead of complex arithmetic method in code AUJP.

The optical potentials[3] considered here are Woods–Saxon form for the real part, Woods–Saxon and derivative Woods–Saxon form for the imaginary parts corresponding to the volume and surface absorptions respectiively, and the Thomas form for the spin–orbit part. In order to improve the agreement between the theoretical and experimental values at the high energy part, the E^2 term is included in the volume absorption part. The 14 parameters: V_0, V_1, V_2, W_{S0}, W_{S1}, W_{V0}, W_{V1}, W_{V2}, r_r, r_S, r_V, a_r, a_S, and a_V can be adjusted. The maximum number of energy points is 31 in this program.

The adjustment of the optical potential parameters is automatically performed by computer to minimize a quantity called χ^2, which represents the deviation of the calculated total and nonelastic cross sections and elstic scattering angular distributions from the experimental values.

We regard χ^2 as the function of the adjustable parameters. In order to search for the minimum of the χ^2, the adjusted parameters are constantly changing along the direction in which the χ^2 decreases fastest. In this program the fastest falling method is improved : each parameter step length can be adjusted respectively and automatically. The calculations of the compound nucleus elastic scattering are within the framework of the width fluctuation corrected Hauser–Feshbach theory. This program is suitable for single element or natural nucleus.

Many practical uses of this code show that the velocity of searching the best parameters is fast and rather successful results can be obtained.

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CALCULATION AND ANALYSIS OF PROTON INDUCED REACTIONS ON ^{63}Cu IN ENERGY REGION 3~55 MeV

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ABSTRACT

A set of proton optical potential parameters for $E<55$ MeV is obtained on the available experimental data of ^{63}Cu and neighbour nucleus ^{62}Ni and ^{64}Zn, and all cross sections of proton induced reactions on ^{63}Cu are calculated. The calculated results are compared with experimental data.

INTRODUCTION

With the rapid development of science and technology, the application fields of intermediate energy charged particle nuclear data are becoming promising and expanding, as in accelerator applications, space radiation effects, medical radioisotope production, radiation damage of materials, activation analysis, and standard reference nuclear data etc.. The radioisotope yield cross sections can tell us what energy region is more suitable for specific radioisotope production in certain nuclear reaction, and these radioisotopes are used in medicine both for diagnostic studies and therapy. Because intermediate energy charged particle experimental data are less, the theoretical calculation is very important. The purpose of this paper is to calculate proton reaction data of ^{63}Cu for $E<55$ MeV.

1 THEORETICAL MODELS AND PARAMETERS

The optical model, evaporation model and pre-equilibrium emission theory-exiton model are used in our calculation.

First, the code APCOM[1], by which the best proton optical potential parameters can be searched automatically with fitting experimental reaction

cross sections and elastic scattering angular distributions, is used to obtain a set of best proton optical potential parameters of ^{63}Cu. Because the experimental data of proton reaction cross sections and elastic scattering angular distributions of ^{63}Cu are less, we also choose proton reaction cross section experimental data of ^{62}Ni[2,3] and ^{64}Zn[4], which are neighbour nuclides of ^{63}Cu. A set of best proton optical potential parameters of ^{63}Cu, ^{62}Ni and ^{64}Zn are obtained as follows:

$$V = 55.886 - 0.4942E - 0.01091E^2 + 24(N-Z)/A + 0.4Z/A^{\frac{1}{3}},$$
$$W_s = 13.3767 - 0.3122E + 12(N-Z)/A,$$
or zero, whichever is greater,

$$W_v = -2.5911 + 0.3264E - 0.00070225E^2,$$
or zero, whichever is greater,

$$V_{so} = 6.2,$$
$$r_r = 1.2271, \quad r_s = 1.1423, \quad r_v = 1.435, \quad r_{so} = 1.01, \quad r_c = 1.251,$$
$$a_r = 0.5604, \quad a_s = 0.6371 + 0.7(N-Z)/A,$$
$$a_v = 0.4745 + 0.7(N-Z)/A, \quad a_{so} = 0.75.$$

Then, using this set of proton optical potential parameters and adjusting some other charged particle and neutron optical potential parameters, level density parameters and the free parameter of square of the average two-body interaction matrix element K in pre-equilibrium exciton model, all reaction cross sections are calculated by the code CMUP2[5].

2 CALCULATED RESULTS AND ANALYSES

Fig. 1 and Fig. 2 show the comparison of proton reaction cross sections for ^{63}Cu and ^{64}Zn in energy region 3~ 55 MeV between the theoretical values (solid line) and experimental data taken from Ref. [2], respectively. The calculated results are in good agreement with the experimental data. The comparisons of proton elastic scattering angular distributions of ^{63}Cu between calculated results and experimental data are given in Fig. 3, the proton incident erengies are 7.34, 8.8, 10.2, 11.03, and 12.29 MeV, respectivelly, the agreement are excellent with each other. The calculated results in Fig. 1 to Fig. 3 show that this set of proton optical potential parameters obtained by us are very good.

Fig. 4 gives the comparison of calculated proton inelastic scattering cross

sections and experimental data[3,9], and shows that the calculated values are in reasonable agreement with experimental data.

The comparisons for theoretical calculated results and experimental data of $^{63}Cu(p,n)^{63}Zn$[6], $^{63}Cu(p,2n)^{62}Zn$[6] and $^{63}Cu(p,3n)^{61}Zn$[7] reaction cross sections are given in Fig. 5 to Fig. 7, respectivelly. The agreement between the calculated values and experimental data are excellent for $^{63}Cu(p,n)^{63}Zn$ and $^{63}Cu(p,3n)^{61}Zn$ reactions in the whole energy range. The calculated value of $^{63}Cu(p,2n)^{61}Zn$ reaction cross sections is in agreement with experimental data for $E_p \geqslant 25$ MeV, but for $E_p < 25$ MeV, the calculated values are higher than experimental data, the reason may be that the effect of discrete level is not considered.

The comparison of theoretical calculated results and experimental data of $^{63}Cu(p,pn+d)^{62}Cu$[8,9] and $^{63}Cu(p,p3n+2nd+nt)\ ^{60}Cu$[7] reactions are given in Fig. 8 and Fig. 9, respectively.The calculated results are agreement with experimental data for $^{63}Cu(p,np+d)^{62}Cu$ cross sections. The difference of calculated results and experimental data is rather large in whole energy range for $^{63}Cu(p,p3n+2nd+nt)^{60}Cu$ cross sections, this difference needs to be studied further in theory and experiment.

Above results show that for $^{63}Cu(p,p')^{63}Cu$, $^{63}Cu(p,n)^{63}Zn$, $^{63}Cu(p,3n)^{61}Zn$ and $^{63}Cu(p,np+d)^{62}Cu$ reactions, the calculated results are in good agreement with the experimental data, for $^{63}Cu(p,2n)^{61}Zn$ and $^{63}Cu(p,2nd+p3n+nt)^{60}Cu$ reactions need to study further not only from theories but also from the experimental measuments.

3 CONCLUSIONS

Based on the available experimental data of ^{63}Cu and neighbour nuclides ^{62}Ni and ^{64}Zn, we obtain a set of proton optical potential parameters for $E_p \leqslant$ 55 MeV. With adjusting neutron and the other charged particle optical potential and level density parameters as well as using $K = 600$ MeV[3], the calculated nuclear data for the most of channels are in good agreement with the experimental data, but some channels need to be improved.

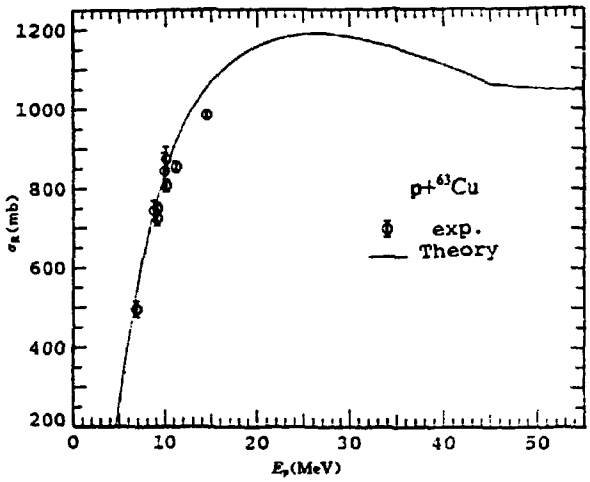

Fig. 1 Comparison of calculated reaction cross sections of ^{63}Cu with experimental data

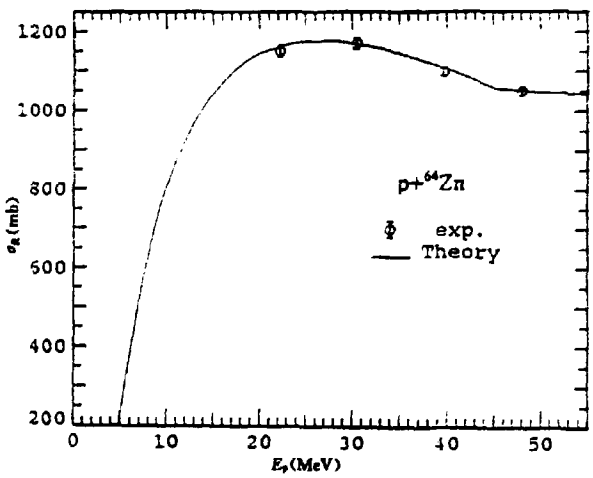

Fig. 2 The same as Fig. 1 but for ^{64}Zn

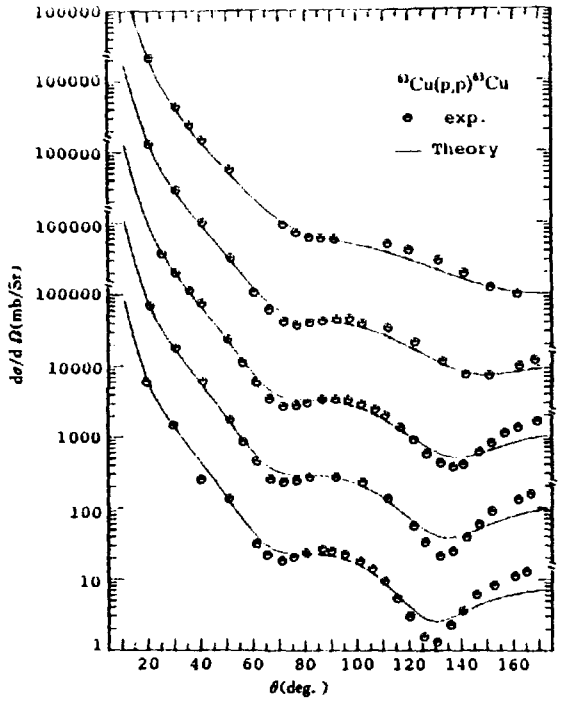

Fig. 3 Comparison of calculated proton elastic scattering angular distributions of ^{63}Cu at 7.34, 8.8, 10.2, 11.03 and 12.29 MeV with experimental data

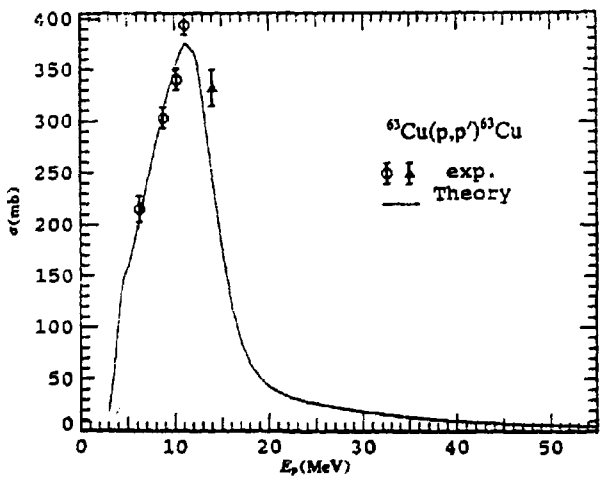

Fig. 4 Comparison of calculated inelastic scattering cross sections of ^{63}Cu with experimental data

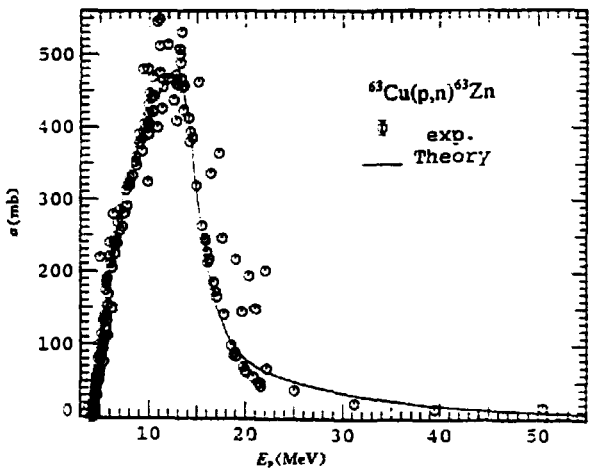

Fig. 5 Comparison of calculated ^{63}Cu(p,n)^{63}Zn reaction cross sections with experimental data

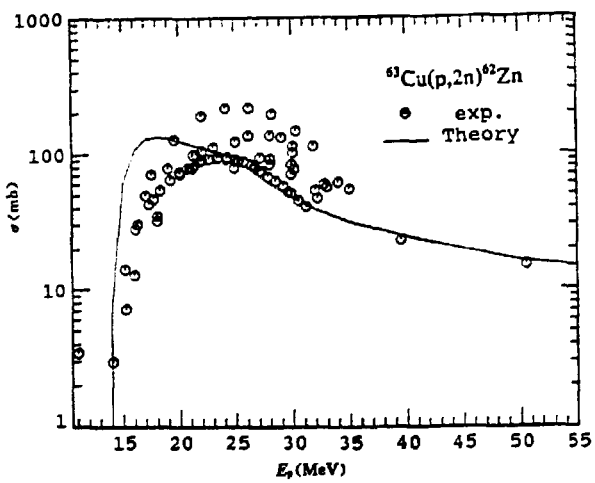

Fig. 6 The same as Fig. 5 but for ^{63}Cu(p,2n)^{62}Zn reaction

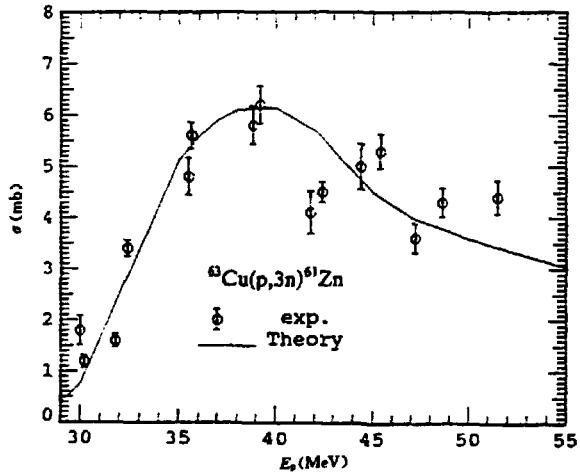

Fig. 7 The same as Fig. 5 but for ^{63}Cu(p,3n)^{61}Zn reaction

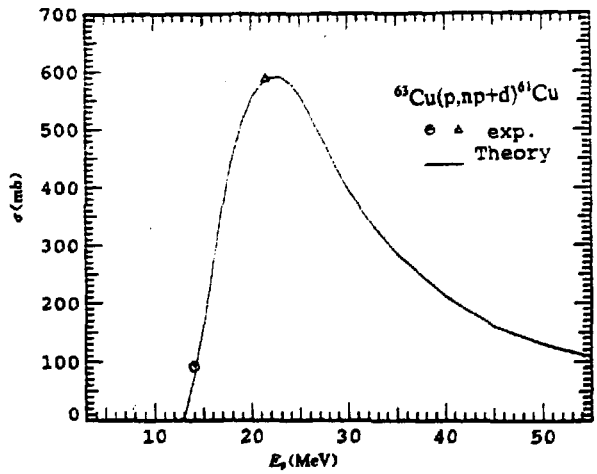

Fig. 8 The same as Fig. 5 but for ^{63}Cu(p,pn+d)^{62}Cu reaction

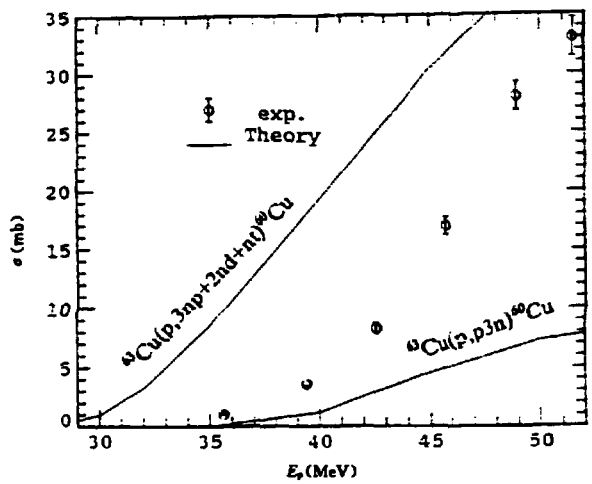

Fig. 9 The same as Fig. 5 but for ^{63}Cu(p,3np+2nd+nt)^{60}Cu reaction

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III DATA EVALUATION

EVALUATION OF $^{197}Au(n,2n)^{196}Au$ REACTION CROSS SECTION

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$^{197}Au(n,2n)^{196}Au$ cross section is one of the important dosimetry reaction cross sections. Since the fifties more than 30 measurements have been completed and the evaluation works have also been reported from time to time. It is noted that most of the measured data published in the eighties are more or less lower than the existed evaluated data[1~4], and some of the newly measured data were not included in these evaluations. Therefore, a new evaluation for $^{197}Au(n,2n)^{196}Au$ reaction cross section seems to be necessary.

Most of the measurements were carried out by using the activation method and a few of them were carried out by using the large liquid scintillators. In the early measurements, the main factors impaired the results measured by the activation method were the imperfect detection technique, inaccurate calibration of detection efficiency and the outmoded decay and standard data used. And the presence of lower energy neutrons in incident beam mainly was that for the large liquid scintillator measurements. Overall, the quality of the data measured in the fifties and sixties is a bit poor as compared with the newly measured data. The weak points of the early measured data are shown in the following aspects :

Large divergence of the data : e. g. the (n,2n) cross section of 2.6 ± 0.2 b for 14.1 MeV neutrons was given bv Ashby[5] and of 1.72 ± 0.01 b for 14.8 MeV neutrons was given by Mangal[6].

Poor accuracy of the measurements : Some of the uncertainties of the data given by the authors, such as Paul[7] and Tewes[8], amounted to or twenty percent, and the data given in Refs. [9] and [10] had a poor accuracy too.

Be replaced by new ones : The data given by Tewes[8] and Prestwood[11] have been superseded by the more recent published data.

Lacking minute description to the measurement, etc..

In consideration of those mentioned above, the data measured in the fifties and sixties are rejected in the evaluation. For the similar reasons, some of the data measured in the seventies and eighties are rejected in the evaluation too. It should be noted here that the data of Frehuat[12], Ikeda[13] and Ryves[14] have been superseded by the new ones and the data of Mather[15] seems too high for the 14.3 MeV neutrons, because the Mather's value is almost the same as that of the nonelastic scattering cross section.

To sum up, our evaluation is based solely on experimentally measured data. For the purpose of establishing the data base, a literature search and study was carried out thoroughly. The experimental data available up to 1990 have been collected. All the data sets have been critically reviewed, and a deeper review of selected experiments has been made. Then the valid data are selected and used in data fitting. When it is necessary and possible, the data are renormalized by using the recent standard cross sections and decay schemes.

The data processing and fitting are carried out in the following three steps :

1. Curve fitting for the cross section data up to 20 MeV;
2. Treatment of the cross section data for 14 MeV neutrons;
3. Normalization of the obtained fitted curve to the evaluated cross section value at 14.7 MeV.

A polynomial fit program[16] is used to fit the experimental data. The experimental data measured by Lu[4], Ikeda[17], Kobayashi[18], Greenwood[19], Herman[20], Garlea[21], Daroczy[22], Reggoug[23], Csikai[24], Ryves[25], Laurec[26], Frehaut[27], Andersson[28], Veeser[29], Bayhurst[30], Paulsen[31], Nethaway[32], Qaim[33], Hankla[34]and Maslov[35]are accepted as the input data. The weights of the data are basically taken on the basis of the experimental errors given by the authors. By way of exception, the errors given in the 12.8～16.4 MeV neutron energy region in Ref. [31] are changed from about 6% to 8%.

In order to make the evaluation of the cross section value in the 14 MeV neutron energy region, 15 experimental data from Refs. [4, 17～21,23～30, 32] are selected and adjusted to the same neutron energy point, 14.7 MeV, according to the cross section trend given by the above-mentioned fitted curve. Some experimental data are renormalized by using the more recent standard and reference data. The standard and reference data are taken from Lu[4], Yuan[36], ENDF / B-6 and Browne[37] for $^{27}Al(n,\alpha)$, $^{56}Fe(n,p)$, $^{56}Cu(n,2n)$ cross sections and decay schemes respectively. Similarly, the weights of the data are basically taken on the basis of the experimental errors given by the authors. An exception is that the error given in Ref. [23] is enlarged to 5%. The weighted average of these results is 2094 ± 25 mb for 14.7 MeV neutrons.

The calculated error of this cross section seems to be small because there is a considerable difference among the existed evaluated values for standard cross section, especially, for the $^{27}Al(n,\alpha)$ cross section. According to the experimental errors given by the authors and the general consistency of the experimental data, a uncertainty of 40 mb is estimated for the evaluated cross section value at 14.7 MeV thus the evaluated value of the $^{197}Au(n,2n)$ cross section for 14.7 MeV neutrons is adopted as

$$\sigma = 2094 \pm 40 \text{ mb}$$

which is in agreement with Ryves[2] (2127 ± 26 mb)

Table 1 shows the selected experimental data and their adjusted data for 14.7 MeV neutrons.

Table 1 $^{197}Au(n,2n)$ **cross section for 14 MeV neutron**

Author (Year)	Ref.	E_n, MeV	σ_{exp}, b	$\sigma_{14.7}$, b
Lu (89)	4	14.6	2.129 ± 0.095	2.141 ± 0.095
Ikeda (88)	17	14.71	1.894 ± 0.097	1.869 ± 0.097
Kobayashi (88)	18	14.05	2.125 ± 0.029	2.126 ± 0.079
Greenwood (85)	19	14.65	2.154 ± 0.109	2.172 ± 0.109
Herman (84)	20	15.0	2.087 ± 0.122*	2.043 ± 0.122
Garlea (84)	21	14.75	2.071 ± 0.093	2.069 ± 0.093
Reggoug (82)	23	14.7	1.990 ± 0.050	1.990 ± 0.100
Csikai (82)	24	14.66	2.087 ± 0.142	2.078 ± 0.142
Ryves (81)	25	14.68	2.170 ± 0.067	2.105 ± 0.067
Laurec (81)	26	14.8	2.010 ± 0.090	2.027 ± 0.090
Frehaut (80)	27	14.76	1.935 ± 0.155	1.932 ± 0.155
Andersson (78)	28	14.9	2.295 ± 0.116	2.307 ± 0.116
Veeser (77)	29	14.7	2.064 ± 0.125	2.064 ± 0.125
Bayhurst (75)	30	14.89	2.116 ± 0.089	2.206 ± 0.089
Nethaway (72)	32	14.72	2.149 ± 0.100	2.189 ± 0.100

* averaged from 2.025 ± 0.122 b and 2.148 ± 0.137 b

The fitted curve is then normalized to the evaluated value at 14.7 MeV, and the evaluated data in the neutron energy region from 8.12 MeV to 20 MeV are obtained. Table 2 shows the present evaluated data. The uncertainties of the data are also derived taking into account both the errors given by the authors and the general consistency of the experimental data. Fig. 1 shows the present result of evaluation compared with those of ENDF / B–6 and the measured data. It

can be seen that the present evaluated data become closer to the experimental data than those of ENDF / B–6, especially in the neutron energy region above 15 MeV.

Table 2 Evaluated data of ^{197}Au(n,2n) cross section

E_n , MeV	σ , mb	E_n , MeV	σ , mb
8.12	11± 1	14.5	2091± 42
8.5	75± 5	14.6	2092± 42
9.0	329± 20	14.7	2094± 40
9.5	718± 43	14.8	2097± 42
10.0	1079± 64	15.0	2100± 63
10.5	1349± 54	15.5	2101± 73
11.0	1546± 62	16.0	2086± 83
11.5	1698± 68	16.5	2042± 101
12.0	1824± 64	17.0	1960± 98
12.5	1923± 67	17.5	1831± 91
13.0	1996± 50	18.0	1663± 112
13.5	2043± 51	18.5	1471± 102
14.0	2073± 41	19.0	1276± 89
14.2	2080± 42	19.5	1101± 77
14.4	2087± 42	20.0	957± 67

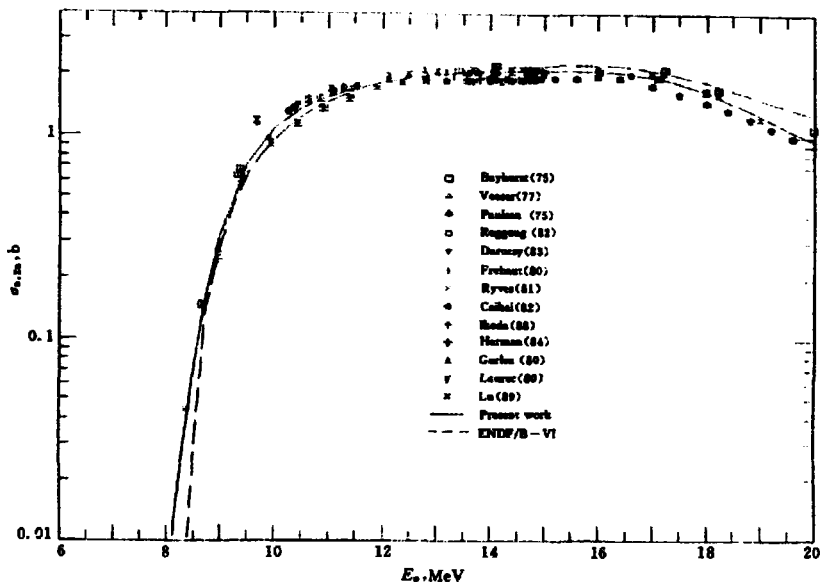

Fig. 1 Comparison of evaluated and measured data for (n,2n) reaction cross section of ^{197}Au

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PROGRESS ON NUCLEAR DATA EVALUATION IN PEKING UNIVERSITY IN 1991

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1 NEUTRON NUCLEAR DATA EVALUATION FOR ^{238}U

The evaluation of neutron nuclear data of ^{238}U for CENDL-2 was finished. Comparing to CENDL-1, the resonance parameters have been added and all pointwise data have been renewed. Comparing to ENDF / B-5, most of the data were renewed. All the relatively measured data (to ^{235}U and ^{197}Au) have been renormalized to ENDF / B-6 data file. For theoretical calculation the new improved code of FUP1 was used. The recommended experimental data and the theoretical calculated data were adjusted and let $\sigma_{tot} = \sigma_{el} + \sigma_{non}$. The resonance parameters in the neutron energy range below 10 keV were took 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.

2 NEUTRON NUCLEAR DATA EVALUATION FOR ^{237}Np

The measured data of (n,f), (n,t) 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 were theoretically calculated. The total cross section, absorption cross section and elastic angular distribution were calcuated by using the parameters got from optical model. All data were calculated by using general computer code FUP1 (the parameters of the optical model used as input data to FUP1). The recommended experimental data and the theortically calculated data were adjusted and let $\sigma_{tot} = \sigma_{el} + \sigma_{non}$. The resonance parameters in the energy range below 30 keV were also added. All the data in the energy range 10^{-5} eV to 20 MeV were recommended as the data file of ^{237}Np for CENDL-2.

3 RENEW OF NEUTRON NUCLEAR DATA FOR NATURAL Si AND Mg

The main advancement of our recommended data is that all data were calculated by using MUP2 code[1] and the data for (n,n'p), (n,n'α), (n,2α) reactions were derived from (n,p), (n,α) reactions. Further detail of our works can be seen from CENDL-2.

Beside the data of total cross section (MT=1), the cross sections of radiative capture, (n,p), (n,α) reactions and all other reactions, the data of angular distributions for elastic and inelastic scattering and the energy distribution of secondary neutrons were taken from the calculations using MUP2 code.

PROGRESS ON NUCLEAR STRUCTURE AND DECAY DATA EVALUATION FOR A-CHAIN

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The nuclear structure and decay data are basic data for the basic research of nuclear physics, nuclear technique applications and nuclear engineering designs. The data evaluations are done by all members of the International Structure and Decay Data Network. Chinese Nuclear Data Center is one of the members, and is permanently responsible for the evaluating and updating data of ten mass chains of $A=$ 51~56 and 195~198, and is temporarily for the evaluating ones of three mass chains of $A=$ 170, 172 and 61. The progress on data evaluations for last year is summarized as follows:

1. **Put Into Evaluated Nuclear Structure Data File And Published:**
   1) $A=51$ update[1], Nuclear Data Sheets, Vol., 63, 229 (1991);
   2) $A=55$ update[2], Nuclear Data Sheets, Vol., 64, 723 (1991).
2. **In Evaluating**
   $A=196$[3], 61
3. **In Updating**
   $A=56$[2], 54[2]

1) Done by China Institute of Atomic Energy, Beijing, and Department of Physics, Jilin University, Changchun.

2) Done by Department of Physics, Jilin University, Changchun.

3) Done by Institute of Nuclear Research, Shanghai.

PARAMETERIZATION OF ROTATIONAL SPECTRA

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The "strongly" deformed nuclei that are commonly encountered in the "rare-earth" region (e. g., $150 < A < 190$) and the actinide region (e. g., $A > 220$) are very interesting ones for basic reseachers of the nuclear structure. The rotational spectra of the strongly deformed nuclei with low rotational frequencies and weak band mixture are generally analyzed by

$$E(k,J) = E_k + AX + BX^2 + CX^3 + \ldots + (-1)^{J+K} \prod_{i=1-K}^{K} (J+i) \{A_{2k} + B_{2k}X + \cdots\} \quad (1)$$

where J is total angular momentum quantum number of the intrinsic state which describes rotational motion, K is the projection of the J onto the nuclear symmetry axis, and X represents either $J(J+1)$ or $J(J+1)-K^2$.

In the derivation of the relationship expressed in Eq. (1), it is assumed that K is, at least approximately, a good quantum number. This means that the coupling (mixing) of the band under consideration with other band in the same nucleus is not too strong and that rotational frequencies of the states are not too high. In such cases, the fitting coefficients (e. g., A, B and A_{2k}) are small.

The typical fitting works with level-energy differences only and the parameter E_K, which serves to locate the energy of the band head, can be neg-

lected. The fitting code has been studied and a lot of data has been analyzed by it. From the analysis we have done, a lot of rotational band knowledges can be given:

1. The fitting parameter B is small, the order of magnitude $B/A \approx 10^{-3}$, and the typical value of the rotational constant A is about 12 keV in the "rare-earth" region and about 6 keV in the actinide region, respectively.
2. The new members of the band under consideration can be predicted by using known fitting parameters.
3. For the $K=1/2$ band, the decoupling parameter a ($a=A_{2k}/A$, $K=1/2$) provides almost unique information about the nature and extent of the single-particle (or one-quasiparticle) content of the band.
4. The rotational constant $A(=h^2/2Z)$ gives the information about the effective moment of inertia (Z) of the band.
5. The parameters A_{2k} and B_{2k} give a shift of a relative placements of the odd and even-spin within the band. The magnitudes of these parameters are decreased rapidly with increasing K value and their effects are the most readily apparent in those bands having the smaller K value.
6. Physically meaningful results are obtained by only a few fitting parameters in Eq. (1).

EVALUATIONS OF INTERNAL CONVERSION COEFFICIENTS

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The calculations of internal conversion coefficients in nuclear structure and decay data evaluations have been studied. The two cases of L and $L+1$ multiporality mixture have been paid more attention to :

1. Mixing With Measured α_k (or α_L)

If α_k is measured internal conversion coefficient of K-shell for L and $L+1$ multiporality mixture, δ is the mixing ratio for L and $L+1$ multiporality mixture components, and $\alpha_k(L)$ and $\alpha_k(L+1)$ are the theoretical internal conversion coefficients of K-shell for L and $L+1$ multiporality,

respectively, we can obtain

$$\alpha_K(\exp) = \frac{\alpha_k(L) + \delta^2 \alpha_K(L+1)}{1+\delta^2} \tag{1}$$

From formula (1) can be deduced

$$\delta = \left\{ \frac{\alpha_K(\exp) - \alpha_K(L)}{\alpha_k(L+1) - \alpha_K(\exp)} \right\}^{1/2} \tag{2}$$

The δ value can be calculated, if known $\alpha_K(\exp)$, $\alpha_K(L)$ and $\alpha_K(L+1)$ are substituted into formula (2). The internal conversion coefficients $\alpha_i(\delta)$ for the different shells and total one $\alpha(\delta)$ can be calculated by

$$\alpha_i(\delta) = \frac{\alpha_i(L) + \delta^2 \alpha_i(L+1)}{1+\delta^2} \tag{3}$$

$$\alpha(\delta) = \sum_i \alpha_i(\delta) = \frac{\alpha(L) + \delta^2 \alpha(L+1)}{1+\delta^2} \tag{4}$$

where i = K, L, M, N, O shell.

2. Mixing With Measured Conversion Electron Intensity Ratio $R(a/b)$ for Subshell a and b

If $\alpha_a(L)$, $\alpha_b(L)$, $\alpha_a(L+1)$ and $\alpha_b(L+1)$ are the theoretical internal conversion coefficients of subshell a and b for L and $L+1$ multiporality, respectively, and δ is the mixing ratio for L and $L+1$ multiporality mixture component, we can obtain

$$R(a/b) = \frac{\alpha_a(L) + \delta^2 \alpha_a(L+1)}{\alpha_b(L) + \delta^2 \alpha_b(L+1)} \tag{5}$$

From fomula (5) can be deduced

$$\delta = \left\{ \frac{\frac{\alpha_a(L)}{\alpha_b(L)} - R(a/b)}{R(a/b) - \frac{\alpha_a(L+1)}{\alpha_b(L+1)}} \times \frac{\alpha_b(L)}{\alpha_b(L+1)} \right\}^{1/2} \tag{6}$$

The δ value can be calculated, if known $R(a/b)$, $\alpha_a(L)$, $\alpha_b(L)$, $\alpha_a(L+1)$ and $\alpha_b(L+1)$ are substituted into formula (6). The internal conversion coefficients $\alpha_i(\delta)$ for different shells and total one $\alpha(\delta)$ can also be calculated from formula (3) and (4) by using known δ, $\alpha_i(L)$, $\alpha_i(L+1)$, $\alpha(L)$ and $\alpha(L+1)$ (calculated by HSICC code).

NUCLEAR DATA EVALUATION PROGRESS AT NUCLEAR PHYSICS LABORATORY, JILIN UNIVERSITY

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1 NUCLEAR STRUCTURE DATA AND DECAY DATA

1.1 $A = 55$ Mass Chain

The nuclei of evaluated nuclear structure and decay data for $A = 55$ mass chain are ^{55}Cr, ^{55}Mn, ^{55}Fe, ^{55}Co, ^{55}Ni, and ^{55}Cu. The 1984 evaluation of Nuclear Data Sheets for $A = 55$ (published in Nuclear Data Sheets, Vol. 44, 463, (1985)) has been revised by using experimental data from nuclear reaction and decay studies. In comparison with the last evaluation there are some new data in following data sets.

^{55}Mn(n,n'γ)	^{55}Fe ε decay
^{55}Fe(p,d) (pol p,d) (HI,xnγ)	^{58}Fe(^{3}He,α)
^{55}Ni adopted levels	^{54}Fe(p,γ)
	^{55}Cu adopted levels

The detailed level schemes, decay schemes, and related experimental data are presented. Adopted values for levels and γ radiations, as well as other nuclear properties are given.

Nuclear data sheets for updating for $A = 55$ has been published in Nuclear Data Sheets, Vol. 64, 723, (1991).

1.2 $A = 56$ Mass Chain

The 1986 evaluation of nuclear data sheets for $A = 56$ (published in Nuclear Data Sheets, Vol. 51, 1, (1987)) has been updated usig experimental nuclear structure and decay data. Many of the data sets presented in the last evaluation are re–evaluated. In comparison with the last evaluation there are some new data in following data sets :

^{58}Ti adopted levels	^{56}V adopted levels
^{54}Cr(α,^{2}He)	^{56}Fe(^{12}C,^{12}N)
^{58}Fe(d,d')	^{56}Fe(n,n')
^{58}(n,n'γ)	^{56}Fe(α,α')
^{58}Fe(π,π')	^{56}Fe(α,^{2}He)
^{58}Ni ε decay	^{56}Co decay
^{58}Cu adopted levels	

The information obtained in various reaction and decay experimental data are summarized and presented, together with adopted level schemes and properties.

The evaluated result has been sent to National Nuclear Data Center, U. S. A., the organizer of International Nuclear Structure and Decay Data Network, and will be published in Nuclear Data Sheets.

1.3 $A = 54$ Mass Chain

International Nuclear Structure and Decay Data Network requires that all of the network members try hard to make the evaluations of the A–chain that they are responsible for, as current as possible. New evaluations should be sent

to National Nuclear Data Center, U. S. A., no later than June 1992. Chinese Nuclear Data Center has reassigned $A = 54$ mass chain to us.

Evaluation of $A = 54$ is in progress.

2 RECOMANDED DECAY DATA FOR SECOND VERSION OF CHINESE EVALUATED NUCLEAR DATA LIBRARY (CENDL-2)

This work has been finished and its result was reviewed and accepted by a specialist group appointed by the Chinese Nuclear Data Center on July 10, 1991.

Based on neutron cross sections which were collected in the First Version of Chinese Evaluated Nuclear Data Library (CENDL-1) and according to the format of MT = 453, 457 in ENDF / B-4, decay data were recomanded.

IV ATOMIC AND MOLECULAR DATA

A DATABASE ON ION–ATOM COLLISION PROCESSES

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A primary atomic and molecular database for controlled thermonuclear fusion was formed at Chinese Nuclear Data Center. The basic feature of data system and retrievable contents are briefly described as follows.

We adopt ALADDIN format[1] which was recommended by IAEA, for storage and exchange of atomic and molecular data.

The advantages of ALADDIN system are :

1) Allowance for maximun flexibility of the database structure so different types of data (such as spectroscopic, collisional, plasma–wall interactive data etc.) and large diversity of data presentations;
2) Direct, multi–level and interactive access to the databases, to allow for an active relation of the data user with database, large freedom in data interfacing to various application codes (e. g. plasma diagnostic, modelling, experiment–interpretative codes, etc.);
3) Use of standard scientific computer language (FORTRAN 77) and possibility to run the system on wide range of computing facitities.

At present, the following retrievable atomic and molecular data at CNDC are contained :

1) Collision ionizations of atoms and ions ($z = 1 \sim 92$) with electron in range of incident energy 10 eV ~ 100 keV.
2) Excited cross sections and rate coefficients of C, O, He atoms and ions with H, H_2, He.

3) Collision ionization, excitation, electron capture, electron emission and assocciation of H, H_2, He, Li and Fe atoms, ions and molecules with H, H_2, He, Li atoms and ions.

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EVALUATION OF TRAPPING AND DESORPTION DATA

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1 TRAPPING DATA

Trapping data are significant for research of controlled thermo-nuclear fusion. With the development of fusion technology, it become clear that plasma-wall interactions involving hydrogenic particles have a major influnce not only on the lifetime of the first wall and other plasma facing components but also on the fundamental properties of heated plasmas. The trapping data of hydrogen and its isotopes have been collected, analysed and evaluated. The trapped fluence, re-emission rate etc. are included.

2 DESORPTION DATA

The surface of the wall material in a fusion reactor is usually covered with adsorbate atoms such as H, D, S etc.. Due to bombardment of ion, electron and photon, these adsorbate atoms are released into the plasma boundary. The surface layers are a significant source of both plasma particles ad impurities and therefore play an important role for hydrogen recycling impurity flux. The desorption yield and cross section data of some elements including stainless

steel, iron and nickel have been collected and evaluated.

After the evaluations of trapping and desorption, the data are completly accomplished, we will send the recommended data to Chinese Nuclear Data Center with ALADDIN format.

V DATA LIBRARY

THE ACTIVITIES ON CENDL EXFOR CINDA AND WRENDA IN CHINA

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1 CENDL-2 AND RELATIVE PROGRAM SYSTEM

The CENDL-2 was started in the beginning of 1986 and finally completed in July 1991.

The CENDL-2 was based on the CENDL-1[1,2], 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 of 1989 and 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 were completed by Chinese evaluators at home or abroad for foreign libraries via 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 update and revision performed by Chinese evaluators.

Table 1 Nuclides Contained in CENDL-2

^{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, ^{23}Na, Mg, ^{27}Al, Si, ^{31}P, S, K, Ca, Zn, Ti, ^{51}V, Cr, ^{55}Mn, Fe, ^{59}Co, Ni, Cu, Zr, ^{93}Nb, Mo, Ag, ^{107}Ag, ^{109}Ag, Cd, In, Sn, Sb, Hf, Ta, W, ^{197}Au, Pb, ^{232}Th, ^{235}U, ^{238}U, ^{237}Np, ^{239}Pu, ^{240}Pu, ^{241}Am, ^{249}Bk, ^{249}Cf

The library contains full sets of neutron data, i. e. resonance parameters in the resonance region and cross sections of all reactions, energy and angular distribution of secondary neutrons, and for some evaluations also double

differential cross sections or γ-production data, in the energy range from 10^{-5} eV to 20 MeV, most of evalautions 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 checked through by CHECKR, PHYCHE, FIZCON and then accepted in CENDL-2.

More detailed descriptions of CENDL-2 and the evaluations contained in CENDL-2 are given in elsewhere[3,4].

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 codes, 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.

Now the CENDL-2, ENDF/B-6, JENDL-3 and BROND Libraries have been loaded in disk of VAX-II and serves the users in China.

2 EXFOR

According to the research contract to IAEA, recently years, much efforts have been paid to develop the EXFOR software system for nuclear data compilation and to compile the EXFOR nuclear data measured in China. Now the EXFOR software system, which includes three parts, i. e. Edition, Check, and Retrieval, has been completed basically and used in the EXFOR data compilation.

Another "PC software assisting the nuclear data compilation in EXFOR" developed by Dr. V. Osorio has also been transplanted to our 386 PC.

The EXFOR processing program system and storage and retrieval system developed by NNDC have also been installed in Micro-VAX-II computer under the IAEA expert Dr. C. Dunford assistance.

So now the conditions for EXFOR nuclear data compilation and management in CNDC is very good.

The main purpose of EXFOR work in CNDC is the data compilation itself, and it will be a long-term task, up to now, we have compiled 10 EXFOR entries and sent them to IAEA/NDS in 1989, 1990 respectively, and we plan to compile at least 20 EXFOR entries in 1992.

In order to coordinate the activity on EXFOR nuclear data compilation in China, the Network for EXFOR data compilation has been established in 1990, the members of the Network consists of several institutes and universities in

China.

In the EXFOR data service, we hope that the entire EXFOR data library will be supplied by IAEA / NDS and loaded in our Micro-VAX-II computer when the new hard disk provided by IAEA is installed.

3 CINDA

Up to now, the CINDA work haven't carried out systematically in CNDC, although we have compiled some CINDA entries in past several years. We hope that this work will be continued hereafter.

Besides, IAEA / NDS has sent us the entire CINDA library and related codes system, we also hope we could build and maintain the CINDA library in Micro-VAX-II computer in future.

4 WRENDA

The WRENDA work was started in CNDC in 1987. We have collected some nuclear data requests in China and compiled the requests list for inclusion in WRENDA 87 / 88 at that time. According to the requirement of IAEA / NDS, we have completed the preparing work for the WRENDA 91 / 92 in last year, the main tasks are as following:

4.1 To ask previous requestors to review, update and make necessary changes on their previous nuclear data requests, or to delete the previous requests if they are satisfied by recent work or no longer needed.

4.2 To collect new requests, check and review them, fill in request form and then submit to IAEA / NDS.

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PROGRESS ON NUCLEAR MODEL PARAMETERS LIBRARY AT CNDC

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INTRODUCTION

As we know, once the nuclear reaction theory and its code has been selected to calculate nuclear data the results will be determined by nuclear model parameters used in the code. The confidence of the calculated results depends on not only the theory but also the reliability of the relevant parameters. Therefore, the nuclear reaction model parameters are a crucial ingredient in the nuclear data calculation. Users often have the difficulty for the lack of the needed parameters. Hence, it will be very convenient and useful if the users could retrieve all the needed basic physical constants and reliable parameters from a computer library and make a primary analysis to study nuclear reaction before running codes. Based on above considering, we are planning to set up a evaluated nuclear parameters library (CENPL) at CNDC.

1 BASIC IDEA ON CONSTRUCTING LIBRARY

The basic idea of constructing the parameters library are as follows:

1.1 The first purpose of constructing the library is to assist nuclear data evaluators in improving the nuclear data calculation.

1.2 This library should collect various model parameters generally adopted. Users may compare the different parameters and make a choice among them by using a code system at our library.

1.3 Users can retrieve the required parameters not only for a single nucleus (single nucleus retrieval), but also for all residual nuclei (neutron reaction retrieval) simultaneously, which includes the first, second and third reaction processes in neutron induced reaction.

1.4 All selected parameters from our library can be assembled a new file which will be used as the input data file of the nuclear model code for calculation.

1.5 The retrieval will be in the way of dialogue between user and computer.

2 SCOPE AND CONTENT

The parameter library will include six files.

2.1 Atomic masses and characteristic constants for nuclear ground state

In this file, there will be the following contents :

i. atomic mass,
ii. spin and parity of ground state,
iii. half-life or abundance,
iv. binding energy.

In addition,for single nucleus retrieval, the file could also provide the information on the separation energies of particles (such as n, p) or groups of particles (such as D, t, ^{3}He, α) for users, and for neutron induced reaction retrieval, user could retrieve the masses of all possible residual nuclei included in the whole reaction processes for a studied neutron reaction. User may also obtain the information on Q-values and threshold energies of every reaction channels.

2.2 Discrete level schemes

The file of the nuclear discrete levels will be based on the evaluated nuclear structure data of BNL. We are making a code to retrieve the discrete levels of single nucleus or all possible residual nuclei in a studied neutron induced reaction.

Evaluator will select a set of discrete levels and gamma branching ratios from this file. Of course, these selected discrete levels must be defined completely for the calculation of nuclear reaction data. In other words, all relevant information (such as the energy, spin, parity, etc.) of the discrete levels have to been known. For the lack of the experimental data on discrete levels, how to deal with nuclear discrete level schemes and branching ratios in nuclear data calculation will be studied further.

2.3 Giant resonance parameters for gamma-ray strength functions

As the first step, we are setting up a file, in which the compiled giant dipole resonance parameters by Dietrich and Berman[1] are stored.

It should be noted that the giant dipole parameters mentioned above could not satisfy the need of nuclear data calculation. Therefore, our next step is to engage in the systematic study of giant resonance parameter for gamma ray strength functions including $E1$, $M1$ and $E2$..We have noticed Kopecky[2] systematics, the recent progress on this subject by Kopecky and Uhl[3] and the other works.

As the third step, we will start a further theoretical research on giant resonance to make them reliable.

2.4 Level density parameters

We plan to set up two sub-files :

Sub-File A. Related experimental data

In order to test the level density formula and to recommend more reliable level density parameters, two kinds of experimental data have been collected and evaluated :

D_0 the S-wave average level spacing at the neutron binding energy B_n evaluated by a AVRPES[4] code.

N_0 the cumulative number of levels at a low excitation energy U_m evaluated by means of histogram. The amount of the collected data is about 650. In addition, we are collecting $\Gamma_\gamma(J, \pi, B_n)$.

These experimental data will be assembled a file (i. e. Sub-File A). All kinds of experimental data are very important for the research of nuclear level density.

Sub-File B. Level density parameters

Sub-File B will include three kinds of level density formulae and several sets of relevant level density parameters.

1. Gilbert-Cameron level density formula

There are three sets of G-C level density parameters that have been collected in this part. Gilbert-Cameron[5], Cook et al.[6] and Su et al.[7].

2. Back-Shifted Fermi gas formula

We have collected the level density parameters of Dilg et al.[8], Huang et al.[9] and Bychkov et al.[10].

3. Ignatyuk level density

Users can select one of the level density formulae and one set of level density parameters mentioned above. The parameters for single nucleus or for all possible residual nuclei in a studied neutron induced reaction can be retrieved with a retrieval code of this file.

In order to obtain the information on different kinds of level density parameters, user can also calculate D_0, N_0, and compare the calculated results with the experimental data stored in Sub-File A by using the retrieval code. These information can help evaluator select suitable level density parameters.

2.5 Optical model parameters

The compiled optical model parameter table by Perey is very significant and useful. It will be more difficult to set up an optical model parameter file than others. Because there have been the tremendous amount of information on optical model parameters in the literature up to now, as well as many and va-

ried types of optical potential (different incident particle types, local vs. nonlocal potentials, spherical, nonspherical, global vs. regional vs. nucleus–specific vs. energy–specific potentials, different geometry shapes and parameter types, ...). Therefore, what is the best way to set up an optical model parameter file should be studied further.

A working group for this work has been organized in China. the group consists of CNDC,Nankai Univ., Sichuan Univ., Shaanxi Normal Univ., Jilin Univ. and Wuhan Univ. and this group is making a plan for the work.

2.6 Fission parameters

The fission barrier parameters and saddle point state density parameters will be assembled a file (fission parameter file). Because the fission barrier parameters must match the saddle point state density parameters, and both will be used together in a practical calculation.

We have collected the following type fission parameters (including fission barrier and relevant saddle point state density parameters): Lynn[11], Back and Britt[12], Zhang and Wang[13], Howard[14]. And these parameters will be assembled as a fission parameter file.

Users can select any type fission parameters and retrieve the fission parameters of single nucleus or of all possible nuclei in (n,f), (n,nf) and (n,2nf) reaction processes.

3 PROGRESS

A group has been organized for the work of CENPL at CNDC and this group consists of CNDC, Guangxi Univ., Zhengzhou Univ., Nankai Univ. and the working group for the optical model parameters. The work of each file for setting up the library has been begun so far, and has been brought into the project of international cooperation organized by IAEA. NEA Data Bank is also interested in this work.

We shall continue to give the information on the related progress and news about the publications.

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VI SYSTEMATICS RESEARCH

THE SYSTEMATICS CALCULATION OF NUCLEAR DATA FOR RADIATION DAMAGE ASSESSMENT AND RELATED SAFETY ASPECTS

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INTRODUCTION

Some charged particle production data of neutron induced reactions and neutron capture cross sections are of great importance to various reactors, particularly in the calculations of nuclear transmutation rate, nuclear heating, radiation damage and related safety aspects.

However, a survey of the available data shows that it is diffcult to measure those data of (n, charged-particle) reactions for some nuclides which have a short lifetime or very low abundance, because of big backgrounds for the former and rare targets for the latter. Thus their experimental excitation functions are scarce and existing data are scattered. Some of these data can be complemented by systematics calculation.

The IAEA encourages all member states to contribute to the improvement of the data for about 250 important neutron-induced reactions listed in Appendix II of INDC(NDS)-231 / L+R (1989)[1]. Therefore I have calculated these data using the systematics programs of (n,p), (n,α) and (n,γ) reaction cross sections contributed by Zhao Zhixiang et al.[2,3,4,5].

1 SYSTEMATICSES OF (n,p), (n,α) AND (n,γ) REACTION

CROSS SECTIONS

1.1 Systematics of Excitation Functions for (n,charged–particle) Reactions

On the basis of an evaporation model in which pre–equilibrium emission is considered under some approximations, analytical expressions including two adjustable parameters for excitation functions of (n, charged–particle) reactions have been derived. With these expressions fitting the available measured data, the adjustable parameters have been extracted and the systematic behavior of the parameters have been obtained by Zhao Zhixiang et al.[2].

Conversely using the systematic parameters, the excitation functions of the (n,p) and (n,α) reactions below 20 MeV have been calculated for ~ 50 nuclei in the region of $23 < A < 197$. The predicted cross sections are consistent with the measured data within the errors calculated from the covariance matrix of systematic parameters. A typical result is shown in Fig. 1.

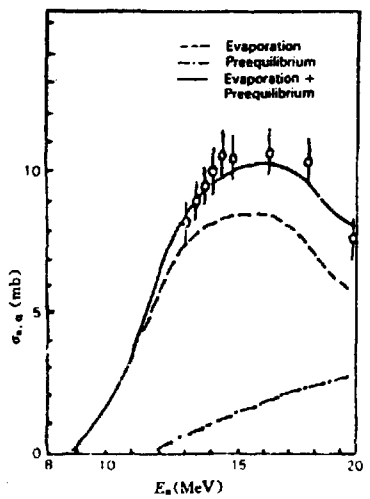

Fig. 1 Excitation function of $^{92}Zr(n,\alpha)^{89}Sr$ reaction

Φ experimental data

1.2 Systematics of Excitation Functions for (n,γ) Reaction

Based on the statistical theory and exciton model, the systematical behavior of excitaion function of (n,γ) reaction has been studied for the targets with mass number of $A = 40 \sim 200$ in the energy regions of $E_n = 25$ keV[3], 1 keV ~ 4 MeV[4] and 4 ~ 20 MeV[5] by Zhao Zhixiang et al.. The excitation functions

predicted by these works are in good agreement with the measured data, as shown in Figs. 2 and 3.

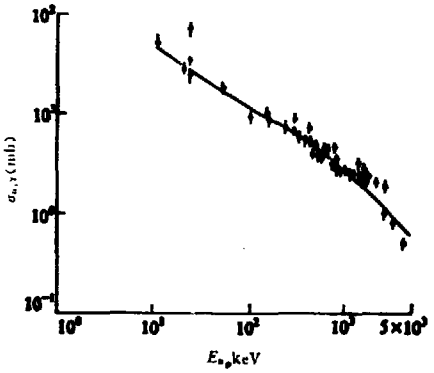

Fig. 2 Excitation function of $^{87}Rb(n,\gamma)$ reaction

—— calculated data from systematics

Φ experimental data

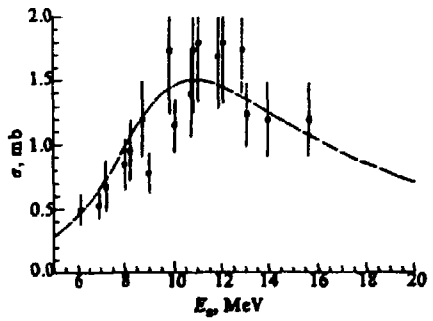

Fig. 3 Excitation function of $^{140}Ce(n,\gamma)$ reaction

—— calculated data from systematics

Φ experimental data

2 SYSTEMATICS CALCULATIONS OF NUCLEAR DATA FOR RADIATION DAMAGE ASSESSMENT AND RELATED SAFETY ASPECTS

2.1 The Excitation Functions of (n,p), (n,α) reactions

The excitation functions of 14 nuclides ^{35}Cl, ^{39}K, ^{41}K, ^{45}Sc, ^{60}Co, ^{60}Ni,

^{63}Cu, ^{64}Zn, ^{93}Nb, ^{94}Mo, ^{107}Ag, ^{121}Sb, ^{137}Ba, ^{158}Dy (n,p) reactions and 27 nuclides ^{23}Na, ^{27}Al, ^{34}S, ^{35}Cl, ^{39}K, ^{40}Ca, ^{42}Ca, ^{44}Ca, ^{45}Sc, ^{46}Ti, ^{47}Ti, ^{48}Ti, ^{49}Ti, ^{51}V, ^{50}Cr, ^{52}Cr, ^{62}Ni, ^{63}Cu, ^{66}Zn, ^{93}Zr, $^{112,116}Sn$, ^{139}La, ^{140}Ce, ^{182}W, ^{190}Os, ^{197}Au (n,α) reactions cross sections are calculated by means of program NX1, which is based on the systematics of excitation functions for (n,charged–particle) reactions with incident energy from 1 MeV or threshold to 20 MeV and mass number of target nuclide from 23 to 197.[2]

The comparison of systematics calculation with experimental data has been carried out, some typical results are given in Figs. 4 and 5.

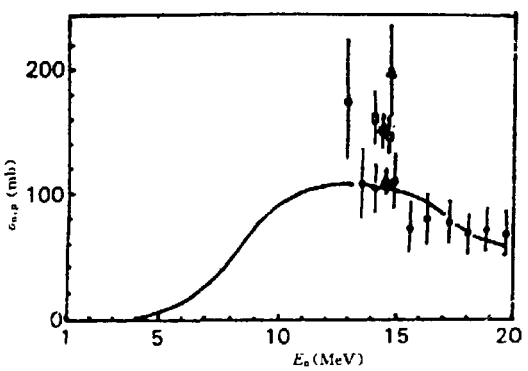

Fig. 4 Excitation function of $^{74}Sc(n,p)$ reaction

—— calculated data from systematics

ǀ experimental data

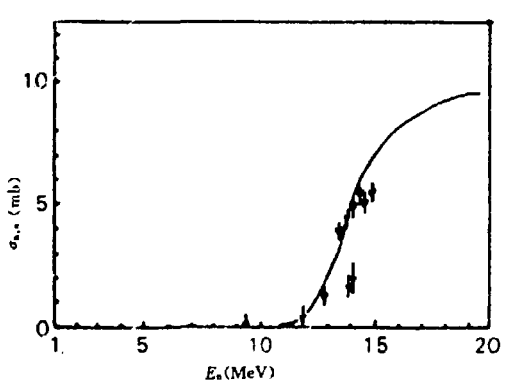

Fig. 5 Excitation function of $^{89}Y(n,\alpha)$ reaction

—– calculated data from systematics

ǀ experimental data

2.2 The Excitation Functions of (n,γ) Reactions

The excitation functions of 64 nuclides $^{40,44,46}Ca$, ^{45}Sc, $^{50,54}Cr$, ^{55}Mn, $^{56,57,58}Fe$, $^{59,60}Co$, $^{61,62}Ni$, ^{63}Cu, ^{64}Zn, $^{92,94}Zr$, ^{93}Nb, $^{92,98}Mo$, ^{103}Rh, $^{104,105,106,107,108}Pd$, $^{107,109}Ag$, $^{110,111,112}Cd$, $^{120,122,124}Sn$, $^{121,123}Sb$, ^{150}Nd, $^{150,151,152}Sm$, $^{151,152,153,154}Eu$, ^{158}Gd, ^{165}Ho, $^{177,179,180}Hf$, $^{181,182}Ta$, $^{182,183,184,186}W$, $^{185,187}Re$, $^{188,189,190,192}Os$, ^{191}Ir, $^{187}Pt(n,\gamma)$ reaction cross sections are calculated by the aid of programs NG25K and NG1, which are based on the systematics of excitation functions for (n,γ) reaction with incident energy from 1 keV to 20 MeV and mass number of target nuclide from 40 to 200[3~5].

The comparisons of (n,γ) reaction cross sections between systematics calculation and experimental data are given in Figs. 6~11.

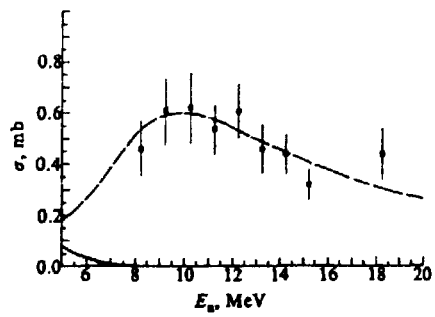

Fig. 6 Excitation function of $^{40}Ca(n,\gamma)$ reaction

——— calculated data from systematics, Φ experimental data

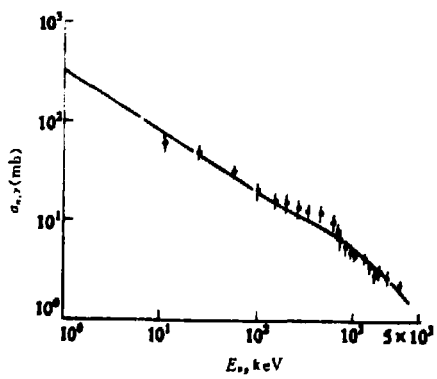

Fig. 7 Excitation function of $^{80}Se(n,\gamma)$ reaction

——— calculated data from systematics, Φ experimental data

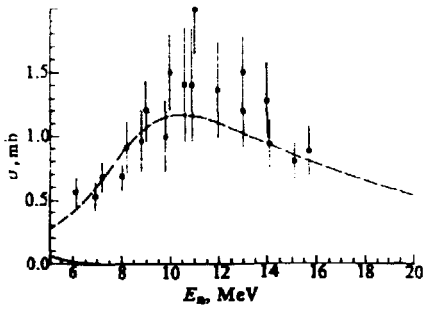

Fig. 8 Excitation function of $^{89}Y(n,\gamma)$ reaction

— — — calculated data from systematics, Φ experimental data

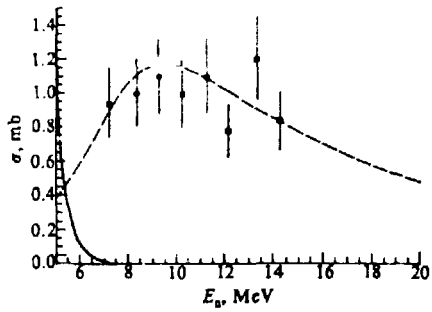

Fig. 9 Excitation function of $^{165}Ho(n,\gamma)$ reaction

— — — calculated data from systematics, Φ experimental data

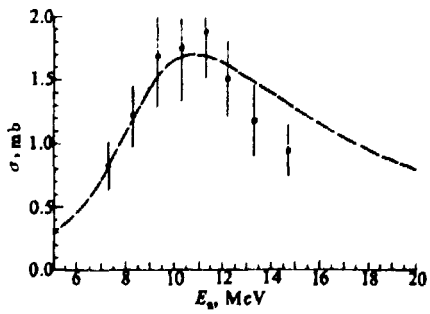

Fig. 10 Excitation function of $^{208}Pb(n,\gamma)$ reaction

— — — calculated data from systematics

Φ experimental data

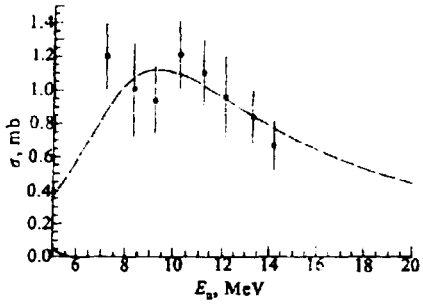

Fig. 11 Excitation function of $^{238}U(n,\gamma)$ reaction

——— calculated data from systematics

Φ experimental data

In the above mentioned figs., the solid line denotes the contribution from statistical process, dotted one from direct and semi–direct interactions.

3 DISCUSSION AND CONCLUSION

Because of the big backgrounds and small reaction cross sections for fast neutron in (n,charged–particle) and (n,γ) measurements, their experimental errors are large; thus differences of measured results and the dissension between various evaluated data are also large sometimes. This is worth notice.

In general, the coincidence of (n,p), (n,α) and (n,γ) cross sections calculated by the relevant systematics with measured data is basically good. The excitation functions calculated from the systematics, especially for the nuclei which are deficient in experimental data, can be recommended to users; because the systematical behaviours of above–mentioned three reactions have been delineated, few of systematics calculations goes too far in measured data.

Of course, if there are more accurate and complete set of experimental data for some nuclei, the evaluated values based on them would be better than those calculated from systematics.

The excitation functions of reactions for neutron on the nuclei which lack experimental data are as follows:

(1) ^{35}Cl, ^{60}Co, ^{121}Sb, ^{137}Ba, ^{158}Dy(n,p) reactions;
(2) ^{42}Ca, $^{46,47,49}Ti$, $^{50,52}Cr$, ^{66}Zn, ^{93}Zr, $^{112,116}Sn$, ^{182}W, ^{190}Os (n,α) reactions;
(3) $^{44,46}Ca$, ^{64}Zn, ^{60}Co, $^{188,189,190,192}Os$, ^{191}Ir, ^{197}Pt(n,γ) reactions.

Thus, it is necessary to calculate the excitation functions for above–mentioned reactions with the systematics.

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SYSTEMATICS OF THE (n,t) REACTION CROSS SECTIONS AT 14 MeV

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ABSTRACT

The systematic behaviour of the (n,t) reaction cross sections have been studied for medium and heavy mass nuclei at 14 MeV. An analysis of the gross trend, the isotope and odd–even effects are given. Possible reaction mechanisms are also discussed. A set of the systematics parameters have been extracted on the basi of the analyzing and fitting of the available data. The (n,t) reaction cross sections of some nuclei have been predicted and a good agreement with the measured data has been obtained.

INTRODUCTION

The (n,t) reaction cross section is very important for design of fission and fusion reactors. Particularly in high neutron flux,the effect of the (n,t) reaction for the structure material of the fusion reactor can't be neglected. The (n,t) reaction cross sections for the light nuclei (^{6,7}Li, ^{9}Be, ^{10,11}B etc.) at 14 MeV are in the mb order of magnitude, and the reaction mechnism is mainly direct process. But, for medium and heavy mass nucleus the (n,t) cross sections are very small (about the μb order of magnitude). The measured data are very scarce and for some measurements only the upper limits are given.

The (n,t) reaction cross section measurements available were mainly performed by Qaim[2, 3], Woo[4, 5], Diksic[6], Sudar[7] and others[8~12]. By using the methods of activation and tritium β^- counting technology, some results of the earliest measurements are erroneous, or are of only upper limits. The main reason is that the effect of the impurity in the target nucleus, and the interfering reactions for researched target nucleus have not been eliminated. Thus measured results are not often consistent and the discrepancies are quite large. For example, tne results of the ^{40}Ca(n,t) cross sections have been reported from 3.5± 1.4 μb[13] to 20± 4 mb[14]. So unless the radiochemical separating technology and high purity target are used in the measurement[2, 3], it has to be careful to choose the measurements in the systematics study.

In the present work, the systematic characteristic features of the (n,t) reaction cross sections at 14 MeV have been further studied on the basis of measured data. Considering the odd–even effect, systematics formula for the (n,t) reaction has been obtained, and some of the fitting parameters were given. The reaction cross sections for medium and heavy mass nuclei of $A = 27 \sim 238$ at 14.6 MeV have been also predicted.

1 DATA ANALYSIS AND REACTION Q–VALUES EFFECTS

The experimental data of (n,t) cross sections around 14 MeV have been collected, analysed and evaluated for 41 nuclei of $A = 27 \sim 238$ up to the end of 1990. Due to the very small (n,t) cross sections the interfering reactions must be considered. Impurity intefering reaction can be eliminated by radiochemical separating technology, and isotopic intefering reaction can be used as standard reaction of internal monitor for measured sample. But, for (n,dn), (n,p2n) reactions, the products are the same as (n,t) reaction. Fortunately, in general case,

for these reaction, the threshold are rather higher in comparing with 14 MeV, therefore, the cross sections for these reactions can be neglected. Finally, as usual, the relative measurements that have to be renormalized to the new standard is neccessary.

On the basis of the analyses and evaluations, the selected data have been processed by using the method of the weighted average. And the averaged cross sections of σ_{nt} and errors $\delta\ \sigma_{nt}$ have been given in the Table 1 and 2 for odd and even mass nuclei, respectively.

Table 1 The cross sections of exp. and cal. for the (n,t) reaction of odd mass nuclei at 14.6 MeV

Nuclides	$(N-Z)/A$	Q-values	σ_{nt}, exp.	$\delta\ \sigma_{nt}$, exp.	σ_{nt}, cal.
		MeV	μb	μb	μb
^{27}Al	0.0370	− 10.882	2321.85	348.30	2117.62
^{55}Mn	0.0909	− 9.305	980.1	99.0	815.34
^{59}Co	0.0847	− 8.930	738.71	147.70	984.99
^{93}Nb	0.1183	− 6.192	368.28	99.00	552.57
^{103}Rh	0.1262	− 6.939	744.6	224.4	481.55
^{141}Pr	0.1631	− 5.948	206.64	41.33	232.11
^{205}Tl	0.2098	− 5.423	34.65	8.40	91.34
^{209}Bi	0.2057	− 2.689	297.0	49.5	102.11

Table 2 The cross sections of exp. and cal. for the (n,t) reaction of even mass nuclei at 14.6 MeV

Nuclides	$(N-Z)/A$	Q–values	σ_{nt}, exp.	$\delta\ \sigma_{nt}$, exp.	σ_{nt}, cal.
		MeV	μb	μb	μb
^{32}S	0.0312	−12.689	7.09	1.42	–
^{40}Ca	0.0250	−12.933	21.48	7.52	–
^{46}Ti	0.0652	−13.190	118.48	36.73	80.67
^{50}Cr	0.0600	−12.644	89.98	26.70	90.64
^{54}Fe	0.0555	−12.425	115.61	40.46	100.54
^{56}Fe	0.0892	−11.931	52.20	13.92	63.86
^{58}Ni	0.0517	−11.072	99.54	29.86	110.13
^{60}Ni	0.0833	−11.510	60.39	19.80	71.96
^{64}Zn	0.0781	−10.080	93	27.93	78.44
^{70}Ge	0.1000	−10.353	47.16	13.10	61.80
^{86}Sr	0.1279	−10.740	33.0	8.8	46.68
^{88}Sr	0.1477	−12.048	69.3	24.2	34.40
^{90}Zr	0.1222	−11.352	43.87	11.77	51.84
^{92}Mo	0.0978	−11.036	69.75	24.41	73.90
^{102}Pd	0.1078	−9.214	64.0	22.0	69.40
^{106}Cd	0.1037	−8.697	81.0	17.0	73.51
^{114}Cd	0.1666	−10.320	36.0	8.0	31.64
^{112}Sn	0.1160	−9.110	61.0	13.0	61.80
^{130}Te	0.2077	−5.240	24.0	8.0	19.11
^{170}Er	0.2059	−6.770	12.0	3.0	22.78
^{204}Pb	0.2010	−5.875	34.97	10.90	27.07
^{238}U	0.2311	−5.110	20.0	8.0	19.37

If the $\sigma_{nt}/(A^{1/3}+1)^2$ is regarded as a radius correction for the target nucleus, the plotting of $\sigma_{nt}/(A^{1/3}+1)^2$ vs. Z of the target nucleus is shown in Fig. 1. From Fig. 1, it can be seen that the cross sections of odd mass nucleus are always higher than those of even mass nucleus about one order of magnitude. So there is a odd–even effect for (n,t) reaction. It is not a general Q–value effect, but a pairing effect in Q–value. Secondly, when Z equals about 25, the cross section distribution shows a maximal value. When $Z<20$, σ_{nt} rises quickly with increasing Z; when $Z>22$, σ_{nt} decreases slowly with increasing Z. It is thus very clear that the systematic features on σ_{nt} vs $(N-Z)/A$ are still existent for medium and heavy mass nucleus although this relation is not so strong than (n,p) and (n,α) reactions. But, the empirical formula of the systematics involved the odd–even effect could be still obtained.

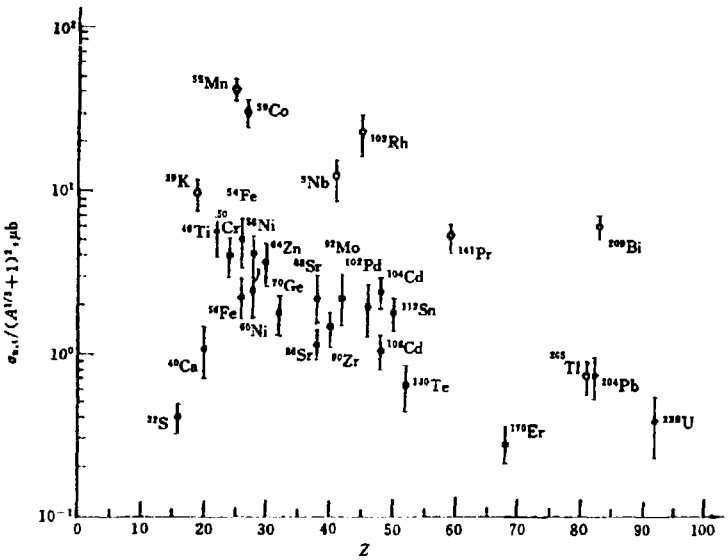

Fig. 1 The (n,t) reaction cross section at 14.6 MeV as a function of nuclear charge number of the target nucleus

2 SYSTEMATICS OF REACTION CROSS SECTIONS

2.1 Systematics Formulae and Empirical Parameters

On the basis of statistical theory model, it is well known that the cross sections emitted x–particle from the compound nucleus with excitation energy E_a^* are :

$$\sigma_{nx} \approx \sigma_R \cdot \Gamma_x / \Gamma_n \tag{1}$$

The decay width Γ_x emitted a x–particle can be written by means of the principle of detailed balance as following :

$$\Gamma_x = \frac{(2s_x + 1)M_x}{\pi^2 \cdot \hbar^2 \rho_a(E_a^*)} \int_{V_x}^{E_a^* - B_x - \delta_x} \varepsilon_x \sigma_c(\varepsilon_x) \rho_b(E_b^*) d\varepsilon_x \tag{2}$$

where, s_x, M_x are the spin and mass of the x–particle respectively; B_x, δ_x are the separating energy of x–particle and the odd–even character of the target nucleus respectively; $\rho_a(E_a^*)$, $\rho_b(E_b^*)$ are the level density of the compound and residual nuclei respectively; V_x is the coulomb barrier of x–particle, and σ_c is inverse cross section. In formula (2), the level density can be appoximately expressed as the function of the entropy of the nuclear system.

$$\rho_b(E_b^*)/\rho_a(E_a^*) \approx \exp[S_b(E_b^*) - S_a(E_a^*)] \tag{3}$$

and the entropy S of the system can be obtained from the following formula :

$$dS/dE^* = 1/T \tag{4}$$

thus

$$S_b(E_b^*) - S_a(E_a^*) \approx (E_b^* - E_a^*)/T = -(\varepsilon_x + B_x + \delta_x)/T \tag{5}$$

by substituting (3～5) into (2), following relation can be obtained :

$$\Gamma_x = \frac{(2s_x+1)M_x}{\pi^2 \cdot h^2} \int_{V_x}^{E_a^* - B_x - \delta_x} \varepsilon_x \sigma_c(\varepsilon_x) \exp[-(B_x + \delta_x + \varepsilon_x)/T] d\varepsilon_x \tag{6}$$

When the energy of incident neutron is not too high, the inverse cross section remains approximately unchanged, and can be taken as following :

for neutrons $\sigma_c(\varepsilon_n) = \pi R^2$

for charged particles

$$\sigma_c(\varepsilon_q) = \begin{cases} \pi R^2 \cdot (1 - V^q/\varepsilon_q) & \varepsilon_q > V_q \\ 0 & \varepsilon_q < V_q \end{cases} \tag{7}$$

Performing integration (6), and making use of some simplification and approximations, the decay width Γ_n emitted a neutron n can be obtained.

$$\Gamma_n \approx \frac{(2s_n+1)M_n \cdot R^2}{\pi h^2} \cdot T^2 \cdot \exp[-(B_n + \delta_n)/T] \tag{8}$$

and the decay width Γ_t emitted a charged particle t can be obtained in the similary form.

$$\Gamma_t \approx \frac{(2s_t + 1)M_t R^2}{\pi h^2} T^2 (1 - V_t / \varepsilon_t) \exp\left[-(B_t + V_t + \delta_t)/T\right] \qquad (9)$$

Therefore, the cross sections of emitted a t-particle is as following :

$$\Gamma_{nt} \approx \sigma_R \frac{(2s_t + 1)M_t}{(2s_n + 1)M_n} \left[1 - (V_t / \varepsilon_t) \exp\left[(Q'_{nt} - V_t)/T\right]\right. \qquad (10)$$

where

$$Q'_{nt} = B_n - B_t + \delta_n - \delta_t \qquad (11)$$

That is what we called effective Q-value.

After considering odd-even effect correction, the systematics formula for the (n,t) reaction cross section is as following :

$$\sigma_{nt} = (A^{1/3} + 1)^2 \cdot \alpha \cdot \exp[\beta(N - Z + \delta)/A] \qquad (12)$$

In the expression (12), α and β are two adjustable parameters.

Finally, the formulae of the systematics have been obtained by fitting available data for the (n,t) reaction in medium and heavy mass nucleus at 14 MeV :

For odd mass nucleus

$$\sigma_{nt} = 327.602(A^{1/3} + 1)^2 \cdot \exp[-24.495(N - Z)/A] \qquad (13)$$

For even mass nucleus

$$\sigma_{nt} = 9.592(A^{1/3} + 1)^2 \cdot \exp[-14.038(N - Z + 1)/A]. \qquad (14)$$

2.2 Isotopic Effects

In a similar way to the (n,p) and (n,d) reactions, the isotopic effects of the (n,t) reaction cross sections have been verified. The cross section ratio of isotopes for mass units apart for the (n,t) reaction can be represented as :

$$\sigma_{nt}(Z,A+2)/\sigma_{nt}(Z,A) \approx \exp[1.9((aE_m)^{1/2}_{A+2} - (aE_m)^{1/2}_A)] \qquad (15)$$

where, a is the level density parameter; $E_m = E_n + Q - \delta$, δ is the pairing energy of the residual nucleus. The calculated values for ^{54,56}Fe and ^{58,60}Ni are 0.41 and 0.71 respectively. These values are in agreement with the average experimental cross section ratios of o.45 and 0.61 respectively. For these nuclei, the odd–even character remains unchanged. Therefore, it is still a result of the general Q–value effect.

2.3 Effects of reaction energy

For the (n,t) reaction cross section, except the restriction of higher Q–value the effects of Coulomb barrier is also a important factor for the (n,t) cross section. From reaction energy relation $E_r = E_n + Q + V$, the E_r–value involved in most reactions will be quite small; small differences in E_r–value might lead to large change in cross section. It is the main reason that the systematics behaviour becomes weaker than the (n,p) and (n,α) reactions. In order to eliminating the effect of the differences of reaction energy,the normalization of the data to the same E_r is therefore more important than for other reactions such as (n,p), (n,α) etc.. However, it is well known that the measured excitation functions for the (n,t) reactions are very deficient. Thus, now, energy normalization is difficult for the (n,t) reaction at 14 MeV.

As mentioned above, the effects of the Q–value and odd–even must be considered in the systematic study of the (n,t) reaction. In the present work, these effects have been taken into account in the systematics formulae. The $\sigma_{nt} / ((A^{1/3}+1)^2$ vs. $(n-z+\delta)/A$ relation can be considered as that the cross sections are directly relative to final a neutron separation energy, and the cited δ value is just corresponding to odd–even effect of the target nucleus.

3 RESULTS AND DISCUSSIONS

The results calculated by means of the formulae (13,14) for the (n,t) reaction cross sections at 14 MeV are shown in Fig. 2. Comparing the cross sections of odd mass nucleus with those of even, from Fig. 2, it can be seen that the odd–even effect obviously exists in the (n,t) reaction. But, because of the deficiency of experimental data, for the plot of odd mass nucleus only a gross systematic trend is given. Where, the experimental values of ^{209}Bi and ^{205}Tl have a larger deviation from fitting curve. Therefore, new measured data are needed for even mass nuclei, the calculated curves are basically in agrement with the measured data. But, the cross sections of ^{170}Er and ^{88}Sr are largely deviated

from the fitting curve. However, the relation of the reaction cross section vs. asymmetry parameter is clear, and the curve of the odd mass nucleus is always located above that of even mass nucleus. The slope of the curve is larger, and the decrease of cross sections of odd mass nuclei is faster. It is clear that with increasing of Z, the difference of the Q–values is more and more small. Therefore, the odd–even effects will decrease gradually and finally disappear.

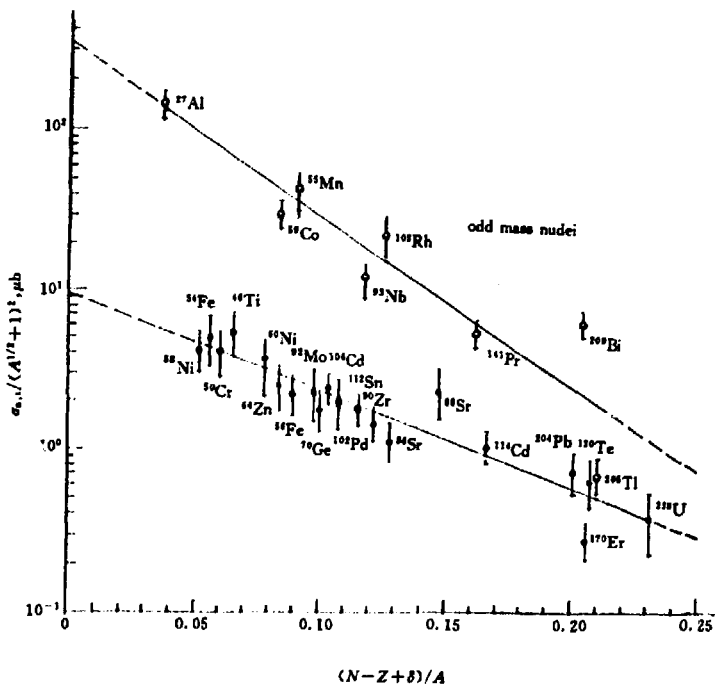

Fig. 2 Systematics of the (n,t) reaction cross sectiion for medium and heavy mass nuclei at 14 MeV

Some of the cross sections of (n,t) reactions for medium and heavy mass nuclei at 14 MeV have been predicted, and the results are consistent with the available measured data satisfactorily.

Mostly the cross section data, the angular distribution and the energy spec-

trum are very necessary for improving study of systematics and reaction mechanism for the (n,t) reactions.

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SYSTEMATICS OF THE (n,^{3}He) REACTION CROSS SECTIONS AT 14 MeV

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ABSTRACT

The systematic behaviour of the (n,^{3}He) reaction cross sections has been studied at 14 MeV. Some systematic trends in the cross sections have been observed. A set of the empirical parameters have been extracted on the basis of analysing and fitting available data, and a good agreement with the experimental data has been obtained. Most possible reaction mechanisms are discussed for the (n,^{3}He) reaction in medium and heavy mass nucleus ranges.

INTRODUCTION

The (n,^{3}He) reaction cross sections is very important for the fusion technology and design of reactor engineering. The charged particles emitted by neutron induced reactions will produce serious damage to the structure materials, especially in reactor with high neutron flux. Due to that the (n,^{3}He) reaction cross sections are very small (in the μb order of magnitude), the data measurements are very difficult. And theoretical calculations depend upon the established nuclear models. Therefore, both experiments and calculations can be supplemented by using systematics of nuclear reaction cross sections if there are not sufficient data.

In present work, a systematics empirical formula of the (n,^{3}He) reaction cross section is given.

1 EXPERIMENTAL DATA ANALYSIS AND EVALUATIONS

The measurement of (n,^{3}He) cross sections are mainly by using the methods of activation and radio-chemical separation technology developed by Qaim [2, 3]. However, the cross sections measured by earliest works are mostly mistaken or only a upper limit. So that the results are not usually consistent

with each other and the differences among the measured data are large. For example, for $^{103}Rh(n,^3He)^{101}Tc$ reaction, the cross sections are from 1.2 ± 1 μb[4] to $3500\ \mu b$[5].

The cross sections measured by means of the activation method would be a sum of the (n,^{3}He), (n,2pn), (n,n'2p), (n,pnp) and (n,dp) reaction processes in the same target, all of which lead to the same product. Fortunately due to their high negative Q values, the reaction processes other than the (n,^{3}He) reaction are not energetically possible at 14 MeV. Therefore, the measured cross sections equal approximately to the (n,^{3}He) cross sections of the investigated target nucleus.

So far, the experimental measurements for the (n,^{3}He) reactions at 14 MeV are mainly performed by the groups in Julich[2,3] and Zegreb[6] respectively and some by others[4,5, 7~10]. In Julich group, the (n,^{3}He) cross sections reported by Qaim[2,3] were measured by using high purity target materials, special radio-chemical separation technique and γ – ray counting system with higher resolution. Moreover, a series of effects including the possible impurity and isotope interfering reactions were corrected. Therefore, the results are more accurate and reliable. In Zagreb group, the (n,^{3}He) cross sections for eight target nuclei (^{31}P, ^{41}K, ^{59}Co, ^{63}Cu, ^{71}Ga, ^{75}As, ^{93}Nb, ^{115}In) at 14 MeV, are higher than ones obtained by Qaim[2] by about 5 to 100 times. For other six nuclei (^{55}Mn, ^{96}Zr, ^{103}Rh, ^{109}Ag, ^{130}Te, ^{187}Re) either chemical separations are not possible such as the (n,^{3}He) reaction of Zirconium or the γ-ray energies are not resolved for the reactions of ^{109}Ag (n,^{3}He) and (n,n'α). So that their errors are large. In summary, the (n,^{3}He) reaction cross sections measured by Diksic[6] are more larger, the measured results are still better than earliest works. Therefore, the cross sections of (n,^{3}He) reaction at 14 MeV which used in this work are mainly based on the values measured by Qaim[2,3] and small weights are given to Diksic's work[6]. For others, earliest data were given up, because their data seem to be erroneous and very unreliable.

According to above mentioned analysis, the experimental data selected have been combined by a method of weighted average. The average values and errors of the (n,^{3}He) cross sections at 14.6 MeV are shown in Table 1.

Table 1 Cross sections of exp. and cal. for (n,^{3}He) reactions at 14.6 MeV

Reactions	$(N-Z)/A$	Q values MeV	σ, exp. μb	$\Delta\sigma$, exp. μb	σ, cal. μb
^{31}P(n,^{3}He)^{29}Al	0.0323	−13.088	20.10	10.05	10.90
^{41}K(n,^{3}He)^{39}Cl	0.0732	−12.622	6.0	3.0	7.95
^{45}Sc(n,^{3}He)^{43}K	0.0667	−11.338	8.6	4.0	8.95
^{59}Co(n,^{3}He)^{57}Mn	0.0847	−11.476	7.06	3.53	8.41
^{63}Cu(n,^{3}He)^{61}Co	0.0794	− 9.519	4.0	2.0	9.25
^{71}Ga(n,^{3}He)^{69}Cu	0.1268	−11.064	20.0	10.0	5.76
^{75}As(n,^{3}He)^{73}Ga	0.120	−10.145	3.5	1.9	6.41
^{81}Br(n,^{3}He)^{79}As	0.1358	−11.142	15.0	7.5	6.09
^{93}Nb(n,^{3}He)^{91}Y	0.1183	− 7.717	5.10	2.55	7.99
^{99}Tc(n,^{3}He)^{97}Nb	0.1313	− 8.583	7.0	3.5	7.14
^{103}Rh(n,^{3}He)^{101}Tc	0.1262	− 8.547	14.4	7.20	7.74
^{109}Ag(n,^{3}He)^{107}Rh	0.1376	− 8.720	23.0	10.0	7.02
^{115}In(n,^{3}He)^{113}Ag	0.1478	− 9.369	11.90	5.95	6.43
^{133}Cs(n,^{3}He)^{131}I	0.1729	− 7.504	3.62	1.81	5.24
^{142}Ce(n,^{3}He)^{140}Ba	0.1831	− 8.103	3.64	1.44	4.84
^{159}Tb(n,^{3}He)^{157}Eu	0.1824	− 6.907	4.6	1.8	5.20
^{169}Tm(n,^{3}He)^{167}Ho	0.1834	− 5.806	4.0	2.0	5.27
^{181}Ta(n,^{3}He)^{179}Lu	0.1934	− 6.616	3.4	1.5	4.94
^{187}Re(n,^{3}He)^{185}Ta	0.1979	− 6.664	4.0	3.0	4.78
^{209}Bi(n,^{3}He)^{207}Tl	0.2057	− 4.10	6.0	3.0	4.67

After the reaction cross sections are corrected on nuclear radius by the same way as that it has been used in the (n,t) and (n,p) reaction cross sections, the plot of $\sigma_{nt}/(A^{1/3}+1)^2$vs $(N-Z)/A$ are shown in Fig. 1. From Fig. 1, it can be seen that the shell effect does not exist for the (n,^{3}He) reactions at 14 MeV. Whether there is odd–even effect which depends on the (n,^{3}He) cross sections measured for the even mass nuclei. Secondly, the (n,^{3}He) cross sections between 2 to 10 μb shown a very slightly decreasing trend with increasing $(N-Z)/A$ and it is differ from (n,t), (n,p) and (n,α) processes. Because of competitive reactions of evaporating neutron process as the (n,xn) and (n,n'γ), the (n,p) and (n,α) reaction cross sections decrease strongly with increasing $(N-Z)/A$. Maybe it means that in the (n,^{3}He) reactions direct interaction processes are dominant than in other reactions. Even so, it is still possible for plotting the (n,^{3}He) cross sections vs. $(N-Z)/A$. Due to that the asymmetry parameter seems to be directly related to the separation energy of the last

neutron from the target nucleus, the plot of $\sigma_{nh} / (A^{1/3}+1)^2$vs $(N-Z)/A$ shows evidently a general characteristic feature of all nuclear reactions in which charged particles are emitted (e. g. (n,p), (n,α)). Therefore, same method used in as (n,p) and (n,α) reactions is used in the (n,^{3}He) reaction systematic study, and the empirical formula could be given.

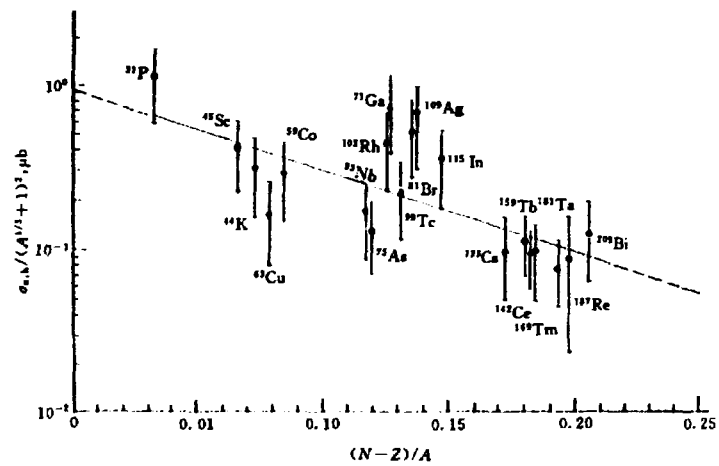

Fig. 1 Systematics of the (n,^{3}He) reactions
$\sigma_{nh} / (A^{1/3}+1)^2$ vs. $(N-Z)/A$

2 SYSTEMATIC TREND OF THE (n,^{3}He) REACTION CROSS SECTIONS

2.1 Systematics Formulae and Empirical Parameters

It is well known from statistical theory that in terms of the principle of detailed balance the decay width Γ_x for particle x emitted by the compound process in excitted state E_x^* could be written as

$$\Gamma_x = \frac{(2s_x + 1)M_x}{\pi^2 \hbar^2 \rho(E_a^*)} \int_{V_x}^{E_a^* - B_x - \delta_x} \varepsilon_x \sigma_c(\varepsilon_x) \rho(E_b^*) d\varepsilon_x \quad (1)$$

where, S_x, M_x are the spin and mass of the particle x respectively; B_x, δ_x are the separate energy of particle x and odd–even character of the target nucleus respectively; $\rho(E_a^*)$, $\rho(E_b^*)$ are the level density of the compound and residual nucleus, respectively; V_x is the Coulomb barrier of particle x. The reaction cross sections emitted a ^{3}He particle can be approximately written as :[11]

$$\sigma_{nh} \approx \sigma_r \Gamma_h / \Gamma_h = \sigma_r \frac{(2s_h + 1)M_h}{(2s_n + 1)M_n} [1 - (V_h / \varepsilon_h)] \exp[Q'_{nh} - V_h) / T] \quad (2)$$

where

$$Q'_{nh} = B_n - B_h + \delta_n - \delta_h \quad (3)$$

is the effective Q–value. The expression (3) has clearly physical meaning : the (n,^{3}He) cross sections, although approximately, shows evidently the dependence on the effective Q–value and formation cross section σ_r of the reaction, Coulomb barrier encountered by emitted a ^{3}He particle, the pairs energy correction (δ_n–δ_h) and the nuclear temperature T. The selected δ–values are relative to the odd–even character of the target nucleus by means of the definition of Ref. [11]. At present, there are only the cross sections of odd nuclei in the (n,^{3}He) reactions, and the δ–value can be only selected as zero. Therefore, the systematics of the (n,^{3}He) cross sections can be approximately obtained for medium and heavy mass nuclei at 14 MeV.

$$\sigma_{nh} = (A^{1/3} + 1)^2 \times \alpha \times \exp[\beta(N - Z) / A] \quad (4)$$

where, α, β are two empirical parameters. Using the formula (4) to fit available data in Table 1 by means of the least square method, the systematics empirical formula for the (n,^{3}He) reaction cross sections at 14.6 MeV can be obtained.

$$\sigma_{nh} = 0.918(A^{1/3} + 1)^2 \exp[-11.338(N - Z) / A] \quad (5)$$

2.2 Effects of the Reaction Energy

The differences in excitation energy of the compound nucleus are implicitly ignored in the plotting $\sigma_{nh} / (A^{1/3}+1)^2$ vs. $(N-Z) / A$ with relative to a fixed

energy at 14 MeV. Besids the Q–values, the effects of Coulomb barrier are also a very important reason for the (n,^{3}He) reaction cross sections. From the reaction energy $E_r = E_n + Q - V$, it can be seen that the reaction energies are quite small, and a small differences in E_r–values might lead to more larger variations in the (n,^{3}He) reaction cross sections. In order to eliminating the effects of the reaction energy differences in the systematics study, the reaction cross sections are always normalized to same E_r–value, other than fixed energy value at 14 MeV. However, due to that currently no excitation function of (n,^{3}He) reactions are available in both of experimental measurements and theoretical calculations, the method of normalizing to the reaction energy E_r–value could not be carried out. Fortunately, the reaction Q–values decrease with increasing $(N-Z)/A$, and the Coulomb barrier increases with increasing $(N-Z)/A$. So E_r–values would not change the systematic trend of the (n,^{3}He) reactions. Evidently, the cross sections are normalized to same E_r–value, the systematic trend shown in Fig. 1 would not be changed too much.

3 RESULTS AND DISCUSSIONS

The (n,^{3}He) reaction cross sections at 14 MeV in medium and heavy mass nucleus ranges have been calculated by using formula (5), the results are shown in the Fig. 1 (solid line) and the data are given in the Table 1. From Fig. 1 it can be seen that the general trend evidently exist in the (n,^{3}He) reaction. The experimental data basically scattered around the both sides of the curve. The trend is similar to the (n,t), (n,p) and (n,α) reactions, and the cross sections are only smaller about by a $1\sim2$ order of magnitude than the reactions above. As mentioned above, basically, the (n,^{3}He) cross sections are relatively independent upon the asymmetry parameter $(N-Z)/A$. These imply statistical process is not dominant, and other non–statistical processes exist. In the (n,^{3}He) reactions, it is very clear that the reaction mechanisms for very light nuclei at 14 MeV are mainly the direct interaction. But, the case is different for the (n,^{3}He) reactions in medium and heavy mass nucleus ranges. The reaction mechanisms are basically speculated by comparing the results between the measured data and theoretical calculations. For example, the direct processes in ^{103}Rh(n,^{3}He) and ^{59}Co(n,^{3}He) reactions are speculated by Csikai(1966)[4] and Frevert(1965)[7]. After this, the results calculated by Qaim[12] in terms of the statistical theory in $A = 27\sim59$ nucleus ranges are smaller by about $2\sim3$ order of magnitude comparing with measured values. It seems to imply the statistical process is not dominant, and it could be considered that due to low excitation energy involved, the evaporation of ^{3}He particles would be rather hindered and

nuclear structure effects might contributes significantly by facilitating the occurrence of direct processes. In this cause, most possible mechanisms of the (n,^{3}He) reactions would be knocked out for the ^{3}He particle and be picked up for a pairs of the p–p particles.

As mentioned above, the following conclusions can be obtained :

The systematic correlations of the (n,^{3}He) reactions at 14 MeV could be expressed by means of the asymmery parameters $(N-Z)/A$.

The direct interactions exist in the (n,^{3}He) reaction at 14 MeV. Most likely mechanisms would be so–called ^{3}He particle knock–out reaction and 2p particles pick–up reaction.

The (n,^{3}He) reaction cross sections with the set of the parameters α = 0.918 and β = −11.338 could be predicted at 14.6 MeV in medium and heavy mass nucleus.

The newly and higher accurate data measured by using activation method are very necessary for the study of the systematics of reaction cross sections and the reaction mechanisms, particularly on the information of angular distributions and energy spectrum of emitted ^{3}He particles.

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VII DATA PROCESSING

CONSTRUCTION OF COVARIANCE MATRIX FOR EXPERIMENTAL DATA

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For evaluators and experimentors, the information is given out con pletely only in the case that the covariance matrix is given.

Suppose the data to be measured is a function of $f(x_k)$ of the parameters x_k, which can be measured directly, then

$$Cov(f_i, f_j) = \sum_k \frac{\partial f}{\partial x_k}|_i \frac{\partial f}{\partial x_k}|_j \rho_{ij}^k \sigma_{ki} \sigma_{kj} \tag{1}$$

$$= \sum_k \rho_{ij}^k \Delta f_{ki} \Delta f_{kj} \tag{2}$$

Where, σ_{ki} (σ_{kj}) is the absolute error of k–th parameter x_k at energy point i (j), ρ_{ij}^k is the correlation coefficient of parameter x_k at energy points i and j, and Δf_{ki} (Δf_{kj}) is the error of the indirectly measured data $f(x_k)$ contributed from k–th parameter at energy point i (j).

It can be seen that the covariance matrix of the indirectly measured data can be constructed according to formula (1) or (2) if the quantities concerned are known.

In order to make the constructed matrix be reasonable in physics, the matrix must be symmetry and positive definite in mathematics.

A practical program was written.

The commonly used methods (activation method, TOF method etc.) for usual various cross section measurements (total, nonelastic, fission, capture etc.) were taken into account in the code. Also the symmetry and positive definite future of the constructed are checked.

The more complicated problem for covariance construction is to give out

the correlation coefficients ρ of the parameters, they must be decided according to the practical situations. In general, $\rho = 0$, for short–range error, e. g. statistical one; $\rho = 1$, for long–range error, e. g. the error of standard cross section; $\rho = 0 - 1$, for medium–range error, e. g. multi–scattering correction.

As an example, the covariance matrix of ^{23}Na(n,2n) cross section measured by Lu et al. was constructed. A reasonable result was obtained.

SPLINE FUNCTION FIT FOR MULTI–SETS OF CORRELATIVE DATA

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There are many works on spline function fit of experimental data, but traditional methods and programs can be used only for uncorrelative data, the correlation between the data points is not taken into acount. The spline fit method for multi–sets of correlative data was developed based on our previous work[1].

Suppose C is the fit coefficint vector, B is the base spline function matrix, Y is the measured data vector, and W, W_1, D are weight matrices, the C is determined by following equation :

$$HC = Y^*$$

Where,

$$H = EB, \qquad Y^* = EY$$

$$E = B^T \left(W - W_1^T \, QDW_1 \right)$$

It should be noted that due to that the data are correlative, the weight matrixes W, W_1, D must be defined and calculated with the inverse matrices of the input data covariance matrices. Also in the program it couldn't simply treated

as diagonal expression, but must be treated as full or block full matrix.

With the code, not only the fit values, but also their covariance can be calculated. Also the order of spline function can be chosen and the knots can be optimized automatically.

Using the code, the properties of correlative data fit were investigated. The variation of the fit value and it's covariance with the correlation coefficient of input data, the width of each set of data and the spline knots were studied in various cases. This is very helpful not only for understanding the characteristics but also for testing the program.

As an practical example, the data of ^{23}Na(n,2n) cross section were fitted in the cases with and without correlation.

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VIII NUCLEAR DATA NEWS

ACTIVITIES AND COOPERATIONS ON NUCLEAR DATA IN CHINA IN 1991

Cai Dunjiu

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1 The following meetings were held by CNDC in 1991 :

"Specialist Meeting of Reviewing and Approving Nuclear Data Task and Topic for 1991～1992", March 4～5, 1991, IAE, Beijing.

"Intercomparison Meeting on Evaluated Neutron Data", March 21–22, 1991, IAE, Beijing. Comparison and analysis of the evaluated neutron data of CENDL–2 with ENDF / B–6 and JENDL–3.

"Coordination Meeting on Nuclear Data for Light Nuclides", April 2～5, 1991, Changchun. Explored the method, discussed and assigned the future task.

"Workshop on the Direct Interaction", April 23～27, 1991, IAE, Beijing. Exchanged and discussed the work and experience of theory, method and code on direct interaction for nuclear data theoretical calculations.

"Training Course on UNF Code" — fast neutron data calculations for structural materials, December 16～18, 1991, IAE, Beijing. Introduced the nuclear reaction theory abount semiclassical multi–step process and the UNF code and practised on Micro–VAX–II computer.

"The Training Course on Evaluation of Covariance File", December 19～21, 1991, IAE, Beijing. Introduced the development and typical examples on covariance evaluation, some methods and codes concerned, exchanged the experiences on covariance treatment.

" Nuclear Data Compilation, Evaluation and Theoretical Calculation Workshop on Charged Particle and Intermediate Energy", December 11～14, 1991, IAE, Beijing. Introduced the development on CPND and discussed the theoretical calculation, and arranged the task in near future.

2 The international meeting held in China, in 1991

"Beijing International Symposium on Fast Neutron Physics", Beijing, Sept. 9~13, 1991. Organized by IAE, Attended by 20 Scientists from 6 countries (including USA, USSR, Japan, Germany, Belgium and Italy) and 40 Chinese scientists

3 The following international meetings, workshops or training couses in the nuclear data field were attended by Chinese scientists in 1991 :

International Conference on Nuclear Data for Science and Technology, Julich, Germany, May 13~17, 1991.

IAEA Advisory Group Meeting on "Technical Aspects of Atomic and Molecular Data Processing and Exchange" — 10th Meeting of the A+M Data Center and ALADDIN Network, Vienna, Sep. 23~24, 1991.

A+M Data for Fusion Plasma Impurities, Vienna, Sep. 25~27, 1991.

The Research Coordination Meeting on Fission Yield Nuclear Data (1st RCM), Vienna, Oct. 7~11, 1991.

11th Nuclear Reaction Data Centers Consultants' Meeting, — IPPE / Obninsk, Moscow, USSR, Oct. 7~11, 1991.

Activation Cross Sections for the Generation of Long-lived Radionuclides (1st RCM), Vienna, Nov. 10~11, 1991.

FENDL-2 and Associated Benchmark Calculations, Vienna, Nov. 18~22, 1991.

IAEA Consultants' Meeting on a "Reference Nuclear Parameters Library for Nuclear Data Computation", Vienna, Nov. 13~15, 1991.

4 In 1991, 5 persons as visit scientists, fellowship of IAEA or STA program (Japan) worked in ENEA-Bologna Italy, ECN / Netherlands, JAERI / NDC, engaged in nuclear data evaluation, nuclear theoretical model study, code development and group constant generation as well as physical calculation of reactor engineering.

5 International cooperation projects during 1985~1991, we undertook ~ 25 IAEA projects (including nuclear data measurement, evaluation as well as theory calculation and processing method study on nuclear data). The technical cooperation project-CPR / 1 / 004, "Development of Nuclear Data Library" was finished on time, the MICRO-VAX-II computer supported by IAEA have operated safety for 3 years and used successfully in nuclear data field at CNDC.

6 The following foreign scientists in nuclear fields visited CNDC / CIAE in 1991 :

July 16～25, 1991, Drs. B. D. Kuzminov, V. N. Manokhin, B. F. Fursov and V. V. Arkhangelsky (IPPE / Obninsk, USSR).

Sep. 11～20, 1991, Dr. G. Reffo (ENEA–Bologna, Italy).

Sep. 7～15, 1991, Dr. S. Chiba (JAERI / NDC, Japan).

Sep. 21～Oct. 6, 1991, Drs. Y. Nakajima and H. Takano (JAERI / NDC).

Nov. 14, 1991, Drs. V. Volkov, G. Gulbekian, S. Dmitriev, Kutner (JINR / Dubna, USSR).

Dec. 25, 1991, Drs. Yu. M. Gledenov, S. S. Starneslov, G. Hunhanhun (JINR / Dubna, USSR).

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Nuclide	Quantity	Energy (eV) Min	Max	Lab	Type	Documentation Ref	Vol	Page	Date
^{7}Li	Inelastic		1.49+7	BJG	Expt	Jour CNDP	7	9	Jun 92
^{23}Na	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{27}Al	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{31}P	(n,^{3}He)		1.46+7	SHN	ExTh	Jour CNDP	7	95	Jun 92
^{32}S	(n,t)		1.46+7	"	ExTh	Jour CNDP	7	85	Jun 92
^{34}S	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{35}Cl	(n,p)	"		"	ExTh	Jour CNDP	7	78	Jun 92
	(n,α)	"		"	ExTh	Jour CNDP	7	78	Jun 92
^{39}K	(n,p)	"		"	ExTh	Jour CNDP	7	78	Jun 92
	(n,α)	"		"	ExTh	Jour CNDP	7	78	Jun 92
^{41}K	(n,p)	"		"	ExTh	Jour CNDP	7	78	Jun 92
	(n,^{3}He)		1.46+7	SHN	ExTh	Jour CNDP	7	95	Jun 92
^{40}Ca	(n,t)	"		"	ExTh	Jour CNDP	7	85	Jun 92
	(n,α)		4.00+6	BJG	Expt	Jour CNDP	7	59	Jun 92
	"	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{42}Ca	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{44}Ca	"	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{46}Ca	"	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{45}Sc	"	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,p)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,^{3}He)		1.46+7	SHN	ExTh	Jour CNDP	7	95	Jun 92
	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{46}Ti	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,p)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
^{47}Ti	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{48}Ti	"	1.00+6	2.00+7	AEP	Expt	Jour CNDP	7	78	Jun 92
	(n,p)	1.35+7	1.48+7	LNZ	ExTh	Jour CNDP	7	4	Jun 92
^{49}Ti	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{50}Ti	"	1.35+6	1.48+7	LNZ	Expt	Jour CNDP	7	4	Jun 92

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Nuclide	Quantity	Energy (eV)		Lab	Type	Documentation			
		Min	Max			Ref	Vol	Page	Date
^{51}V	(n,α)	1.00+6	2.00+7	LNZ	Expt	Jour CNDP	7	78	Jun 92
	(n,n'α)		1.45+7	LNZ	Expt	Jour CNDP	7	4	Jun 92
^{50}Cr	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{52}Cr	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{54}Cr	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{55}Mn	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,t)		1.46+7	AEP	ExTh	Jour CNDP	7	85	Jun 92
^{54}Fe	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
	(n,t)		1.47+7	LNZ	Expt	Jour CNDP	7	4	Jun 92
^{56}Fe	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
	p Emission		1.45+7	AEP	Theo	Jour CNDP	7	14	Jun 92
	α Emission		1.41+7	"	Theo	Jour CNDP	7	14	Jun 92
	n Emission		1.41+7	"	Theo	Jour CNDP	7	14	Jun 92
	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{57}Fe	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{58}Fe	(n,γ)	"		AEP	ExTh	Jour CNDP	7	78	Jun 92
^{59}Co	(n,γ)	"		AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,^{3}He)		1.46+7	SHN	ExTh	Jour CNDP	7	95	Jun 92
	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
^{60}Co	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,p)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{58}Ni	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
	(n,p)	1.36+7	1.46+7	LNZ	Expt	Jour CNDP	7	4	Jun 92
	(n,d)	"		LNZ	Expt	Jour CNDP	7	4	Jun 92
	(n,t)		1.45+7	LNZ	Expt	Jour CNDP	7	4	Jun 92
	(n,2n)	1.36+7	1.45+7	LNZ	Expt	Jour CNDP	7	4	Jun 92
^{60}Ni	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
	(n,p)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{61}Ni	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{62}Ni	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92

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Nuclide	Quantity	Energy (eV)		Lab	Type	Documentation			
		Min	Max			Ref	Vol	Page	Date
^{63}Cu	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,p)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,^{3}He)		1.46+7	SHN	ExTh	Jour CNDP	7	95	Jun 92
	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{64}Zn	(n,γ)	1.00+3	2.00+7	"	ExTh	Jour CNDP	7	78	Jun 92
	(n,p)	1.00+6	2.00+7	"	ExTh	Jour CNDP	7	78	Jun 92
	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
^{66}Zn	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{71}Ga	(n,^{3}He)		1.46+7	SHN	ExTh	Jour CNDP	7	95	Jun 92
^{70}Ge	(n,t)	"		"	ExTh	Jour CNDP	7	85	Jun 92
^{75}As	(n,^{3}He)	"		"	ExTh	Jour CNDP	7	95	Jun 92
^{81}Br	(n,^{3}He)	"		"	ExTh	Jour CNDP	7	95	Jun 92
^{74}Se	(n,p)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{80}Se	(n,γ)	1.00+3	2.00+7	"	ExTh	Jour CNDP	7	78	Jun 92
^{87}Rb	(n,γ)	"		"	ExTh	Jour CNDP	7	78	Jun 92
^{86}Sr	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
^{88}Sr	(n,t)		1.46+7	"	ExTh	Jour CNDP	7	85	Jun 92
^{89}Y	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{90}Zr	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
^{92}Zr	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{93}Zr	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{94}Zr	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{93}Nb	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,p)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
	(n,^{3}He)		1.46+7	"	ExTh	Jour CNDP	7	95	Jun 92
^{92}Mo	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
	(n,d)		1.47+7	LNZ	Expt	Jour CNDP	7	4	Jun 92
	(n,n'α)		1.45+7	LNZ	Expt	Jour CNDP	7	4	Jun 92
^{94}Mo	(n,p)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92

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^{95}Mo	(n,p)	1.35+7	1.48+7	LNZ	Expt	Jour CNDP	7	4	Jun 92
	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{98}Mo	(n,α)	1.35+7	1.48+7	LNZ	Expt	Jour CNDP	7	4	Jun 92
	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{99}Tc	(n,^{3}He)		1.46+7	SHN	Expt	Jour CNDP	7	95	Jun 92
^{103}Rh	(n,^{3}He)		1.46+7	SHN	ExTh	Jour CNDP	7	95	Jun 92
	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{102}Pd	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
^{104}Pd	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{105}Pd	(n,γ)	〃		AEP	ExTh	Jour CNDP	7	78	Jun 92
^{106}Pd	(n,γ)	〃		AEP	ExTh	Jour CNDP	7	78	Jun 92
^{107}Pd	(n,γ)	〃		AEP	ExTh	Jour CNDP	7	78	Jun 92
^{108}Pd	(n,γ)	〃		AEP	ExTh	Jour CNDP	7	78	Jun 92
^{107}Ag	(n,γ)	〃		AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,p)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{109}Ag	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,^{3}He)		1.46+7	SHN	ExTh	Jour CNDP	7	95	Jun 92
	(n,2n)	1.36+7	1.48+7	LNZ	Expt	Jour CNDP	7	4	Jun 92
^{106}Cd	(n,d)		1.47+7	LNZ	ExTh	Jour CNDP	7	4	Jun 92
	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
^{108}Cd	(n,p)		1.46+7	LNZ	Expt	Jour CNDP	7	4	Jun 92
^{110}Cd	(n,γ)	1.00−3	2.00+7	AEP	Expt	Jour CNDP	7	78	Jun 92
^{111}Cd	(n,γ)	1.00+3	2.00+7	〃	ExTh	Jour CNDP	7	78	Jun 92
^{112}Cd	(n,γ)	1.00+3	2.00+7	〃	ExTh	Jour CNDP	7	78	Jun 92
^{114}Cd	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
^{115}In	(n,^{3}He)		1.46+7	SHN	ExTh	Jour CNDP	7	95	Jun 92
^{112}Sn	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{116}Sn	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{120}Sn	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{122}Sn	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{124}Sn	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92

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Nuclide	Quantity	Energy (eV)		Lab	Type	Documentation			
		Min	Max			Ref	Vol	Page	Date
^{121}Sb	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,p)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{123}Sb	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{130}Te	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
^{133}Cs	(n,^{3}He)		1.46+7	SHN	ExTh	Jour CNDP	7	95	Jun 92
^{137}Ba	(n,p)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{139}La	(n,p)	〃		AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,γ)	1.00+3	2.00+7	〃	ExTh	Jour CNDP	7	78	Jun 92
^{140}Ce	(n,γ)	1.00+3	2.00+7	〃	ExTh	Jour CNDP	7	78	Jun 92
	(n,α)	1.00+6	2.00+7	〃	ExTh	Jour CNDP	7	78	Jun 92
^{142}Ce	(n,^{3}He)		1.46+7	SHN	ExTh	Jour CNDP	7	95	Jun 92
^{141}Pr	(n,t)		1.46+7	〃	ExTh	Jour CNDP	7	85	Jun 92
^{150}Nd	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{150}Sm	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{151}Sm	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{152}Sm	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{151}Eu	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,2n)	1.35+7	1.48+7	LNZ	Expt	Jour CNDP	7	4	Jun 92
^{152}Eu	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{153}Eu	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,2n)	1.35+7	1.48+7	LNZ	Expt	Jour CNDP	7	4	Jun 92
^{154}Eu	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{158}Gd	(n,γ)	1.00+3	2.00+7	〃	ExTh	Jour CNDP	7	78	Jun 92
^{159}Tb	(n,^{3}He)		1.46+7	SHN	ExTh	Jour CNDP	7	95	Jun 92
	(n,2n)	1.35+7	1.48+7	LNZ	Expt	Jour CNDP	7	4	Jun 92
^{158}Dy	(n,p)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{165}Ho	(n,γ)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{170}Er	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
^{169}Tm	(n,^{3}He)		1.46+7	SHN	ExTh	Jour CNDP	7	95	Jun 92
^{177}Hf	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{179}Hf	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,2n)		1.48+7	LNZ	Expt	Jour CNDP	7	4	Jun 92
^{180}Hf	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92

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^{181}Ta	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,^{3}He)		1.46+7	SHN	ExTh	Jour CNDP	7	95	Jun 92
	(n,p)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,2n)	1.35+7	1.48+7	LNZ	Expt	Joun CNDP	7	4	Jun 92
^{182}Ta	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{182}W	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,α)	1.00+6	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{183}W	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{184}W	(n,γ)	"		AEP	ExTh	Jour CNDP	7	78	Jun 92
^{186}W	(n,γ)	"		AEP	ExTh	Jour CNDP	7	78	Jun 92
^{185}Re	(n,γ)	"		AEP	ExTh	Jour CNDP	7	78	Jun 92
^{187}Re	(n,γ)	"		AEP	ExTh	Jour CNDP	7	78	Jun 92
	(n,^{3}He)		1.46+7	SHN	ExTh	Jour CNDP	7	95	Jun 92
^{188}Os	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{189}Os	(n,γ)	1.00+3	2.00+7	"	ExTh	Jour CNDP	7	78	Jun 92
^{190}Os	(n,γ)	1.00+3	2.00+7	"	ExTh	Jour CNDP	7	78	Jun 92
	(n,α)	1.00+6	2.00+7	"	ExTh	Jour CNDP	7	78	Jun 92
^{192}Os	(n,γ)	1.00+3	2.00+7	"	ExTh	Jour CNDP	7	78	Jun 92
^{191}Ir	(n,γ)	"		"	ExTh	Jour CNDP	7	78	Jun 92
^{197}Pt	(n,γ)	"		"	ExTh	Jour CNDP	7	78	Jun 92
^{197}Au	(n,α)	1.00+6	2.00+7	"	ExTh	Jour CNDP	7	78	Jun 92
	(n,2n)	8.00+6	2.00+7	"	Eval	Jour CNDP	7	53	Jun 92
^{205}Tl	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
^{204}Pb	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
^{208}Pb	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92
^{209}Bi	(n,2n)		1.46+7	LNZ	ExTh	Jour CNDP	7	4	Jun 92
	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
	(n,^{3}He)		1.46+7	SHN	ExTh	Jour CNDP	7	95	Jun 92
	n Emission	1.00+7	1.42+7	AEP	Theo	Jour CNDP	7	14	Jun 92
^{238}U	(n,t)		1.46+7	SHN	ExTh	Jour CNDP	7	85	Jun 92
	(n,γ)	1.00+3	2.00+7	AEP	ExTh	Jour CNDP	7	78	Jun 92

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