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## EDITORIAL NOTE

This is the 24th issue of Communication of Nuclear Data Progress (CNDP), in which the achievements in nuclear data field for the last year in China are carried. It includes the measurements of cross sections of ${ }^{75} \mathrm{As}(\mathrm{n}, \gamma){ }^{76} \mathrm{As}$ reaction from 0.50 to 1.50 MeV ; theoretical calculations of $\mathrm{n}+{ }^{10,11} \mathrm{~B},{ }^{16} \mathrm{O},{ }^{144,147-152,154} \mathrm{Sm},{ }^{238} \mathrm{Pu},{ }^{241,242} \mathrm{Am}$ reactions in the energy region below 20 MeV ; evaluations of $\mathrm{n}+{ }^{127,135} \mathrm{I}$, ${ }^{129,131,132,134-136} \mathrm{Xe},{ }^{176-180 . \mathrm{Na}} \mathrm{Hf},{ }^{206} \mathrm{~Pb},{ }^{240} \mathrm{Pu}$ reactions; the effect of the charge distribution in nucleus on the calculation of highly ionized atoms; construction of covariance matrix for measured relative fission yield data and WWW chart of the nuclides.

The editors hope that our readers and colleagues will not spare their comments in order to improve this publication. If you have any, please contact us by following address:

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## I EXPERIMENTAL MEASUREMENT

## Measurement of Cross Sections of the ${ }^{75} \mathbf{A s}(\mathrm{n}, \gamma)^{76} \mathrm{As}$

## Reaction

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#### Abstract

The cross sections of the ${ }^{75} \mathrm{As}(\mathrm{n}, \gamma)^{76} \mathrm{As}$ reaction are measured in the neutron energy range from 0.50 to 1.50 MeV by using the activation technique. Neutrons are produced via the $\mathrm{T}(\mathrm{p}, \mathrm{n}){ }^{3} \mathrm{He}$ reaction and the cross sections of the ${ }^{197} \mathrm{Au}(\mathrm{n}, \gamma){ }^{198} \mathrm{Au}$ reaction are used to determine the absolute neutron fluence. Present results are compared with existing measurements and evaluations.


## Introduction

The cross sections of the ${ }^{75} \mathrm{As}(\mathrm{n}, \gamma)^{76} \mathrm{As}$ reaction are important for evaluating the radiation damage of the material. Experiments ${ }^{[1-6]}$ and evaluations have been performed to determine the cross sections of ${ }^{75} \mathrm{As}(\mathrm{n}, \gamma)^{76} \mathrm{As}$ reaction, but there are large discrepancies among them especially in the MeV neutron energy region. Therefor, new experiment is needed.

## 1 Experiment Procedure

The measurements were performed at the 4.5 MV Van de Graaff accelerator of the Institute of Heavy Ion Physics, Peking University. Quasi monoenergetic neutrons
with energies of $0.5,1.15$ and 1.50 MeV were produced through the $\mathrm{T}(\mathrm{p}, \mathrm{n}){ }^{3} \mathrm{He}$ reaction on a solid $\mathrm{T}-\mathrm{Ti}$ target of $1.30 \mathrm{mg} / \mathrm{cm}^{2}$ in thickness. The cross sections of the ${ }^{197} \mathrm{Au}(\mathrm{n}, \gamma){ }^{198} \mathrm{Au}$ reaction taken from the ENDF/B-6 library were used to determine the absolute neutron fluence.

The arsenic samples made of natural $\mathrm{As}_{2} \mathrm{~S}_{3}$ powder were pressed into disks of 19.1 mm in diameter, about 1 mm in thickness and about 1 gram in weight. Each arsenic sample was sandwiched between two gold foils with the diameter of 19.1 mm and with the total weight of about 1 gram. The sample groups were wrapped with cadmium foils 0.5 mm in thickness.

The samples were placed at $0^{\circ}$ to the incident proton beam, and the distance from the sample to the target was about 2.2 cm . The irradiation durations for the three samples corresponding to $0.50,1.15$ and 1.50 MeV were about 11,15 and 23 hours, respectively. The proton energies before entering the T-Ti target were 1.427 , 2.025 and 2.378 MeV , respectively. The proton beam current was about $10 \mu \mathrm{~A}$. The neutron fluence was monitored by a $\mathrm{BF}_{3}$ long counter placed at $0^{\circ}$ to the proton beam and at a distance of 3.0 m from the neutron source. For calculating the correction factor of the neutron fluence fluctuation, the integral counts of the long counter per 2 minutes was recorded continuously by a microcomputer multiscalar.

After irradiation, the activities of the residual nuciei ${ }^{76} \mathrm{Se}\left({ }^{76} \mathrm{As} \beta^{-}\right.$decay to $\left.{ }^{76} \mathrm{Se}\right)$ and ${ }^{198} \mathrm{Au}$ were measured with an ORTEC HPGe $\gamma$-detector $\left(105 \mathrm{~cm}^{3}\right)$ calibrated by a set of standard $\gamma$ sources. The measuring duration for each arsenic and gold sample was about 20 minutes and 10 minutes to ensure statistics of counts better than $1 \%$. The decay data of the residual nuclei including the half-life, $\gamma$-ray energy and $\gamma$ transition intensity were taken from the reference [7] and listed in Table 1. The two peaks corresponding to 559.10 and $563.23 \mathrm{keV} \gamma$-rays couldn't be separated, so we added them together during the measurement and the calculation.

Table 1. Decay data of the residual nuclei

| Nucleus | $T_{1 / 2}$ | $E_{\gamma}$ | $I_{\gamma}$ |
| :---: | :---: | :---: | :---: |
| ${ }^{76} \mathrm{Se}$ | 1.0778 d | 559.10 keV | $45.0 \%$ |
|  |  | 563.23 keV | $1.2 \%$ |
| ${ }^{198} \mathrm{Au}$ | 2.6943 d | 411.80 keV | $95.57 \%$ |

## 2 Corrections

Two main corrections are described as the following.

## $2.1 \gamma$-ray Self-absorption in the Sample

The correction factor of $\gamma$-ray self-absorption in the arsenic sample was measured by means of the $\gamma$-ray from the activated arsenic sample passed through a series of non-activated arsenic samples with different thickness. The values of the correction factor of $\gamma$-ray self-absorption in the arsenic samples are around 0.953 , depending on the thickness of the samples. The correction factor of the gold sample is about 0.970 .

### 2.2 Cascade Correction

Because of the coincidence of the 1228.6 and $657.0 \mathrm{keV} \gamma$-ray with the 559.10 $\mathrm{keV} \gamma$-ray, the measured rate of $559.10 \mathrm{keV} \gamma$-ray will be lower than the real one. So the correction was made. This correction factor for our measurement is 1.02 , according to the decay scheme ${ }^{[7]}$ and the efficiency curve of the HPGe detector.

## 3 Results

After considering the detector efficiency, $\gamma$-intensity, correction factors from the fluctuation of the neutron fluence, $\gamma$-ray self absorption in the samples and cascade correction, the cross sections of the ${ }^{75} \mathrm{As}(\mathrm{n}, \gamma)^{76} \mathrm{As}$ reaction were calculated by using the well known activation formula. The results of present experiment and the reference cross sections of the ${ }^{197} \mathrm{Au}(\mathrm{n}, \gamma){ }^{198} \mathrm{Au}$ reaction are listed in Table 2.

Table 2. Measured results and the reference cross section data

| $E_{\mathrm{n}} / \mathrm{MeV}$ | Cross section/mb |  |
| :---: | :---: | :---: |
|  | ${ }^{75} \mathrm{As}(\mathrm{n}, \gamma)^{76} \mathrm{As}$ | ${ }^{199} \mathrm{Au}(\mathrm{n}, \gamma)^{198} \mathrm{Au}$ |
| $0.50 \pm 0.08$ | $46.4 \pm 2.4$ | $132.4 \pm 4.6$ |
| $1.15 \pm 0.08$ | $18.2 \pm 1.1$ | $75.4 \pm 3.4$ |
| $1.50 \pm 0.08$ | $13.4 \pm 0.8$ | $67.6 \pm 3.0$ |

Main sources of error of our measurements are given in Table 3. Errors from the decay scheme were ignored.

Table 3. Main sources of error and their magnitudes

| Source of uncertainty | Relative error / \% |
| :--- | :---: |
| Reference cross section | $3.5 \sim 4.5$ |
| $\gamma$-counting statistics for ${ }^{66} \mathrm{Se}$ | 1.0 |
| $\gamma$-counting statistics for ${ }^{198} \mathrm{Au}$ | 1.0 |
| $\gamma$-detection efficiency for ${ }^{76} \mathrm{Se}$ | 1.5 |
| $\gamma$-detection efficiency for ${ }^{198} \mathrm{Au}$ | 1.5 |
| Correction of self absorption for ${ }^{76} \mathrm{Se}$ | 1.0 |
| Correction of self absorption for ${ }^{198} \mathrm{Au}$ | 0.5 |
| ${ }^{73} \mathrm{As}$ sample weight | 0.2 |
| ${ }^{197} \mathrm{Au}$ sample weight | 0.2 |
| Peak area determination | 2.5 |
| Total | $5.1 \sim 5.9$ |

The results of our measurements and other measurements as well as evaluations are plotted in Fig.1. It can been seen that our results agree with the JENDL-3.2 evaluation. At 0.50 MeV our result is in good agreement with that of Macklin et al. ${ }^{[2]}$ At 1.15 and 1.50 MeV , our data are smaller than those of Johnsrud et al. ${ }^{[1]}$, and much smaller than the ENDF/B-6 evaluation.


Fig. 1 The comparison of present measurement with other measurement and evaluation
This work was supported by China Nuclear Data Center. The authors would like to attaind their thanks to the crew of the 4.5 MV Van de Graaff accelerator at IHIP, Peking University for their kind cooperation.

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## II THEORETICAL CALCULATION

# Model Calculation of $n+{ }^{\mathbf{1 0}} \mathrm{B}$ below 20 MeV 

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## Introduction

A new model has been developed for calculating nuclear data of light nuclei ${ }^{[11)}$, with which the cross sections and double differential cross sections of outgoing neutron of $\mathrm{n}+{ }^{10} \mathrm{~B}$ were calculated.

The reaction mechanism of light nucleus is more complicated. In the reaction processes of light nucleus, the pre-equilibrium emissions dominate the reaction mechanism, while the equilibrium state only gives lightl improvement even at low neutron incident energies. The emission processes from discrete levels in the preequilibrium stage are very important. In whole reaction processes the angular momentum and parity are conserved in this model calculation. To fit the experimental data the level broadening effect and the energy resolution must be considered. Meanwhile, the residual nuclei can decay spontaneously into two clusters or carry out multi-particle break-up process, these are the characteristic for light nucleus reaction. The three-body breakup process was taken into account in this case of $\mathrm{n}+{ }^{10} \mathrm{~B}$. Because of light mass, the recoil effect must be taken into account exactly to maintain the energy balance.

In order to acquire a precise transmission coefficient, the optical model is used. The optimum optical model parameters of neutrons have been obtained by means of fitting the relevant experimental data, such as the total, elastic scattering, and nonelastic scattering cross sections, as well as the angular distributions of the elastic
scattering. The APN94 code was employed in this fitting procedure, the calculated total cross section, non-elastic cross section, and the elastic scattering angular distributions are shown in Figs. 1~2, respectively, while for the charged particles, we adjusted their optical model parameters by modifying the cross sections of the corresponding reaction channels. Using LUNF code the calculated results of double differential cross sections of outgoing neutron at $E_{\mathrm{n}}=14.2 \mathrm{MeV}$ are shown in section 2. The reaction channel of $\left(\mathrm{n}^{5}{ }^{5} \mathrm{He}\right)^{6} \mathrm{Li}$ is included in the model calculation, the fitting to the experimental data of the total outgoing neutron energy-angular spectra could be improved obviously by using LUNF. In the case of neutron induced light nucleus reactions, the pre-equilibrium emission mechanism dominates the reaction processes. The discussion is given in the last section.


Fig. 1 Comparison of calculated total and nonelastic cross section with experimental data


Fig. 2 Comparison of calculated elastic angular distribution with experimental data

## 1 Reaction Channels of $n+{ }^{10} B$

In view of $\mathrm{n}+{ }^{10} \mathrm{~B}$ for $E_{\mathrm{n}}<20 \mathrm{MeV}$ the reaction channels are listed as follows:

$$
n+{ }^{10} \mathrm{~B}=\left\{\begin{array}{l}
\gamma+{ }^{11} \mathrm{~B} \\
\mathrm{n}^{\prime}+{ }^{10} \mathrm{~B} \\
\mathrm{p}+{ }^{10} \mathrm{Be} \\
\alpha+{ }^{7} \mathrm{Li} \\
{ }^{3} \mathrm{He}+{ }^{8} \mathrm{Li} \\
\mathrm{~d}+{ }^{9} \mathrm{Be}
\end{array} \quad \mathrm{n}+{ }^{10} \mathrm{~B}=\left\{\begin{array}{l}
\mathrm{t}+{ }^{8} \mathrm{Be} \\
2 \mathrm{n}+{ }^{9} \mathrm{~B} \\
\mathrm{np}+{ }^{9} \mathrm{Be} \\
\mathrm{n} \alpha+{ }^{6} \mathrm{Li} \\
\mathrm{nd}+{ }^{8} \mathrm{Be} \\
\mathrm{nn}+{ }^{9} \mathrm{Be}
\end{array} \quad \mathrm{n}+{ }^{10} \mathrm{~B}=\left\{\begin{array}{l}
\mathrm{p} \alpha+{ }^{6} \mathrm{He} \\
\alpha \mathrm{n}+{ }^{6} \mathrm{Li} \\
\alpha p+{ }^{6} \mathrm{He} \\
2 \alpha+\mathrm{t} \\
\mathrm{dn}+{ }^{8} \mathrm{Be}
\end{array}\right.\right.\right.
$$

Reaction mechanism in the $\mathrm{n}+{ }^{10} \mathrm{~B}$ system leading to the decay into one t and two alpha particles reactions ( $\mathrm{n}, \mathrm{t} 2 \alpha$ ) may proceed via a number of different reaction channels, such as sequential two-body reaction or two body break-up process, even three body break-up process. The reactions to ${ }^{10} \mathrm{~B}(\mathrm{n}, \mathrm{t} 2 \alpha)$ channel is involved in the model calculation are as follows:
a. $\quad \mathrm{n}+{ }^{10} \mathrm{~B} \rightarrow \mathrm{t}+{ }^{8} \mathrm{Be}{ }^{*}$

$$
{ }^{8} \mathrm{Be} \rightarrow \alpha+\alpha
$$

b. $\quad \mathrm{n}+{ }^{10} \mathrm{~B} \rightarrow \alpha+{ }^{7} \mathrm{Li}^{+}$

$$
{ }^{7} \mathrm{Li}^{*} \rightarrow \mathrm{t}+\alpha
$$

c. $\mathrm{n}+{ }^{10} \mathrm{~B} \rightarrow \alpha+\alpha+\mathrm{t}$

The reaction to ${ }^{10} \mathrm{~B}(\mathrm{n}, 2 \mathrm{np} 2 \alpha)$ channel is involved in the model calculation are as follows:
a. $\mathrm{n}+{ }^{10} \mathrm{~B} \rightarrow \mathrm{n}+\mathrm{p}+{ }^{9} \mathrm{Be}{ }^{*}$

$$
{ }^{9} \mathrm{Be}^{*} \rightarrow \mathrm{p}+\alpha+\alpha
$$

b. $\mathrm{n}+{ }^{10} \mathrm{~B} \rightarrow \mathrm{p}+\mathrm{n}+{ }^{9} \mathrm{Be}{ }^{*}$

$$
{ }^{9} \mathrm{Be}^{*} \rightarrow \mathrm{p}+\alpha+\alpha
$$

c. $\mathrm{n}+{ }^{10} \mathrm{~B} \rightarrow \mathrm{p}+\alpha+{ }^{6} \mathrm{He}{ }^{*}$

$$
{ }^{6} \mathrm{He}{ }^{*} \rightarrow \mathrm{n}+\mathrm{n}+\alpha
$$

d. $\quad \mathrm{n}+{ }^{10} \mathrm{~B} \rightarrow \alpha+\mathrm{p}+{ }^{6} \mathrm{He}$

$$
{ }^{6} \mathrm{He} \rightarrow \mathrm{n}+\mathrm{n}+\alpha
$$

the three-body breakup processes of ${ }^{6} \mathrm{He}^{*} \rightarrow \mathrm{n}+\mathrm{n}+\alpha$ occur in the case of c and d .
The reactions to ${ }^{10} \mathrm{~B}(\mathrm{n}, \mathrm{nd} 2 \alpha)$ channel involved in the model calculation are as follows:
a. $\mathrm{n}+{ }^{10} \mathrm{~B} \rightarrow \mathrm{n}+\mathrm{d}+{ }^{8} \mathrm{Be}{ }^{-}$

$$
{ }^{8} \mathrm{Be}^{\circ} \rightarrow \alpha+\alpha
$$

b. $\mathrm{n}+{ }^{10} \mathrm{~B} \rightarrow \mathrm{~d}+\mathrm{n}+{ }^{8} \mathrm{Be}{ }^{-}$

$$
{ }^{8} \mathrm{Be}^{\circ} \rightarrow \alpha+\alpha
$$

c. $\mathrm{n}^{10} \mathrm{~B} \rightarrow \mathrm{~d}+{ }^{9} \mathrm{Be}{ }^{*}$

$$
{ }^{9} \mathrm{Be}^{-} \rightarrow \mathrm{n}+\alpha+\alpha
$$

The reaction channels below 20 MeV are listed in Table 1 in detail:
Table 1 The reaction situation from the compound nucleus ${ }^{11} B^{*}$ to the discrete levels of the residual nucleus

| channel | $K_{1}{ }^{11}$ | $K_{2}(\max )^{2}$ | E-th | channel | $K_{1}$ | $K_{2}($ max $)$ | $E$-th |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| ( $\mathrm{n}, 2 \mathrm{n}$ ) | 22 | g.s** | 9.576 | ( $n, \alpha n$ ) | 4 | g.s | 5.140 |
| $(\mathrm{n}, 2 \mathrm{n})$ | 30 | 4 | 15.851 | (n, $\alpha \mathrm{n}$ ) | 9 | 5 | 13.110 |
| ( $\mathrm{n}, \mathrm{np}$ ) | 13 | g.s | 7.566 | ( $\mathrm{n}, \alpha \mathrm{p}$ ) | 7 | g.s | 9.301 |
| (n,np) | 30 | 6 | 15.851 | (n, $\alpha \mathrm{p}$ ) | 9 | 1 | 13.110 |
| $(\mathrm{n}, \mathrm{n} \alpha)$ | 5 | g.s | 5.255 | $(\mathrm{n}, 2 \alpha)$ | 2 | g.s | 2.025 |
| $(\mathrm{n}, \mathrm{n} \alpha)$ | 30 | 5 | 15.851 | $(\mathrm{n}, 2 \alpha)$ | 9 | g.s | 13.110 |
| (n,nd) | 11 | g.s | 6.744 | $(\mathrm{n}, \mathrm{dn})$ | 1 | g. 5 | 6.656 |
| ( $\mathrm{n}, \mathrm{nd}$ ) | 30 | 1 | 15.851 | ( $\mathrm{n}, \mathrm{dn}$ ) | 9 | 1 | 17.801 |
| (n.pn) | 6 | g.s | 7.866 |  |  |  |  |
| Notation: 1) $K_{1}$ and $K_{2}$ mean that the reaction channel reach kl level through the first emission, then reach to k 2 level of the residual nucleus through the second emission. |  |  |  |  |  |  |  |
| 2) k 2 (max) is the maximum levels of the residual nucleus via kl level. |  |  |  |  |  |  |  |
| In the table above, g.s stands for ground state, while 2, 3...stand for 2nd, 3rd excited state... |  |  |  |  |  |  |  |

## 2 Calculated Results and Discussion

The comparisons of the theoretical calculated total cross section, nonelastic cross section with the experimental data ${ }^{[3,4]}$ are shown in Fig. 1. Because of light mass, the resonance phenomenon is obvious, in the calculation of total cross section, only the smooth was part of the data used this model calculation. Since the experimental data of cross sections are not only very few but also outdated, it is used just as reference.

The comparisons of calculated elastic angular distributions are shown in Fig.2, the experimental data are taken from Refs $5 \sim 7$. The incident neutron energies are
3.02, $4.02,6.02,7.00,8.01,9.01,10.01,11.01,14.1,14.96 \mathrm{MeV}$, respectively. Among these data, from 3.02 to 11.01 MeV are taken from OHO in 1990 , that of 14.1 MeV is taken from OSA in 1988 , that of 14.96 MeV is taken from TNL in 1985. The plotting in the figures, from the top to the bottom, is ten times less than the group above. As shown by their figures, the calculated values are in agreement fairly good with experimental data.


Fig. 3 Comparison of calculated ${ }^{10} \mathrm{~B}(\mathrm{n}, \mathrm{t}) 2 \alpha$ reaction cross section with experimental data

As an example of the cross section, the comparison of theoretical calculated results and experimental data ${ }^{[8-13]}$ of ${ }^{10} \mathrm{~B}(\mathrm{n}, \mathrm{t})$ reaction cross section is shown in Fig. 3. As the figure shows, there exists a data source (diamond) between 1 to 9 MeV , which was measured in 1961, diverges greatly from others, while another data source (star) was measured in 1988, so we believe the latter is better than the former, which was used for the fitting procedure. From this point of view, the theoretical calculated curve pass through the measured data. The results could be acceptable.

The comparisons of calculated energy-angular spectra and the experimental data ${ }^{[14]}$ of outgoing neutrons are shown in Fig. 4 at neutron incident energy $E_{\mathrm{n}}=14.2 \mathrm{MeV}$, for outgoing angle $25.0,30.0,45.0,60.0,75.0,85.0,100.0,120.0$, $135.0,150.0$, respectively. The data in the figures, from the top to the bottom, is a hundred times less than the group above, moreover for the sake of clear, all errors of the experimental data were reduced to $1 / 10$ of the original. The discrepancy occurs mainly in the small angle region. Previously the calculated results are lower than the experimental data in this region. The model calculations indicate that there is contradiction between the measured data of the energy-angular spectra of the outgoing neutrons and the cross sections of the reaction channel ${ }^{10} \mathrm{~B}(\mathrm{n}, \mathrm{nd})$. As a matter of fact the higher the calculated cross sections of channel ${ }^{10} \mathrm{~B}(\mathrm{n}, \mathrm{nd})$, the
better the calculated results of the double differential cross section agree with the experimental data. With the rising of the calculated cross section of the reaction channel ( n , nd ), the fitting of the total outgoing neutron spectra could be improved. Meanwhile, the emission of the ${ }^{5} \mathrm{He}$ was taken into account, with which the calculated results in the spectra of small angle have been improved.


Fig. 4(a)


Fig. 4 Comparison of calculated outgoing neutron double differential cross section with experimental data

## 3 Remarks

A new model for neutron induced light nucleus reactions has been developed. The key point in this model is the description of the particle emissions from the excited composit system to the discrete levels of the residual nuclei in preequilibrium state. The pre-equilibrium emission mechanism dominants the reaction
processes. In whole reaction processes the angular momentum and parity are conserved and the energy balance is taken into consideration. To fit the experimental data the level broadening effect and the energy resolution must be considered. The comparisons of the total outgoing neutron energy-angular spectra with the experimental data of $\mathrm{n}+{ }^{10} \mathrm{~B}$ at the incident neutron energy of 14.2 MeV have been performed. From the calculation we can see that the optical model still works well to give the emission branch from levels in the case of light nucleus reaction. The comparisons indicate that this new model can reproduce the nuclear data of $n+{ }^{10} \mathrm{~B}$ successfully.

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# Model Calculation of $\mathbf{n}+{ }^{11} \mathbf{B}$ bellow 20 MeV 

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## Introduction

The element "B has long been selected as the shielding material in nuclear engineering because of light mass and large neutron absorption cross-section. The reaction mechanism of $\mathrm{n}+{ }^{11} \mathrm{~B}$ is very complex, many reaction channels are opened below 20 MeV . A new model has been developed for description of neutron induced light nucleus reaction ${ }^{[11}$. In this model the angular momentum conservation, parity conservation of the emissions from composite system to the discrete levels in preequilibrium emission are involved. Meanwhile, the energy balance is strictly taken into account. The improved pick-up mechanism is still employed to calculate composite particle emission in this model ${ }^{[2,3]}$. The experimental data of double differential cross sections were measured by M. Baba et al in 1985 ${ }^{[4]}$, which have been analyzed with this new approach.

In case of $E_{\mathrm{n}} \leqslant 20 \mathrm{MeV}$, the total cross sections, elastic scattering, and nonelastic cross sections, elastic angular distributions, and the energy-angular spectra of outgoing neutrons have been calculated. The comparisons with the measured data are shown in the figures.
In the calculations, the optical model is used, from the fitting procedure to get the optical potential parameters both for the neutron and the charged particles. There are strong resonance structures in the total, non-elastic scattering cross section, limited by this model, only the smooth parts of them are fitted to determine the optical model parameters.

In the case of neutron induced light target nucleus reactions, the pre-equilibrium emission dominates the reaction mechanism as the same as other light nuclei, like lithium, carbon.

## 1 Reaction Channel

For $\mathrm{n}^{11} \mathrm{~B}$ reactions below $E_{\mathrm{n}} \leqslant 20 \mathrm{MeV}$, the opened reaction channels are listed as fellow:

$$
\mathrm{n}^{11}{ }^{11} \mathrm{~B}\left\{\begin{array}{lll}
\gamma+{ }^{12} \mathrm{~B} & Q=3.370 \mathrm{MeV} & E_{\mathrm{th}}=0.000 \mathrm{MeV} \\
\mathrm{n}^{11}+{ }^{11} \mathrm{~B} & Q=0.000 \mathrm{MeV} & E_{\mathrm{th}}=0.000 \mathrm{MeV} \\
\mathrm{p}+{ }^{11} \mathrm{Be} & Q=-10.724 \mathrm{MeV} & E_{\mathrm{th}}=11.707 \mathrm{MeV} \\
\alpha+{ }^{8} \mathrm{Li} & Q=-6.630 \mathrm{MeV} & E_{\mathrm{th}}=7.237 \mathrm{MeV} \\
{ }^{5} \mathrm{He}+{ }^{7} \mathrm{Li} & Q=-9.559 \mathrm{MeV} & E_{\mathrm{th}}=10.4348 \mathrm{MeV} \\
\mathrm{~d}+{ }^{10} \mathrm{Be} & Q=-9.004 \mathrm{MeV} & E_{\mathrm{th}}=9.829 \mathrm{MeV} \\
\mathrm{t}+{ }^{9} \mathrm{Be} & Q=-9.558 \mathrm{MeV} & E_{\mathrm{th}}=10.434 \mathrm{MeV} \\
2 \mathrm{n}+{ }^{10} \mathrm{~B} & Q=-11.453 \mathrm{MeV} & E_{\mathrm{th}}=12.502 \mathrm{MeV} \\
\mathrm{n}+\mathrm{p}+{ }^{10} \mathrm{Be} & Q=-11.228 \mathrm{MeV} & E_{\mathrm{th}}=12.257 \mathrm{MeV} \\
\mathrm{n}+\alpha+{ }^{7} \mathrm{Li} & Q=-8.663 \mathrm{MeV} & E_{\mathrm{th}}=9.457 \mathrm{MeV} \\
\mathrm{n}+\mathrm{d}+{ }^{9} \mathrm{Be} & Q=-15.815 \mathrm{MeV} & E_{\mathrm{th}}=17.264 \mathrm{MeV} \\
\mathrm{n}+\mathrm{t}+2 \alpha & Q=-11.223 \mathrm{MeV} & E_{\mathrm{th}}=12.251 \mathrm{MeV} \\
2 \alpha+{ }^{4} \mathrm{H} & Q=-16.413 \mathrm{MeV} & E_{\mathrm{th}}=17.917 \mathrm{MeV} \\
\alpha+\mathrm{t}+{ }^{5} \mathrm{He} & Q=-12.025 \mathrm{MeV} & E_{\mathrm{th}}=13.127 \mathrm{MeV}
\end{array}\right.
$$

The reaction channel of ( $n,{ }^{3} \mathrm{He}$ ) is not open due to the threshold energy lager than 20 MeV . The reaction channel of $(\mathrm{n}, \mathrm{t})$ is reached by emitting a $\alpha$ to the ground state of ${ }^{9} \mathrm{Be}$, while the excited states of ${ }^{9} \mathrm{Be}$ decay to one neutron and two $\alpha$ particles, so they belong to the ( $n, n t$ ) $2 \alpha$ reaction channel. The reaction mechanism of $n+{ }^{11} B$ leading to the decay into one $t$ particle, one neutron and two $\alpha$ particles may proceed through different channels. The reactions to ${ }^{11} \mathrm{~B}(\mathrm{n}, \mathrm{nt}) 2 \alpha$ reaction channels involved in the calculation are as follow:
(a) $\mathrm{n}+{ }^{11} \mathrm{~B} \rightarrow \mathrm{t}+{ }^{9} \mathrm{Be}^{*}$

$$
\begin{aligned}
& { }^{9} \mathrm{Be}^{*} \rightarrow \mathrm{n}+{ }^{8} \mathrm{Be} \\
& { }^{8} \mathrm{Be} \rightarrow 2 \alpha
\end{aligned}
$$

(b) $\mathrm{n}+{ }^{11} \mathrm{~B} \rightarrow \mathrm{n}+\mathrm{t}+{ }^{8} \mathrm{Be}$

$$
{ }^{8} \mathrm{Be} \rightarrow 2 \alpha
$$

(c) $\mathrm{n}+{ }^{11} \mathrm{~B} \rightarrow \alpha+\mathrm{t}+{ }^{5} \mathrm{He}$

$$
{ }^{5} \mathrm{He} \rightarrow \mathrm{n}+\alpha
$$

(d) $\mathrm{n}+{ }^{11} \mathrm{~B} \rightarrow \mathrm{t}+\alpha+{ }^{5} \mathrm{He}$

$$
{ }^{5} \mathrm{He} \rightarrow \mathrm{n}+\alpha
$$

(e)

$$
\begin{aligned}
\mathrm{n}+{ }^{11} \mathrm{~B} \rightarrow \alpha+\alpha+{ }^{4} \mathrm{H} \\
{ }^{4} \mathrm{H} \rightarrow \mathrm{n}+\mathrm{t}
\end{aligned}
$$

In $n+{ }^{11} \mathrm{~B}\left(E_{\mathrm{n}} \leqslant 20 \mathrm{MeV}\right)$ reactions, there is no three-body breakup process, all reaction channels proceed with the sequential particle emissions from composite system to the discrete levels. The reaction situation is listed in Table 1.

Table 1 The reaction situation from the compound nucleus ${ }^{12} B^{*}$ to the discrete levels of the residual nucleus

|  | $K_{1}$ | $K_{2}$ |  | $K_{1}$ | $K_{2}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| ( $\mathrm{n}, 2 \mathrm{n}$ ) | 20-22 | gs | ( $\mathrm{n}, \mathrm{nt}$ ) | 19-29 | gs |
| ( $\mathrm{n}, 2 \mathrm{n}$ ) | 23-26 | 1 | ( $\mathrm{n}, \mathrm{nt}$ ) | 30-34 | 1 |
| $(\mathrm{n}, 2 \mathrm{n})$ | 27-29 | 3 | (n,pn) | 2-4 | gs |
| $(\mathrm{n}, 2 \mathrm{n})$ | 30-31 | 4-5 | (n,pn) | 5-7 | 1 |
| $(\mathrm{n}, 2 \mathrm{n})$ | 32-33 | 8-9 | (n,pn) | 8 | 5 |
| $(\mathrm{n}, 2 \mathrm{n})$ | 34 | 11 | (n. $\alpha \alpha$ ) | 10 | 1 |
| ( $\mathrm{n}, \mathrm{np}$ ) | 18-29 | gs | ( $\mathrm{n}, \mathrm{nd}$ ) | 31-34 | gs |
| ( $\mathrm{n}, \mathrm{np}$ ) | 30-31 | 1 | ( $\mathrm{n}, \alpha \mathrm{t}$ ) | 5-9 | gs |
| (n,np) | 32-33 | 3 | (n, $\alpha \mathrm{t})$ | 10 | 1 |
| ( $\mathrm{n}, \mathrm{np}$ ) | 34 | 5 | ( $\mathrm{n}, \alpha \mathrm{n}$ ) | 2 | gs |
| $(\mathrm{n}, \mathrm{n} \alpha)$ | 9-10 | gs | ( $\mathrm{n}, \alpha \mathrm{n}$ ) | 3.9 | 1 |
| $(\mathrm{n}, \mathrm{n} \alpha)$ | 11-26 | 1 | ( $\mathrm{n}, \alpha \mathrm{n}$ ) | 10 | 4 |
| ( $\mathrm{n}, \mathrm{n} \boldsymbol{\alpha}$ ) | 27-30 | 2 | ( $\mathrm{n}, \mathrm{dn}$ ) | 6 | gs |
| $(\mathrm{n}, \mathrm{n} \alpha)$ | 31-34 | 4 |  |  |  |

## 2 Calculated Results and Discussion

By using the optical model, the fitting procedures are issued to the total cross section, non-elastic cross section and elastic scattering angular distribution. The comparisons of the theoretical calculated results with the experimental data are shown in Figs. $1 \sim 2$, the data of total cross section are taken from Refs. 5~9.

From the Figs. 1~2, one can see that there are the same resonance structures obviously below $E_{\mathrm{n}} \leqslant 8 \mathrm{MeV}$ in total cross section and non-elastic cross section. The elastic scattering angular distributions for some incident neutron energies are shown in Figs. 3~4. All of the fittings agree well with the measurements, the data are taken from Refs. $10 \sim 14$.

The comparison of cross sections between theoretical results and the experimental data in ${ }^{11} \mathrm{~B}(\mathrm{n}, \alpha){ }^{8} \mathrm{Li},{ }^{11} \mathrm{~B}(\mathrm{n}, \mathrm{t}){ }^{9} \mathrm{Be}$ reaction channels are shown in Figs. 5-6. The data are taken from Refs. 15~18.

One can see that the fittings of the reaction channels of ${ }^{11} \mathrm{~B}(\mathrm{n}, \alpha)^{8} \mathrm{Li}$ and ${ }^{11} \mathrm{~B}(\mathrm{n}, \mathrm{t})$ ${ }^{9} \mathrm{Be}$ are all in good agreements with the experimental data.


Fig. 1 The total cross section of $\mathrm{n}+{ }^{11} \mathrm{~B}$ reaction


Fig. 3 The elastic scattering angular distributions of $n+{ }^{11} B$ reaction


Fig. 2 The non-elastic cross section of $\mathrm{n}^{+1} \mathrm{~B}$ reaction


Fig. 4 The elastic scattering angular distributions of $n+{ }^{11} B$ reaction

The calculations of the total double-differential cross sections of the outgoing neutrons from each reaction channels have been performed. The comparisons between the calculated results and the measured data are shown in Figs.7~9 at neutron incident energy $E_{\mathrm{n}}=14.2 \mathrm{MeV}$ for outgoing angles of $25,30,45,60,75,85$, $100,120,135$, and 150 degree. The entire fitting agree fairly good with the measurements.


Fig. 5 The cross section of ${ }^{14} B(n, \alpha)$


Fig. 7 The neutron energy-angular spectra of $25,30,45 \mathrm{deg}$ at $E_{\mathrm{n}}=14.2 \mathrm{MeV}$

Fig. 6 The cross section of ${ }^{11} B(n, t)$


Fig. 8 The neutron energy-angular spectra of $60,75,85 \mathrm{deg}$ at $E_{\mathrm{n}}=14.2 \mathrm{MeV}$

The total energy-angular spectrum for each angle consists of many partial spectra from differential reaction channels, which are shown in Fig.10, as an example, iat $\theta=90^{\circ}$. and $E_{\mathrm{n}}=14.2 \mathrm{MeV}$. The thin solid lines denote the individual spectra of the first outgoing neutrons, and the dot lines denote the individual spectra of the second outgoing neutrons. At low energy region, especially at $E_{\mathrm{n}} \leqslant 2 \mathrm{MeV}$, the partial spectra come from the secondary outgoing neutrons denoted with dot lines, of which the spectra are too dense to be specified with the designations. The full line is the calculated energy-angular spectrum.

The percentages of equilibrium and pre-equilibrium emission processes from different $J, \pi$ channels and the corresponding absorption cross sections at $E_{\mathrm{n}}=14.2$ MeV are given in the Table 2 . One can see that the pre-equilibrium emissions are the dominant reactions mechanism, especially at the small angular momentum region
$(J=0 \sim 6)$, in which the absorption cross sections have the large values. Meanwhile, the equilibrium emissions mainly contribute to the high angular momentum part, which correspond to the multi-step collision processes. Averaged by the angular momentum the percentage of pre-equilibrium emission is $74.69 \%$, while percentage of equilibrium is only $25.31 \%$.


Fig. 9 The neutron energy-angular spectra of $100,120,135,150 \mathrm{deg}$. at $E_{\mathrm{n}}=14.2 \mathrm{MeV}$


Fig. 10 The partial spectra of the emitted neutrons of 90 deg. at $E_{\mathrm{n}}=14.2 \mathrm{MeV}$.

Table 2. The equilibrium and pre-equilibrium percentage at $E_{\mathrm{n}} \mathbf{= 1 4 . 2} \mathbf{~ M e V}$

| $J$ | $\mathrm{eq}(\%)$ | pre-eq(\%) | $\sigma_{2}^{(+)}(\mathrm{mb})$ | $\sigma_{a}^{(-1)}(\mathrm{mb})$ |
| :---: | :---: | :---: | :---: | :---: |
| 0 | 0.0632 | 0.9368 | 0.00514 | 0.00533 |
| 1 | 0.1583 | 0.8417 | 0.04759 | 0.04885 |
| 2 | 0.2182 | 0.7818 | 0.10726 | 0.08593 |
| 3 | 0.2453 | 0.7547 | 0.11469 | 0.08731 |
| 4 | 0.2473 | 0.7527 | 0.10185 | 0.06432 |
| 5 | 0.2547 | 0.7453 | 0.06302 | 0.02002 |
| 6 | 0.3155 | 0.6845 | 0.00184 | 0.0119 |
| 7 | 0.4439 | 0.5561 | 0.00107 | 0.00017 |
| 8 | 0.6899 | 0.3101 | 0.00002 | 0.0001 |
| 9 | 0.7887 | 0.2113 | 0.00001 | 0 |

## 3 Remarks

A new model for neutron induced light nucleus reaction has been developed. In this model, the particle emission from the composite system to discrete levels in preequilibrium mechanism is taken into account, because the pre-equilibrium emission mechanism dominates the reaction processes. The angular momentum conservation,
parity conservation and energy balance are all considered in whole reaction processes. In this model calculation, we can find out that the optical model works well to give the emission branch from levels to levels in the case of light nucleus reaction. To fit experimental data of neutron double differential cross section the level broadening and energy resolution must be include in calculation, and the Gaussian expansion is used for the level broadening effect. From the calculated results, one can see that this model works well in calculation both for cross sections and for energy-angular distributions of outgoing neutrons.

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# Model Calculation of $\mathrm{n}+{ }^{\mathbf{1 6}} \mathrm{O}$ Reactions from 3 to 20 MeV 

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## Introduction

In view of the emission mechanism for a light nucleus, from ${ }^{6} \mathrm{Li}$ up to ${ }^{16} \mathrm{O}$, besides the equilibrium emission, the pre-equilibrium emission must be taken into account, a new model has been developed for this kind of reactions. The analysis of
the outgoing particle spectra for $\mathrm{n}+{ }^{12} \mathrm{C}^{[1]}$ indicates that the new model can reproduce the experimental data fairly well. With this new model the cross sections and double-differential cross sections of outgoing neutrons of reaction $n+{ }^{16} \mathrm{O}$ are calculated. The calculated results show that the pre-equilibrium particle emission processes are the dominant part in whole reaction process, while the equilibrium mechanism is only the secondary part.

In this model the angular momentum dependent exciton model ${ }^{[2]}$ is used for conserving angular momentum conservation in pre-equilibrium emission process. The optical model is also used to calculate the emission rates of all kinds of particles. The optical potential parameters of neutron are determined by fitting the total, elastic, non-elastic cross sections, as well as elastic angular distributions, for the charged particles, the optical potential parameters are determined by the corresponding reaction cross section. Because of the light mass of target, the recoil effect must be taken into account exactly to maintain the energy balance ${ }^{[3]}$.

There are many reaction channels opend in the case of $E_{\mathrm{n}} \leqslant 20 \mathrm{MeV}$, besides the sequential particle emissions, the cluster separation is also involved, and the second particle emissions are all from discrete levels to discrete levels.

In view of the emission mechanism for the light nucleus ${ }^{16} \mathrm{O}$, very strong resonance phenomena appear in the reaction cross section, in this new model, only the smooth part can be obtained for determining the optical model parameters. The total neutron energy-angular spectra consist of the outgoing neutron from various reaction channels, which strongly differ from each other. The double-differential cross section of outgoing neutrons were was measured by M . Baba at $E_{\mathrm{n}}=14.1 \mathrm{MeV}$ and 18.0 MeV in $1985^{[4]}$, M. Baba also measured the data at $E_{\mathrm{n}}=14.2 \mathrm{MeV}$ in $1988^{[5]}$. The double-differential measurements could provide information for analysing the components from differential reaction mechanism.

## 1 Reaction Channels of $\mathrm{n}+{ }^{16} \mathrm{O}$ Reaction

For reaction $\mathrm{n}+{ }^{16} \mathrm{O}$, in the case of $E_{\mathrm{n}} \leqslant 20 \mathrm{MeV}$, the reaction channels are list as follows: ( $Q$ and $E_{\mathrm{th}}$ are in unit of MeV )

$$
\mathrm{n}+{ }^{16} \mathrm{O}\left\{\begin{array}{lll}
\gamma+{ }^{17} \mathrm{O} & Q=4.1430 & E_{\mathrm{th}}=0 \\
\mathrm{n}+{ }^{16} \mathrm{O} & Q=0.0 & E_{\mathrm{th}}=0 \\
\mathrm{p}+{ }^{16} \mathrm{~N} & Q=-9.6370 & E_{\mathrm{th}}=10.2447 \\
\alpha+{ }^{13} \mathrm{C} & Q=-2.2150 & E_{\mathrm{th}}=2.3547 \\
{ }^{5} \mathrm{He}+{ }^{12} \mathrm{C} & Q=-8.0560 & E_{\mathrm{th}}=8.5640 \\
\mathrm{~d}+{ }^{15} \mathrm{~N} & Q=-9.9030 & E_{\mathrm{th}}=10.5275 \\
\mathrm{t}+{ }^{14} \mathrm{~N} & Q=-14.4790 & E_{\mathrm{th}}=15.3921 \\
2 \mathrm{n}+{ }^{15} \mathrm{O} & Q=-15.6630 & E_{\mathrm{th}}=16.6507 \\
\mathrm{n}, \mathrm{p}+{ }^{15} \mathrm{~N} & Q=-12.1270 & E_{\mathrm{th}}=12.8917 \\
\mathrm{n}, \alpha+{ }^{12} \mathrm{C} & Q=-7.1610 & E_{\mathrm{th}}=7.6126 \\
2 \alpha+{ }^{9} \mathrm{Be} & Q=-12.1270 & E_{\mathrm{th}}=13.6742 \\
2 \alpha, \mathrm{n}+{ }^{8} \mathrm{Be} & Q=-7.1610 & E_{\mathrm{th}}=15.3474 \\
2 \alpha, \alpha+{ }^{5} \mathrm{He} & Q=-12.8610 & E_{\mathrm{th}}=15.3474
\end{array}\right.
$$

The ${ }^{16} \mathrm{O}(\mathrm{n}, 2 \alpha){ }^{9} \mathrm{Be}$ reaction channel comes from sequential two $\alpha$ particle emissions reaching the ground state of residual nucleus ${ }^{9} \mathrm{Be}$, while the excited state of ${ }^{9} \mathrm{Be}$ contributes to the $(\mathrm{n}, \mathrm{n}) 4 \alpha$ channel via n emission and spontaneously cluster separation process of ${ }^{8} \mathrm{Be}\left({ }^{8} \mathrm{Be} \rightarrow \alpha+\alpha\right)$. But the calculat:ons show the cross section of $(\mathrm{n}, \mathrm{n}) 4 \alpha$ reaction channel is very small below 20 MeV , which can be neglected. The main reaction channel of $\mathrm{n}+{ }^{16} \mathrm{O}$ below 20 MeV is ${ }^{16} \mathrm{O}(\mathrm{n}, \mathrm{n} \alpha)^{12} \mathrm{C}$, the reaction channels to $(\mathrm{n}, \mathrm{n} \alpha)^{12} \mathrm{C}$ channel involved in calculation are as follows:
(a) $\mathrm{n}+{ }^{16} \mathrm{O} \rightarrow \mathrm{n}+{ }^{16} \mathrm{O}^{-}$

$$
{ }^{16} \mathrm{O}^{*} \rightarrow \alpha+{ }^{12} \mathrm{C}
$$

(b) $\mathrm{n}+{ }^{16} \mathrm{O} \rightarrow \alpha+{ }^{13} \mathrm{C}^{-}$

$$
{ }^{13} \mathrm{C}^{*} \rightarrow \mathrm{n}+{ }^{12} \mathrm{C}
$$

(c) $\mathrm{n}+{ }^{16} \mathrm{O} \rightarrow{ }^{5} \mathrm{He}+{ }^{12} \mathrm{C}^{\circ}$

$$
{ }^{5} \mathrm{He} \rightarrow \mathrm{n}+\alpha
$$

The reaction situation from the compound nucleus ${ }^{17} \mathrm{O}$ to the discrete levels of the residual nuclei up to $E_{\mathrm{n}}=20 \mathrm{MeV}$ is represented in Table 1

Table 1 The reaction situation from the compound nucleus ${ }^{17} O^{*}$ to the discrete level $K_{2}$ of the residual nuclei via the $K_{1}$ level up to $E_{\mathrm{n}}=\mathbf{2 0} \mathbf{~ M e V}$

| channel | $K_{1}$ | $K_{2}$ |  | channel | $K_{1}$ | $K_{2}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $(\mathrm{n}, 2 \mathrm{n})^{13} \mathrm{O}$ | 39~73 | gs ${ }^{1 \prime}$ |  | $(\mathrm{n}, \mathrm{n} \alpha)^{12} \mathrm{C}$ | 5~15 | gs |
| $(\mathrm{n}, \mathrm{np})^{15} \mathrm{~N}$ | 16~53 | gs |  | $(n, n \alpha)^{12} \mathrm{C}$ | 16-37 | 1 |
| $(\mathrm{n}, \mathrm{np})^{15} \mathrm{~N}$ | 54 | 1 |  | $(\mathrm{n}, \mathrm{n} \alpha)^{12} \mathrm{C}$ | 38-53 | 2 |
| (n,np) ${ }^{15} \mathrm{~N}$ | 55~68 | 2 |  | $(\mathrm{n}, \mathrm{n} \alpha)^{12} \mathrm{C}$ | 54~60 | 3 |
| $(\mathrm{n}, \mathrm{np})^{15} \mathrm{~N}$ | 69~73 | 3 |  | $(\mathrm{n}, \mathrm{n} \alpha)^{12} \mathrm{C}$ | 61~68 | 4 |
| (n,pn) ${ }^{15} \mathrm{~N}$ | 4-27 | gs |  | $(\mathrm{n}, \mathrm{n} \alpha)^{12} \mathrm{C}$ | 69-73 | 5 |
| $(\mathrm{n}, 2 \alpha)^{9} \mathrm{Be}$ | 15~24 | gs |  | $(\mathrm{n}, \alpha \mathrm{n})^{12} \mathrm{C}$ | 4~9 | gs |
| $(\mathrm{n}, 2 \alpha)^{9} \mathrm{Be}$ | 25 | 1 |  | $(\mathrm{n}, \alpha \mathrm{n})^{12} \mathrm{C}$ | 10~24 | 1 |
| $(\mathrm{n}, 2 \alpha)^{9} \mathrm{Be}$ | 26~29 | 5 |  | $(\mathrm{n}, \alpha \mathrm{n})^{12} \mathrm{C}$ | 25~29 | 2 |

Note: 1) The acronym gs refers to ground state
From Table 1 one can see that following the sequential two alpha-particle emissions, the residual nucleus is ${ }^{9} \mathrm{Be}$. As well known, all of the excited levels of ${ }^{9} \mathrm{Be}$ can emit neutrons, and its residual nucleus ${ }^{8} \mathrm{Be}$ is separated spontaneously into two alpha-particles. The third alpha particle can be emitted from the level above the second excited levels of ${ }^{9} \mathrm{Be}$ with the residual nucleus ${ }^{5} \mathrm{He}$, which is separated spontaneously into $\mathrm{n}+\alpha$. Since ${ }^{5} \mathrm{He}$ and ${ }^{8} \mathrm{Be}$ are unstable, so the reaction channel $(n, 2 \alpha n)^{8} \mathrm{Be}$ and $(\mathrm{n}, 3 \alpha)^{5} \mathrm{He}$ belong to ( $n, n$ ) $4 \alpha$ channel.

## 2 Calculated Results and Discussion

The LUNF code for $\mathrm{n}+{ }^{16} \mathrm{O}$ is developed to calculate all kinds of the reaction cross sections and elastic scattering angular distribution, as well as the doubledifferential cross section of outgoing neutrons. As an example of cross section, total cross section and non-elastic cross section are shown in Figs. 1 and Figs. 2, the calculated results and experimental data ${ }^{[6-10]}$ agree well. The comparisons of calculated results and experimental data of elastic scattering angular distribution are shown in Figs. 3 and Figs. 4, the data of $E_{\mathrm{n}}=4.99,5.66,8.0,11.6 \mathrm{MeV}$ are taken from USALOK in $(1961)^{[11]}$; the data of $E_{\mathrm{n}}=6.0,7.0 \mathrm{MeV}$ are taken from USALAS in $1960^{[12]}$; the data of $E_{\mathrm{n}}=14.0 \mathrm{MeV}$ are taken from USAOHO in $1967^{[13]}$, and USRLAL in $1963^{[14]}$; the data of $E_{\mathrm{n}}=14.1 \mathrm{MeV}$ are taken from CANOTU in $1966^{[15]}$, and USARIC in $1953^{[16]}$; the data of $E_{\mathrm{n}}=18.0,20.0 \mathrm{MeV}$ are taken from USAOHO in $1987^{[17]}$. Which are all in good agreements.


Fig. 1 The total cross section of $n+{ }^{16} O n+{ }^{16} O$


Fig. 3 The elastic angular distribution of $\mathrm{n}+{ }^{16} \mathrm{O}$ at $E_{\mathrm{n}}=4.99,5.66,6,7,8$ and 9 MeV


Fig. 2 The non-elastic cross section of $n+{ }^{16} \mathrm{O}$


Fig. 4 The elastic angular distribution of $\mathrm{n}+{ }^{16} \mathrm{O}$ at $E_{\mathrm{n}}=11.6,14,14.1,18,20 \mathrm{MeV}$

The calculations of total double-differential cross section of outgoing neutrons from each reaction channel have been performed. The comparison between the calculated results and experimental data are shown in Figs. 5~11. The fitting agrees fairly well with the measurements at $E_{\mathrm{n}}=14.1 \mathrm{MeV}$. At $E_{\mathrm{n}}=14.2 \mathrm{MeV}$ and $E_{\mathrm{n}}=18.0$ MeV , the comparisons of the calculated results with measurements are all in good agreement at the high-energy region but at the low energy region, the calculated results lower than the measured data. The results have been improved with the reaction channel ( $n,{ }^{3} \mathrm{He}$ ) is replaced by ( $\mathrm{n},{ }^{5} \mathrm{He}$ ), meanwhile, there is only very few experimental data, and the experimental data were measured in many years ago, so they are for reference only.

The total neutron energy-angular spectra for each angle consist of neutrons from various reaction channels which strongly differ from each other, as an example, the partial spectrum of $90^{\circ}$ at $E_{\mathrm{n}}=14.1 \mathrm{MeV}$ are shown in Fig. 12 and Fig. 13.


Fig. 5 The energy-angular spectra of $\mathrm{n}+{ }^{16} \mathrm{O}$ at $E_{\mathrm{n}}=14.1 \mathrm{MeV}$ for $25^{\circ}, 30^{\circ}, 37.5^{\circ}, 45^{\circ}$


Fig. 7 The energy-angular spectra of $n+{ }^{16} \mathrm{O}$ at $E_{\mathrm{n}}=14.1 \mathrm{MeV}$ for $25^{\circ}, 120^{\circ}, 135^{\circ}, 150^{\circ}$


Fig. 6 The energy-angular spectra of $\mathrm{n}+{ }^{16} \mathrm{O}$ at $E_{\mathrm{n}}=14.1 \mathrm{MeV}$ for $52.5^{\circ}, 60^{\circ}, 80^{\circ}, 90^{\circ}$


Fig. 8 The energy-angular spectra of $\mathrm{n}+{ }^{16} \mathrm{O}$ at $E_{\mathrm{n}}=14.2 \mathrm{MeV}$ for $25^{\circ}, 30^{\circ}, 45^{\circ}, 60^{\circ}, 75^{\circ}$

The partial spectra of the first neutron are shown in Fig. 12. At the incident energy of $E_{\mathrm{n}}=14.1 \mathrm{MeV}$, the partial spectra of the first neutron come from the emissions from ${ }^{17} \mathrm{O}$ t to the first, through twenty-second excited levels of ${ }^{16} \mathrm{O}$. The three peaks on the right side of the total energy-angular neutron spectrum mainly come from the emission from ${ }^{17} \mathrm{O}^{*}$ to the first, through fifth excited levels of ${ }^{16} \mathrm{O}$, the
designation (1) to (6) represent the partial spectra of the first to sixth excited levels of ${ }^{16} \mathrm{O}$. Because there are too many partial spectra of the first neutron, the designations of the partial spectra of the first neutron above the sixth excited levels of ${ }^{16} \mathrm{O}$ are not given, which are all contribute to the low-energy region of the total neutron spectra.


Fig. 9 The energy-angular spectra of $\mathrm{n}+{ }^{16} \mathrm{O}$ at $E_{\mathrm{n}}=14.2 \mathrm{MeV}$ for $80^{\circ}, 105^{\circ}, 120^{\circ}, 135^{\circ}, 150^{\circ}$

The partial spectra of the secondary neutron are shown in Fig.13, which are all come from the ( $\mathrm{n}, \mathrm{\alpha} \mathrm{n}$ ) channel from the forth to eleventh excited levels of ${ }^{13} \mathrm{C}^{*}$, all of them contribute to the low-energy region of the total outgoing neutron spectra. The forth level has a large width of 1.47 MeV and gives a very wide partial spectrum, which comes from the emission from the forth excited level of ${ }^{13} \mathrm{C}^{*}$ to the ground state of ${ }^{12} \mathrm{C}$ ".

The pre-equilibrium mechanism dominates reaction process of $n+{ }^{16} \mathrm{O}$ bellow 20 MeV , at


Fig. 10 The energy-angular spectra of $\mathrm{n}^{16} \mathrm{O}$ at $E_{\mathrm{n}}=18 \mathrm{MeV}$ for $30^{\circ}, 45^{\circ}, 60^{\circ}$


Fig. 11 The energy-angular spectra of $\mathrm{n}^{+16} \mathrm{O}$ at $E_{\mathrm{n}}=18 \mathrm{MeV}$ for $90^{\circ}, 120^{\circ}, 147.5^{\circ}$
$E_{\mathrm{n}}=14.1 \mathrm{MeV}$, as an example, the pre-equilibrium processes occupy the percentage of $P_{\text {pre-rq }}=65.05 \%$, while the equilibrium processes only have the percentage of $P_{\mathrm{rq}}$ $=34.95 \%$. The parameter in the exciton model $K=200 \mathrm{MeV}^{3}$ is used in the calculations.

## 3 Conclusion

From the calculation we can see that the optical model still works well to give the emission branch from the compound nucleus to the discrete levels in the case of light nucleus reaction, all of the second particle emissions are from discrete level to discrete level. In whole reaction process, the angular momentum and party conversations, as well as the recoil effect are taken into account.

Since all of the particle emissions are emitted between discrete levels, we do not need the level density parameters, except for that of the


Fig. 12 The partial spectra of first emitted neutron of $90^{\circ}$ at 14.1 MeV


Fig. 13 The partial spectra of secondary emitted neutron of $90^{\circ}$ at 14.1 MeV compound nucleus. The level-broadening effect and energy resolution in measurements must be taken into account for fitting energy- angular spectra of outgoing emitted particles ${ }^{[1]}$.

Because the light nucleus reactions have very strong recoil motion, the particle emitted from the residual recoil nucleus have a very strong backward tendency, while the first emitted particle have a obvious forward tendency. Combining these effects, one can obtain the reasonable shapes of the energy-angular spectrum.

The calculation indicates that this new model can reproduce the experimental data of outgoing neutrons very well．

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# Theoretical Calculations of $\mathbf{n}+{ }^{238} \mathbf{P u}$ Reaction in the Energy Region up to 20 MeV 

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The isotope ${ }^{238} \mathrm{Pu}$ is one of the important fission nuclei. Its fission cross sections in fast neutron energy region are larger than other fission nuclei. It can be used as the nuclear fuel of the microscopic reactor on the satellite.

The code APFO $96^{[1]}$ was used to automatically get the optimal optical potential parameters for neutron channel based on the neighbor nuclei experimental data. The obtained optimal neutron optical potential parameters in energy region up to 20 MeV are as follows:

$$
\begin{align*}
& V=41.4820-0.7857 E_{\mathrm{n}}-0.000097 E_{\mathrm{n}}^{2}-24(N-Z) / A  \tag{1}\\
& W_{\mathrm{s}}=18.5219-0.8 E_{\mathrm{n}}-12(N-Z) / A  \tag{2}\\
& W_{\mathrm{v}}=0.80714-0.57145 E_{\mathrm{n}}+0.11354 E_{\mathrm{n}}^{2}  \tag{3}\\
& V_{\mathrm{so}}=6.2  \tag{4}\\
& r_{\mathrm{r}}=1.4022, \quad r_{\mathrm{s}}=1.1568, \quad r_{\mathrm{v}}=1.01, \quad r_{\mathrm{so}}=1.4022  \tag{5}\\
& a_{\mathrm{r}}=0.4935, \quad a_{\mathrm{s}}=0.3118, \quad a_{\mathrm{v}}=0.8000, \quad a_{\mathrm{so}}=0.4935 \tag{6}
\end{align*}
$$

where $E_{\mathrm{n}}$ is incident neutron energy in laboratory system and $Z, N, A$ are proton, neutron, mass number of the target nucleus.

The coupled channel optical model code ECIS95 ${ }^{[2]}$ was used to calculate the direct inelastic scattering cross sections and angular distributions for 5 excited states belong to ground state rotational band ( $2^{+}, 4^{+}, 6^{+}, 8^{+}, 10^{+}$). The coupled channel optical model parameters are as follows ${ }^{[3]}$ :

$$
\begin{align*}
& V=51.32134-0.57 E_{\mathrm{n}}+0.02 E_{\mathrm{n}}^{2}-24(N-Z) / A  \tag{7}\\
& W_{\mathrm{s}}=5.04567+0.4 E_{\mathrm{n}}+0.001 E_{\mathrm{n}}^{2}  \tag{8}\\
& W_{\mathrm{v}}=0 \tag{9}
\end{align*}
$$

$$
\begin{array}{lll}
V_{\mathrm{so}}=6.0 & \\
r_{\mathrm{r}}=1.256, & r_{\mathrm{s}}=1.26, & r_{\mathrm{sc}}=1.12 \\
a_{\mathrm{r}}=0.62, & a_{\mathrm{s}}=0.58, & a_{\mathrm{so}}=0.5 \\
\beta_{2}=0.2, & \beta_{4}=0.07 & \tag{13}
\end{array}
$$

The $\mathrm{FUNF}^{[4]}$ is used as key code in this work. The main statistical theory parameters obtained by code $\mathrm{ADFP}^{[5]}$ are as follows:

|  | $(n, \gamma)$ | $(n, f)$ | $\left(n, n^{\prime}\right)$ | $\left(n, n^{\prime} f\right)$ | $(n, 2 n)$ | $(n, 2 n f)$ | $(n, 3 n)$ |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Level density $(a):$ | 27.4774 | 26.6586 | 26.0700 | 26.4216 | 23.0000 | 31.0445 | 27.5611 |
| Pair correction $(\Delta):$ | 0.6837 | -0.0029 | 0.5169 | 1.2283 | -0.2727 | -0.0266 | 0.0265 |
| Fission barrier $\left(V_{f}\right)$ : |  | 5.8483 |  | 4.1644 |  | 7.0595 |  |
| Fission curvature $(\hbar \omega)$ : |  | 0.4861 |  | 1.0000 |  | 1.0000 |  |
| Saddle level density factor $\left(K_{\mathrm{l}}\right):$ | 5.355 |  | 1.109 |  | 1.246 |  |  |
| Exciton model parameter: | $C K=5751.4$ |  |  |  |  |  |  |
| $(\mathrm{n}, \gamma)$ factor: | $C_{\mathrm{E},}=0.375$ |  |  |  |  |  |  |
| Direct $(\mathrm{n}, \gamma)$ factor: | $\mathrm{DGMA}=0.13$ |  |  |  |  |  |  |

Fig. 1 shows the comparison between the calculated $\sigma_{\mathrm{tot}}$ and those given in ENDF/B-6 and JENDL-3 libraries, from which we can see that they are comparable. Fig. 2 presents the comparison of the $\sigma_{n, F}$ between the calculated results and the experimental data, the agreements with each other are better. The comparison of $\sigma_{\mathrm{n}, 7}$ for our calculated values, the values in ENDF/B-6 and JENDL-3 libraries, and the experimental data is shown in Fig. 3, they are in basically agreement with each other. In high energy region our calculated $\sigma_{n, \gamma}$ are more reasonable since they are more closed to the experimental data of ( $\mathrm{n}, \gamma$ ) cross sections of other fission nuclei. Fig. 4 shows the comparison between the calculated values and the values in ENDF/B-6 and JENDL-3 libraries for ( $\mathrm{n}, \mathrm{inl}$ ) reaction. Their shapes are very different, which should be studied in the future. Figs. 5 and Figs. 6 show the comparisons between the calculated values and the values in ENDF/B-6 and JENDL-3 libraries for ( $n, 2 n$ ) and ( $n, 3 n$ ) reactions, respectively. The values given in ENDF/B-6 library are not reasonable. Fig. 7 shows the calculated inelastic scattering excitation functions of 5 discrete levels (their excited energies are $0.04408,0.14596,0.3034,0.5134,0.7728$ MeV ) by statistical theory and coupled channel theory. Fig. 8 is the comparison between our calculated values and the values in ENDF/B-6 and JENDL-3 libraries for inelastic scattering of the first excited state. Since the direct reaction is included


Fig. $1{ }^{238} \mathrm{Pu}$ total cross sections



Fig. $2{ }^{238} \mathrm{Pu}$ fission cross sections


Fig. $4{ }^{238} \mathrm{Pu}$ (n,inl) cross sections


Fig. $5{ }^{238} \mathrm{Pu}(\mathrm{n}, 2 \mathrm{n})$ cross sections


Fig. $7{ }^{238}$ Pu discrete level inelastic scattering cross sections


Fig. $6{ }^{238} \mathrm{Pu}(\mathrm{n}, 3 \mathrm{n})$ cross sections


Fig. $8{ }^{238} \mathrm{Pu}$ first excited state inelastic scattering cross sections
by using the coupled channel theory, in our calculations there are long tails in high energy region in out calculation results, which are reasonable.

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# Calculations of Complete Set of Data for $\mathbf{n}+{ }^{241,242} \mathrm{Am}$ in the Energy Region up to 20 MeV 

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For ${ }^{241} \mathrm{Am}$, there are sufficient experimental data for $\sigma_{\mathrm{tot}} \sigma_{\mathrm{f}}$, some experimental data below 0.4 MeV for $\sigma_{\mathrm{n}, \gamma}$, a few experimental data for $\sigma_{\mathrm{n}, 2 \mathrm{n}}$ and $\sigma_{\mathrm{n}, 3 \mathrm{n}}$; there are no experimental data for other reaction cross sections, secondary neutron spectra and elastic scattering angular distributions; all experimental data are taken from EXFOR. For ${ }^{242} \mathrm{Am}$, there are no experimental data reported up to now. Because ${ }^{241} \mathrm{Am}$ and ${ }^{242} \mathrm{Am}$ are important in much real application, it is necessary to do systematical theoretical calculation to get complete sets of neutron data of them.

## 1 Programs and Parameters

The spherical optical model, the coupled channel optical model and the unified model of statistical theory are the basic theoretical frame in this work.

Firstly, the Code CAPFO ${ }^{[1]}$ is used to automatically get the optimal parameters of spherical optical potential. The experimental $\sigma_{\mathrm{tot}}$ of ${ }^{241} \mathrm{Am}$ and $\sigma_{\text {non }}$ of ${ }^{241} \mathrm{Am}$ in ENDF/B-6 library are used in automatically searching for the optimal set of spherical optical potential parameters for ${ }^{241} \mathrm{Am}$. The experimental $\sigma_{\text {tot }}$ of ${ }^{241} \mathrm{Am}$ and $\sigma_{\text {non }}$ of ${ }^{242} \mathrm{Am}$ in JENDL-3 library are used in automatically searching for the optimal set of spherical optical potential parameters for ${ }^{242} \mathrm{Am}$. In this way, the final optimum set of spherical optical potential parameters for neutron channel are obtained. For ${ }^{241} \mathrm{Am}$ they are:

$$
\begin{array}{lll}
V_{0}=52.115070, & V_{1}=-0.213793, & V_{2}=0.009512, \\
W_{0}=7.352938, & W_{1}=-0.054000, & \\
U_{0}=-1.206030, & U_{1}=0.254579, & U_{2}=0.003046, \\
a_{\mathrm{r}}=0.582480, & a_{\mathrm{s}}=0.618354, & a_{\mathrm{v}}=0.717496, \\
r_{\mathrm{r}}=1.208394, & r_{\mathrm{s}}=1.331843, & r_{\mathrm{v}}=1.300077,
\end{array}
$$

And for ${ }^{242}$ Am they are:

$$
\begin{array}{lcc}
V_{0}=53.68465, & V_{1}=0.049064, & V_{2}=-0.000173 \\
W_{0}=7.662266, & W_{1}=-0.153344, & \\
U_{0}=-0.977375, & U_{1}=0.116866, & U_{2}=0.008748 \\
a_{\mathrm{r}}=0.685409, & a_{\mathrm{s}}=0.577788, & a_{\mathrm{v}}=0.699829, \\
r_{\mathrm{r}}=1.152801, & r_{\mathrm{s}}=1.342827, & r_{\mathrm{v}}=1.427385
\end{array}
$$

Secondarily, in direct inelastic scattering, the coupled channel optical model code $\mathrm{ECIS}^{[2]}$ is used to calculate the cross sections and angular distributions of 4 lower levels for ${ }^{241} \mathrm{Am}$ and 3 levels for ${ }^{242} \mathrm{Am}$, respectively. For ${ }^{241} \mathrm{Am}$, the ground state and these 4 excited states in the rotational band are with excited energies 0.0 , $0.0412,0.0936,0.1580$ and 0.2340 MeV , spins $2.5,3.5,4.5,5.5$ and 6.5 , parity-1. For ${ }^{242} \mathrm{Am}$, the ground state and these 3 excited states in the rotational band are with excited energies $0.0,0.0529,0.1480$ and 0.1900 MeV , spins $1.0,3.0,5.0$ and 7.0 ,
parity -1 . The coupled channel optical potential parameters used in this calculation are: for ${ }^{241} \mathrm{Am}^{[3]}$, real part potential: $46.23-0.3 E$, surface absorption imaginary part potential:

$$
\begin{aligned}
& 3.314+0.45 E \text { for } E \leqslant 8 \mathrm{MeV} \\
& 7.282-0.046 E \quad \text { for } 8 \leqslant E \leqslant 30 \mathrm{MeV}
\end{aligned}
$$

volume absorption imaginary part potential:

$$
\begin{aligned}
& 0.0 \text { for } E \leqslant 8 \mathrm{MeV} \\
& -1.6+0.2 E \text { for } 8 \leqslant E \leqslant 30 \mathrm{MeV} \text {, }
\end{aligned}
$$

spin-orbital coupling potential: 6.2 , radial parameters: $1.25,1.24$ and 1.01 for real, imaginary and spin-orbital coupling, diffusion parameters: $0.60,0.55$ and 0.75 for real, imaginary and spin-orbital coupling; and for ${ }^{242} \mathrm{Am}^{[4]}$, real part potential: $51.32134-0.57 E+0.02 E^{2}-24(N-Z) / A$, surface absorption imaginary part potential: $5.04567+0.4 E+0.001 E^{2}$, volume absorption imaginary part potential: 0.0 , spinorbital coupling potential: 6.0 , radial parameters: $1.256,1.260$ and 1.120 for real, imaginary and spin-orbital coupling, diffusion parameters: $0.62,0.58$ and 0.50 for real, imaginary and spin-orbital coupling. The deformed parameters are $\beta_{2}=0.21$, $\beta_{4}=0.0756$ for ${ }^{241} \mathrm{Am}$ and $\beta_{2}=0.218, \beta_{4}=0.046$ for ${ }^{242} \mathrm{Am}$, respectively.

Thirdly, based on the kernel calculation program: FUNF ${ }^{[5]}$, a code ADFP ${ }^{[6]}$ can be developed to automatically search an optimum set of fission parameters for first, second and third plateau, respectively. The parameters used in statistical theory are exciton model parameter $C K$, the multiplying factor $C_{\mathrm{EI}}, C_{\mathrm{in}}$ and $C_{2 \mathrm{n}}$ of height of giant resonance in $\sigma_{\mathrm{n}, \gamma}, \sigma_{\mathrm{n}, \mathrm{n}^{2}}$ and $\sigma_{\mathrm{n}, 2 \mathrm{n}}$ calculations, respectively, DGMA (a parameter for adjusting the value of direct $\sigma_{\mathrm{n}, \mathrm{r}}$ near $13 \sim 14 \mathrm{MeV}$ ); level density parameters $\mathrm{a}_{\mathrm{n}, \gamma}, \mathrm{a}_{\mathrm{n}, \mathrm{n}^{\prime}}, \mathrm{a}_{\mathrm{n}, 2 \mathrm{n}}$, and $\mathrm{a}_{\mathrm{n}, \mathrm{m}_{\mathrm{n}}}$, pair energy corrections $\Delta_{\mathrm{n}, \mathrm{r}}, \Delta_{\mathrm{n}, \mathrm{n}}, \Delta_{\mathrm{n}, \mathrm{f}}, \Delta_{\mathrm{n}, 2 \mathrm{n}}, \Delta_{\mathrm{n}, \mathrm{n} \mathrm{f}}, \Delta_{\mathrm{n}, 3 \mathrm{n}}$, and $\Delta_{\mathrm{n}, 2 \mathrm{nf}}$, the height of fission barrier $V_{\mathrm{f}}(1), V_{\mathrm{f}}(2)$ and $V_{\mathrm{f}}(3)$, the curvature parameter of fission barrier $\hbar \omega(1), \hbar \omega(2)$ and $\hbar \omega(3)$ and the multiplying factor of fission level density $c k_{t}(1), c k_{f}(2)$ and $c k_{f}(3)$ for first, second and third plateaus. And the optimum set of adjustable fission parameters is obtained with the code ADFP for ${ }^{241} \mathrm{Am}$ to make its $\sigma_{\mathrm{f}}, \sigma_{\mathrm{n}, \gamma}, \sigma_{\mathrm{n}, 2 \mathrm{n}}$ and $\sigma_{\mathrm{n}, 3 \mathrm{n}}$ in optimum accordance with experimental data. Because there are no experimental data for ${ }^{242} \mathrm{Am}$, the $\sigma_{\mathrm{f}}$ of ${ }^{242} \mathrm{Am}^{\mathrm{m}}$ in BNL-325 and its cross
sections in JENDL-3 library are taken as reference to get a reasonable set of fission parameters.

The final optimal parameters used in this work are: for ${ }^{241} \mathrm{Am}, C K=6000.0$, $C_{\mathrm{E} 1}=2.200, \quad C_{\mathrm{in}}=0.300, \quad C_{2 \mathrm{n}}=0.6206, \quad \mathrm{DGMA}=0.85, a_{\mathrm{n}, \mathrm{r}}=28.0844, \quad \Delta_{\mathrm{n}, \mathrm{y}}=0.9970$, $a_{\mathrm{n}, \mathrm{n}}=29.7294, \quad \Delta_{\mathrm{n}, \mathrm{n}}=0.8154, \quad \Delta_{\mathrm{n}, \mathrm{r}}=0.0075, \quad V_{\mathrm{f}}(1)=6.2050, \quad \hbar \omega(1)=0.5759, \quad c k_{\mathrm{f}}$ $(1)=12.3845$ for $\sigma_{n, f}$ in the first plateau, $a_{n, 2 n}=30.6509, \Delta_{\mathrm{n}, 2 \mathrm{n}}=-0.0152, \Delta_{\mathrm{n}, \mathrm{r}}=-0.0097$, $V_{\mathrm{f}}(2)=6.0384, \hbar \omega(2)=1.0912, c k_{\mathrm{f}}(2)=5.0681$ for $\sigma_{\mathrm{n}, \mathrm{n}^{\prime} \mathrm{f}}$ in the second plateau, $a_{\mathrm{n}, 3 \mathrm{n}}$ $=27.6601, \Delta_{\mathrm{n}, 3 \mathrm{n}}=-0.9151, \Delta_{\mathrm{n}, 2 \mathrm{nf}}=-0.2014, V_{\mathrm{f}}(3)=5.1405, \hbar \omega(3)=0.4542, c k_{\mathrm{f}}(3)=4.8358$ for $\sigma_{\mathrm{n}, 2 \mathrm{nf}}$ in the third plateau; for ${ }^{242} \mathrm{Am}, C K=6000.0, C_{\mathrm{El}}=3.4940, \quad C_{\mathrm{in}}=0.2597$, $C_{2 \mathrm{n}}=0.2166$, DGMA $=1.30, a_{\mathrm{n}, y}=26.4593, \Delta_{\mathrm{n}, \mathrm{y}}=1.7233, a_{\mathrm{n}, \mathrm{n}}=26.1314, \Delta_{\mathrm{n}, \mathrm{n}}=-0.0335$, $\Delta_{\mathrm{n}, \mathrm{f}}=0.1795, V_{\mathrm{f}}(1)=5.8942, \hbar \omega(1)=0.9811, c k_{\mathrm{f}}(1)=5.7226$ for $\sigma_{\mathrm{n}, \mathrm{f}}$ in the first plateau, $a_{\mathrm{n}, 2 \mathrm{n}}=26.3233, \quad \Delta_{\mathrm{n}, 2 \mathrm{n}}=0.7180, \quad \Delta_{\mathrm{n}, \mathrm{f} \mathrm{f}}=0.0501, \quad V_{\mathrm{f}}(2)=5.6760, \quad \hbar \omega(2)=1.1638$, $c k_{\mathrm{f}}(2)=4.5332$ for $\sigma_{\mathrm{n}, \mathrm{nf}}$ in the second plateau, $a_{\mathrm{n}, 3 \mathrm{n}}=27.6053, \Delta_{\mathrm{n}, 3 \mathrm{n}}=-0.9500$, $\Delta_{\mathrm{n}, 2 \mathrm{nf}}=0.0288, \quad V_{\mathrm{f}}(3)=5.6612, \hbar \omega(3)=0.8016, c k_{\mathrm{f}}(3)=2.7486$ for $\sigma_{\mathrm{n}, 2 \mathrm{nf}}$ in the third plateau.

All these fission parameters, direct inelastic scattering data and the optimum set of spherical optical potential parameters mentioned above are the input data of the program FUNF ${ }^{[5]}$, with which the whole sets of neutron data for ${ }^{241} \mathrm{Am}$ and ${ }^{242} \mathrm{Am}$ are calculated. The calculated results are given in ENDF/B-6 fornat.

## 2 Results and Discussions

The calculated $\sigma_{\text {tot }}, \sigma_{\text {non }}$ and $\sigma_{\mathrm{cl}}$ are given in Fig. 1(a) and Fig. 1(b), respectively, from which we can see that both the calculated $\sigma_{\text {tot }}$ of ${ }^{241} \mathrm{Am}$ and of ${ }^{242} \mathrm{Am}$ are in good accordance with the experimental data of ${ }^{241} \mathrm{Am}$ except near 13 MeV . The calculated $\sigma_{\mathrm{f}}$ and the experimental data of ${ }^{241} \mathrm{Am}$ are given in Fig. 2(a) and Fig. 2(b), from which we can see that the calculated $\sigma_{\mathrm{f}}$ are in very good accordance with the experimental data in $1.7 \sim 20 \mathrm{MeV}$ energy region, the calculated $\sigma_{\mathrm{f}}$ are obviously lower than experimental data in $0.9 \sim 1.7 \mathrm{MeV}$ and below 0.1 MeV energy regions, higher than experimental data in $0.3 \sim 0.8 \mathrm{MeV}$ energy region. ${ }^{241} \mathrm{Am}$ is one of few even neutron fission nuclei whose calculated $\sigma_{\mathrm{f}}$ are not in good accordance with the experimental data in lower energy region. The $\sigma_{\mathrm{f}}$ of ${ }^{242} \mathrm{Am}$ are 36
given in Fig. 2(c) and Fig. 2(d), from which we can see that both the calculated $\sigma_{\mathrm{f}}$ and those of JENDL-3 are in agreement with the experimental $\sigma_{f}$ of ${ }^{242} \mathrm{Am}^{m}$ from BNL-325. And there are obviously first, second and third plateau in our calculated $\sigma_{\mathrm{f}}$, but only first and second plateau in the $\sigma_{\mathrm{f}}$ of JENDL-3. The $\sigma_{\mathrm{n}, \gamma}$ of ${ }^{241} \mathrm{Am}$ and of ${ }^{242} \mathrm{Am}$ are given in Fig. 3(a) and Fig. 3(b), respectively. From Fig. 3(a) we can see that the calculated $\sigma_{\mathrm{n}, \mathrm{r}}$ of ${ }^{241} \mathrm{Am}$ are in very good agreement with the experimental data. And from Fig. 3(b) we can see that the calculated $\sigma_{\mathrm{n}, \mathrm{r}}$ of ${ }^{242} \mathrm{Am}$ and those of JENDL-3 are with little difference in lower energy region, but it seems that in higher energy region the calculated values are more reasonable than those of JENDL-3 both in shape and in values. The total ( $\mathrm{MT}=4$ ) and the continuous ( $\mathrm{MT}=91$ ) inelastic cross sections of ${ }^{241} \mathrm{Am}$ and ${ }^{242} \mathrm{Am}$ are given in Fig. 4(a) and Fig. 4(b), respectively, from which we can see that the calculated values are physically reasonable. Four ( $\mathrm{MT}=51,52,53,55$ ) of ${ }^{241} \mathrm{Am}$ and three $(53,56,58)$ of ${ }^{242} \mathrm{Am}$ discrete level inelastic cross sections included direct action component are given in Fig. 5(a) and Fig. 5(b), respectively, from which we can see that our calculated values are physically reasonable. And from Fig. 5(b) we can see that the discrete level inelastic cross sections of ${ }^{242} \mathrm{Am}$ from JENDL-3 do not include direct action component. In ${ }^{242} \mathrm{Am}$ data of JENDL-3 we did not find the level with same excited energy as our MT=53, so MT=53 of JENDL-3 is not included in Fig. 5(b). $\sigma_{n, 2 n}$ and $\sigma_{n, 3 \mathrm{n}}$ are given in Fig. 6(a) and Fig. 6(b), respectively, from which we can see that the calculated $\sigma_{\mathrm{n}, 2 \mathrm{n}}$ and $\sigma_{\mathrm{n}, 3 \mathrm{n}}$ are in good agreement with experimental data for ${ }^{241} \mathrm{Am}$, and the calculated values are physically reasonable for ${ }^{242} \mathrm{Am}$. All kinds of calculated cross sections of ${ }^{241} \mathrm{Am}$ and of ${ }^{242} \mathrm{Am}$ are given in Fig. 7(a) and Fig. 7(b), respectively, in which those with charged outgoing particles are directly calculated with the universal parameters. The calculated secondary neutron spectra of continuous inelastic (MT=91), (n,2n) reaction ( $\mathrm{MT}=16$ ) and fission $(\mathrm{MT}=18)$ at $E_{\mathrm{n}}=8$ and 14 MeV are given in Fig. 8(a), Fig. 8(b) and Fig. 8(c), respectively, from which we can see that the calculated values are physically reasonable. From Fig. 8(c) we can see that ${ }^{242} \mathrm{Am}$ are with almost the same fission spectra as ${ }^{241} \mathrm{Am}$ at same incoming neutron energy. As a matter of fact, the fission spectra of many different fission nuclei at same incoming neutron energy are always with very few differences.
${ }_{\infty}$


Fig.1(a) Total cross sections of ${ }^{241} \mathrm{Am}$ and ${ }^{242} \mathrm{Am}$


Fig.2(a) Fission cross sections of ${ }^{241} \mathrm{Am}$


Fig.1(b) Elastic and non-elastic cross sections of ${ }^{241} \mathrm{Am}$ and ${ }^{242} \mathrm{Am}$


Fig.2(b) Fission cross sections of ${ }^{241} \mathrm{Am}$


Fig.2(c) Fission cross sections of ${ }^{242} \mathrm{Am}$


Fig.3(a) Radiative capture cross sections of ${ }^{241} \mathrm{Am}$


Fig.2(d) Fission cross sections of ${ }^{242} \mathrm{Am}$


Fig.3(b) Radiative capture cross sections of ${ }^{242} \mathrm{Am}$

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Fig.4(a) Total inelastic(MT=4) cross sections of ${ }^{241} \mathrm{Am}$ and ${ }^{242} \mathrm{Am}$


Fig.5(a) Discrete level inelastic cross sections of ${ }^{241} \mathrm{Am}$


Fig.4(b) Continuous inelastic(MT=91) cross sections of ${ }^{241} \mathrm{Am}$ and ${ }^{242} \mathrm{Am}$


Fig.5(b) Discrete level inelastic cross sections of ${ }^{242} \mathrm{Am}$


Fig.6(a) ( $\mathrm{n}, 2 \mathrm{n}$ ) reaction cross sections of ${ }^{241} \mathrm{Am}$ and ${ }^{242} \mathrm{Am}$



Fig.6(b) ( $\mathrm{n}, 3 \mathrm{n}$ ) reaction cross sections of ${ }^{241} \mathrm{Am}$ and ${ }^{242} \mathrm{Am}$


Fig.7(b) All kinds of calculated cross sections of ${ }^{242} \mathrm{Am}$


Fig.8(a) Neutron spectra of continuous inelastic(MT=91) of ${ }^{241} \mathrm{Am}$ and ${ }^{242} \mathrm{Am}$


Fig.8(b) ( $n, 2 \mathrm{n}$ ) outgoing neutron spectra of ${ }^{241} \mathrm{Am}$ and ${ }^{242} \mathrm{Am}$


Fig.8(c) Fission( $\mathrm{MT}=18$ ) neutron spectra of ${ }^{241} \mathrm{Am}$ and ${ }^{242} \mathrm{Am}$

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# Calculations of $n+{ }^{144,147-152,154} \mathrm{Sm}$ Reactions in the Energy Region up to 20 MeV 

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The element samarium ( Sm ) is one of the important fission product nuclei. The natural samarium consists of 7 isotopes, ${ }^{144} \mathrm{Sm}(3.07 \%),{ }^{147} \mathrm{Sm}(14.99 \%),{ }^{148} \mathrm{Sm}$ (11.24\%), ${ }^{149} \mathrm{Sm}(13.82 \%),{ }^{150} \mathrm{Sm}(7.38 \%),{ }^{152} \mathrm{Sm}(26.75 \%),{ }^{154} \mathrm{Sm}$ (22.75). The evaluated neutron nuclear data in the energy region up to 20 MeV of the various samarium isotopes including some unstable nuclei (such as ${ }^{151} \mathrm{Sm}$ ) are useful in the design of the nuclear engineering.

There are some experimental data of total, ( $\mathrm{n}, \gamma$ ), $(\mathrm{n}, 2 \mathrm{n}),(\mathrm{n}, \mathrm{p}),(\mathrm{n}, \alpha)$ cross sections and elastic scattering distributions for even nuclei ${ }^{144} \mathrm{Sm},{ }^{148} \mathrm{Sm},{ }^{150} \mathrm{Sm},{ }^{152} \mathrm{Sm}$, and ${ }^{154} \mathrm{Sm}$ in the energy region up to 20 MeV . But there are only some experimental data of ( $\mathrm{n}, \gamma$ ) cross sections for odd nuclei ${ }^{147} \mathrm{Sm}$ and ${ }^{149} \mathrm{Sm}$. All the experimental data are taken from EXFOR library.

Firstly, the code APMN ${ }^{[1]}$ is used to automatically get the optimal optical potential parameters for neutron channel based on various neutron experimental data. The optical potential forms are as follows:

$$
\begin{align*}
& V=V_{0}+V_{1} E_{\mathrm{n}}+V_{2} E_{\mathrm{n}}^{2}+V_{3}(N-Z) / A+V_{4} Z / A^{1 / 3}  \tag{1}\\
& W_{\mathrm{s}}=\max \left\{0, W_{0}+W_{1} E_{\mathrm{n}}+W_{2}(N-Z / A\},\right.  \tag{2}\\
& W_{\mathrm{v}}=\max \left\{0, U_{0}+U_{1} E_{\mathrm{n}}+U_{2} E_{\mathrm{n}}^{2}\right\}, \tag{3}
\end{align*}
$$

where $E_{\mathrm{n}}$ is the incident neutron energy and $Z, N, A$ are the number of proton, neutron, mass of the target nucleus, respectively. The obtained optical potential parameters for ${ }^{144} \mathrm{Sm},{ }^{148} \mathrm{Sm},{ }^{150} \mathrm{Sm},{ }^{152} \mathrm{Sm}$ and ${ }^{154} \mathrm{Sm},{ }^{147} \mathrm{Sm}$ and ${ }^{149} \mathrm{Sm}$ are listed in Table 1. The optical potential parameters for the unstable nucleus ${ }^{151} \mathrm{Sm}$ are taken as the same with isotopes ${ }^{147} \mathrm{Sm}$ and ${ }^{149} \mathrm{Sm}$. The spin-obit potential parameters are taken as: $V_{\mathrm{so}}=6.2, r_{\mathrm{so}}=r_{\mathrm{r}}, a_{\mathrm{so}}=a_{\mathrm{r}}$.

Table 1 The obtained optical potential parameters of various isotopes of element samarium

| Isotope | ${ }^{144} \mathrm{Sm}$ | ${ }^{148} \mathrm{Sm}$ | ${ }^{150} \mathrm{Sm}$ | ${ }^{152,154} \mathrm{Sm}$ | ${ }^{1177,{ }^{149},{ }^{151} \mathrm{Sm}}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $V_{0}$ | 53.2885 | 53.4108 | 52.8947 | 52.9032 | 52.9445 |
| $V_{1}$ | -0.3421 | -0.3790 | -0.3975 | -0.3477 | 0.02402 |
| $V_{2}$ | 0.01968 | 0.01545 | 0.01598 | -.00111 | -.01325 |
| $V_{3}$ | -37.009 | -34.263 | -20.453 | -19.993 | -39.677 |
| $V_{4}$ | 0.05867 | 0.06739 | 0.03082 | 0.03053 | 0.03518 |
| $r_{\mathrm{r}}$ | 1.20788 | 1.20796 | 1.17561 | 1.17528 | 1.20503 |
| $a_{\mathrm{r}}$ | 0.68699 | 0.69095 | 0.70815 | 0.70874 | 0.58695 |
| $W_{0}$ | 9.30168 | 9.48175 | 9.69651 | 9.87603 | 7.33324 |
| $W_{1}$ | -0.6054 | -0.5524 | -0.4381 | -0.4375 | -0.3486 |
| $W_{2}$ | 0.79336 | -1.1226 | -8.1457 | -9.8232 | -7.8269 |
| $r_{\mathrm{s}}$ | 1.32142 | 1.31177 | 1.33742 | 1.29474 | 1.32188 |
| $a_{\mathrm{s}}$ | 0.58067 | 0.56540 | 0.56788 | 0.59070 | 0.79076 |
| $U_{0}$ | -1.1667 | -1.0739 | -0.9753 | -0.9534 | -0.8648 |
| $U_{1}$ | 0.15077 | 0.14938 | 0.14808 | 0.15621 | 0.15 |
| $U_{2}$ | 0.01229 | 0.01014 | .009366 | 0.016 | 0.004 |
| $r_{\mathrm{r}}$ | 1.62244 | 1.56056 | 1.58102 | 1.58665 | 1.68997 |
| $a_{v}$ | 0.2900 | 0.2900 | 0.33313 | 0.31447 | 0.37786 |

Then the code DWUCK $4^{[2]}$ is used to calculate the direct inelastic scattering cross sections and angular distributions. The main code SUNF ${ }^{[3]}$ is used to calculate the various data. In this calculations the Gilbert-Cameron level density formula ${ }^{[4]}$ is applied. Through fitting the experimental data the obtained level density parameters for ( $\mathrm{n}, \gamma),\left(\mathrm{n}, \mathrm{n}^{\prime}\right),(\mathrm{n}, 2 \mathrm{n}),(\mathrm{n}, 3 \mathrm{n}),(\mathrm{n}, \mathrm{p}),(\mathrm{n}, \alpha)$ channels are listed in Table 2. The exciton model constant $K$ used in this work are given in Table 3.

Table 2 The obtained level density parameters of various isotopes of element samarium

| Isotope | ${ }^{1+4} \mathrm{Sm}$ | ${ }^{147} \mathrm{Sm}$ | ${ }^{148} \mathrm{Sm}$ | ${ }^{159} \mathrm{Sm}$ | ${ }^{150} \mathrm{Sm}$ | ${ }^{15} \mathrm{Sm}$ | ${ }^{152} \mathrm{Sm}$ | ${ }^{155} \mathrm{Sm}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\cdot(\mathrm{n}, \gamma)$ | 11.595 | 17.369 | 18.882 | 19.942 | 22.789 | 19.108 | 22.049 | 19.449 |
| $(\mathrm{n}, \mathrm{n})$, | 11.382 | 18.099 | 21.344 | 23.282 | 19.372 | 23.189 | 20.638 | 20.282 |
| $(\mathrm{n}, 2 \mathrm{n})$ | 7.828 | 13.820 | 28.099 | 21.344 | 16.782 | 24.072 | 17.189 | 24.349 |
| $(\mathrm{n}, 3 \mathrm{n})$ | 23.127 | 19.595 | 14.820 | 22.099 | 14.344 | 23.282 | 14.372 | 17.338 |
| $(\mathrm{n}, \mathrm{p})$ | 12.433 | 20.146 | 22.071 | 23.655 | 23.953 | 18.940 | 23.470 | 22.627 |
| $(\mathrm{n}, \alpha)$ | 15.148 | 8.216 | 21.343 | 13.141 | 21.508 | 21.089 | 23.374 | 22.890 |

Table 3 The exciton model constant $K$ of various isotopes of element samarium

| Isotope | ${ }^{144} \mathrm{Sm}$ | ${ }^{1+7} \mathrm{Sm}$ | ${ }^{1+8} \mathrm{Sm}$ | ${ }^{1+9} \mathrm{Sm}$ | ${ }^{150} \mathrm{Sm}$ | ${ }^{151} \mathrm{Sm}$ | ${ }^{152} \mathrm{Sm}$ | ${ }^{154} \mathrm{Sm}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $K / \mathrm{MeV}^{3}$ | 2980 | 600 | 600 | 950 | 600 | 1000 | 600 | 600 |

Finally, through adjusting of some other parameters of level density and charged particle optical potential, various calculated cross sections are in good agreement with the experimental data and some systematic rules of the calculated data are obtained.

Figs. 1(a) $\sim(\mathrm{e})$ show the comparisons of the neutron total cross sections between the calculated values and the experimental data in the energy region up to 20 MeV for $\mathrm{n}+{ }^{147,148,150,152,154} \mathrm{Sm}$ reactions, for ${ }^{147} \mathrm{Sm}$ the experimental data are mainly taken from the natural samarium. The theoretical values are in good agreement with the experimental data. Figs. 2(a)~(c) show the comparisons of the calculated and experimental elastic scattering angular distributions for ${ }^{148,150,152} \mathrm{Sm}$ at 3 incident energies. The calculated results are also in good agreement with the experimental data. Figs. 3(a)~(f) show that the calculated ( $\mathrm{n}, \gamma$ ) cross sections for ${ }^{147 \cdot 150,152.154} \mathrm{Sm}$ are
basically in agreement with the experimental data. Obviously, the ( $\mathrm{n}, \gamma$ ) cross sections of the odd nuclei are higher than that of even nuclei at low energy region. Figs. 4 (a) $\sim(\mathrm{f})$ give the comparisons of the calculated and experimental ( $\mathrm{n}, 2 \mathrm{n}$ ) and $(\mathrm{n}, 3 \mathrm{n})$ cross sections of ${ }^{144,148,15,151,152,154} \mathrm{Sm}$. They are in good agreement with each other. In Fig. 4(d) the calculated (n,3n) cross sections of ${ }^{151} \mathrm{Sm}$ are compared with the $(\mathrm{n}, 3 \mathrm{n})$ experimental data of the neighbored nucleus ${ }^{151} \mathrm{Eu}$. From this figure one can see that the ( $\mathrm{n}, 3 \mathrm{n}$ ) cross sections for different isotopes become larger as the isotope mass A increases. The comparisons of the calculated and experimental ( $\mathrm{n}, \mathrm{p}$ ) cross sections of ${ }^{144,148,150,154} \mathrm{Sm}$ are given in Figs. 5(a) $\sim$ (d), respectively. The calculated $(\mathrm{n}, \mathrm{p})$ cross sections for different isotopes become smaller as the isotope mass A increases and some experimental data are not suitable. Figs. 6(a) $\sim(\mathrm{d})$ show the comparisons of the calculated and experimental ( $\mathrm{n}, \alpha$ ) cross sections for ${ }^{144,150,152,154} \mathrm{Sm}$. Similarly, the calculated ( $\mathrm{n}, \alpha$ ) cross sections for different isotopes become smaller as the isotope mass A increases and some experimental data are not suitable. The calculated ( $\mathrm{n}, \alpha$ ) cross sections of ${ }^{147,199} \mathrm{Sm}$ in $0.01 \sim 0.2 \mathrm{MeV}$ energy region are in good agreement with the experimental data. The calculated ( $\mathrm{n}, \mathrm{d}$ ) cross section of ${ }^{154} \mathrm{Sm}$ at 14.54 MeV is in agreement with the measured value. The theoretical values of inelastic scattering cross sections are also reasonable.

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Fig. 1(a) Comparison of neution total cross sections of ${ }^{147} \mathrm{Sm}$ between the calculated values and the experimental data.


Fig.1(c) The same as Fig.1(a) but for ${ }^{150} \mathrm{Sm}$.


Fig.1(b) The same as Fig. 1(a) but for ${ }^{148} \mathrm{Sm}$.


Fig.1(d) The same as Fig.1(a) but for ${ }^{152} \mathrm{Sm}$.
${ }_{\infty}^{\infty}$


Fig.1(e) The same as Fig.1(a) but for ${ }^{154} \mathrm{Sm}$.


Fig.2(b) The same as Fig.2(a) but for ${ }^{150} \mathrm{Sm}$.


Fig.2(a) Comparison of neutron elastic scattering angular distributions of ${ }^{148} \mathrm{Sm}$ between the calculated values and the experimental data.


Fig.2(c) The same as Fig.2(a) but for ${ }^{152} \mathrm{Sm}$.


Fig.3(a) Comparison of ( $n, \gamma$ ) cross sections of ${ }^{147} \mathrm{Sm}$ between the calculated values and the experimental data.


Fig.3(c) The same as Fig.3(a) but for ${ }^{149} \mathrm{Sm}$.


Fig.3(b) The same as Fig.3(a) but for ${ }^{148} \mathrm{Sm}$.


Fig.3(d) The same as Fig.3(a) but for ${ }^{150} \mathrm{Sm}$.


Fig.3(e) The same as Fig.3(a) but for ${ }^{152}$ Sm.


Fig.4(a) Comparison of ( $n, 2 n$ ) and ( $n, 3 n$ ) cross sections of ${ }^{144} \mathrm{Sm}$ between the calculated values and the experimental data.


Fig.3(f) The same as Fig.3(a) but for ${ }^{154} \mathrm{Sm}$.


Fig.4(b) The same as Fig.4(a) but for ${ }^{188} \mathrm{Sm}$.


Fig.4(c) The same as Fig.4(a) but for ${ }^{150} \mathrm{Sm}$.


Fig.4(e) The same as Fig.4(a) but for ${ }^{152} \mathrm{Sm}$.


Fig.4(d) The same as Fig.4(a) but for ${ }^{151} \mathrm{Sm}$.


Fig.4(f) The same as Fig.4(a) but for ${ }^{154} \mathrm{Sm}$.


Fig.5(a) Comparison of ( $\mathrm{n}, \mathrm{p}$ ) cross sections of ${ }^{144} \mathrm{Sm}$ between the calculated values and the experimental data.


Fig.5(c) The same as Fig.5(a) but for ${ }^{150} \mathrm{Sm}$.


Fig.5(b) The same as Fig.5(a) but for ${ }^{148} \mathrm{Sm}$.


Fig.5(d) The same as Fig.5(a) but for ${ }^{154} \mathrm{Sm}$.


Fig.6(a) Comparison of ( $\mathrm{n}, \alpha$ ) cross sections of ${ }^{144} \mathrm{Sm}$ between the calculated values and the experimental data.


Fig.6(c) The same as Fig.6(a) but for ${ }^{152} \mathrm{Sm}$.


Fig.6(b) The same as Fig.6(a) but for ${ }^{150}$ Sm.


Fig.6(d) The same as Fig.6(a) but for ${ }^{154} \mathrm{Sm}$.


# Calculations of All Kinds of Reactions for $\mathrm{n}+{ }^{241} \mathrm{Pu}$ in $\boldsymbol{E}_{\mathrm{n}}=\mathbf{0 . 0 1} \sim 20 \mathrm{MeV}$ 

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${ }^{241} \mathrm{Pu}$ are an important fissile nucleus for fast neutron reactor in ${ }^{239} \mathrm{Pu}-{ }^{238} \mathrm{U}$ recurrence, good evaluation values of its neutron reaction data are necessary. There are sufficient experimental data for $\sigma_{\mathrm{f}}$, some experimental data below 0.03 MeV for $\sigma_{\mathrm{n}, r}$. There are no experimental data for other reaction cross sections, secondary neutron spectra and elastic scattering angular distributions. All experimental data are taken from EXFOR. Therefore, we have to do systematical theoretical calculations to get a complete neutron data set of ${ }^{241} \mathrm{Pu}$.

Firstly, the code CAPFO ${ }^{[1]}$ is used to automatically get the optimal parameters of spherical optical potential. There are no experimental data for total and nonelastic cross sections as well as elastic scattering angular distributions of ${ }^{241} \mathrm{Pu}$. From the consideration of systematics, $\sigma_{\text {tot }}$ of ${ }^{241} \mathrm{Pu}$ and ${ }^{239} \mathrm{Pu}$ should be almost the same. And the evaluation values of $\sigma_{\mathrm{f}}$ for ${ }^{241} \mathrm{Pu}$ in ENDF/B6 library are in very good agreement with the newest experimental data. So the $\sigma_{\text {tot }}$ of ${ }^{239} \mathrm{Pu}$ and $\sigma_{\text {non }}$ of ${ }^{241} \mathrm{Pu}$ in ENDF/B-6 library are used in automatically searching for the optimal set of spherical optical potential parameters. In this way, the final optimum set of spherical optical potential parameters for neutron channel is obtained:

$$
\begin{array}{lll}
V_{0}=46.408570, & V_{1}=-0.471376, & V_{2}=0.063832, \\
W_{0}=10.620060, & W_{1}=0.178786, & \\
U_{0}=0.016819, & U_{1}=0.328978, & U_{2}=-0.029545, \\
a_{\mathrm{r}}=0.450434, & a_{\mathrm{s}}=0.620025, & a_{\mathrm{v}}=0.551695, \\
r_{\mathrm{r}}=1.325580, & r_{\mathrm{s}}=1.137591, & \mathrm{r}_{\mathrm{v}}=1.211296 .
\end{array}
$$

Secondarily, the coupled channel optical model code ECIS ${ }^{[2]}$ is used to calculate the cross sections and angular distributions of 4 lower levels in direct inelastic scattering. The ground state and these 4 excited states in the rotational band are with excited energies $0.0,0.0420,0.0957,0.1611$ and 0.2350 MeV , spins $2.5,3.5,4.5,5.5$ and 6.5 , parity +1 . The coupled channel optical potential parameters ${ }^{[3]}$ used in this work are: Real part potential: 51.32134-0.57E+0.02E2-24(N-Z)/A; Surface absorption imaginary part potential: $5.04567+0.4 E+0.001 E^{2}$; Volume absorption imaginary part potential: 0.0 ; Spin-orbital coupling potential: 6.0; Radial parameters are $1.256,1.260$ and 1.120 for real, imaginary and spin-orbital coupling, respectively; Diffusion parameters are $0.62,0.58$ and 0.50 for real, imaginary and spin-orbital coupling, respectively. The deformed parameters are $\beta_{2}=0.22, \beta_{4}=0.07$.

These direct inelastic scattering data obtained with the code ECIS and the optimum set of spherical optical potential parameters obtained with the code CAPFO are the input of the kernel calculation program FUNF ${ }^{[4]}$. Besides these two kinds of input data, for correct calculations of the complete neutron data set with FUNF, it is also necessary to find out the optimum fission parameters. With the code ADFP ${ }^{[5]}$, which can automatically search for an optimum set of fission parameters for first, second and third plateau, respectively, we can obtain the optimum set of adjustable fission parameters to make $\sigma_{\mathrm{f}}$ and $\sigma_{\mathrm{n}, \mathrm{y}}$ in optimum accordance with experimental data. The meaning of these fission parameters can be found in Reference [6].

The optimal fission parameters we got are: $C K=6000.0, C_{\mathrm{E1}}=1.9716$, $C_{\text {in }}=0.2255, C_{2 \mathrm{n}}=0.3450$, DGMA $=0.6 ; a_{\mathrm{n}, \mathrm{r}}=26.4005, \Delta_{\mathrm{n}, \mathrm{y}}=1.6462, a_{\mathrm{n}, \mathrm{n}}=27.4575$, $\Delta_{\mathrm{n}, \mathrm{n}}=0.1584, \Delta_{\mathrm{n}, \mathrm{f}}=0.1837, V_{\mathrm{f}}(1)=6.1324, \hbar \omega(1)=0.9870, c k_{\mathrm{f}}(1)=5.7988$ for $\sigma_{\mathrm{n}, \mathrm{f}}$ in the first plateau; $a_{\mathrm{n}, 2 \mathrm{n}}=26.2308, \Delta_{\mathrm{n}, 2 \mathrm{n}}=0.7471, \Delta_{\mathrm{n}, \mathrm{n} \mathrm{f}}=0.0654, V_{\mathrm{f}}(2)=5.8944, \hbar \omega(2)=1.1348$, $c k_{\mathrm{f}}(2)=4.4019$ for $\sigma_{\mathrm{n}, \mathrm{nf}}$ in the second plateau; $a_{\mathrm{n}, 3 \mathrm{n}}=26.9673, \Delta_{\mathrm{n}, 2 \mathrm{n}}=-0.7801$, $\Delta_{\mathrm{n}, \mathrm{2nf}}=0.0331, V_{\mathrm{f}}(3)=5.5369, \hbar \omega(3)=0.7920, c k_{\mathrm{f}}(3)=3.0882$ for $\sigma_{\mathrm{n}, 2 \mathrm{nf}}$ in the third plateau.

The calculated $\sigma_{\text {tot }}, \sigma_{\mathrm{el}}$ and those from ENDF/B-6 library for ${ }^{241} \mathrm{Pu}$ as well as experimental $\sigma_{\text {tot }}$ of ${ }^{239} \mathrm{Pu}$ are given in Fig. 1, respectively, from which we can see that both the calculated $\sigma_{\text {tot }}$ and those in ENDF/B-6 are in good accordance with the experimental $\sigma_{\text {tot }}$ of ${ }^{239} \mathrm{Pu}$, as they should be.


Fig. 1 Total and elastic cross sections of ${ }^{241} \mathrm{Pu}$

For the calculated values, ENDF/B-6 and experimental data of $\sigma_{\mathrm{f}}$ are given in Fig. 2(a) and Fig. 2(b). Our calculated $\sigma_{\mathrm{f}}$ are in good agreement with the experimental data except a little worse in $0.24 \sim 0.4 \mathrm{MeV}$ and $1.6 \sim 5.0 \mathrm{MeV}$ energy region. The calculated and experimental $\sigma_{\mathrm{n}, \mathrm{y}}$ are given in Fig. 3, from which we can think both our calculated values and those of ENDF/B-6 are in good agreement with the experimental data, and in higher energy region our calculated $\sigma_{\mathrm{n}, \mathrm{y}}$ are more reasonable than those of ENDF/B-6 both in shape and in value. The total (MT=4) and the continuous (MT=91) inelastic cross sections are given in Fig. 4 (a) and Fig. 4(b), respectively, from which we can see that our calculated values are more reasonable than those of ENDF/B-6 in shape. Two calculated discrete level inelastic cross sections ( $\mathrm{MT}=51,52$ ) included direct action component are given in Fig. 5, from which we can see that the MT=51,52 cross sections of ENDF/B-6 does not include direct action component, and we can not understand why those of MT=51,52 suddenly drop to zero at $3 \mathrm{MeV} . \sigma_{\mathrm{n}, 2 \mathrm{n}}$ and $\sigma_{\mathrm{n}, 3 \mathrm{n}}$ are given in Fig. 6(a) and Fig. 6(b), respectively, from which we can see that our calculated $\sigma_{\mathrm{n}, 2 \mathrm{n}}$ are better than those of ENDF/B-6 in shape, and for $\sigma_{n, 3 n}$, ENDF/B-6 are not reasonable in shape, our calculated values are also a little better than JENDL-3 in shape. All kinds of calculated cross sections of ${ }^{241} \mathrm{Pu}$ are given in Fig. 7, in which those with charged outgoing particles, are directly calculated with the universal parameters. The calculated secondary neutron spectra of continuous inelastic (MT=91), (n,2n) reaction ( $\mathrm{MT}=16$ ) and fission ( $\mathrm{MT}=18$ ) at $E_{\mathrm{n}}=8$ and 14 MeV are given in Fig. 8(a), Fig. 8(b) and Fig. 8(c), respectively, from which we can see that our calculated values are physically reasonable.


Fig. 2(a) Fisson cross sections of ${ }^{241} \mathrm{Pu}$


Fig. 3 Radiative capture cross sections of ${ }^{241} \mathrm{Pu}$


Fig. 2(b) Fisson cross sections of ${ }^{241} \mathrm{Pu}$


Fig. 4(a) Total inelastic $(M T=4)$ cross sections of ${ }^{241} \mathrm{Pu}$

4


Fig. 4(b) Continuous inelastic(MT=91) cross sections of ${ }^{241} \mathrm{Pu}$


Fig. 6(a) (n,2n) reaction cross sections of ${ }^{241} \mathrm{Pu}$


Fig. 5 Discrete level inelastic cross sections of ${ }^{241} \mathrm{Pu}$


Fig. 6(b) ( $\mathrm{n}, 3 \mathrm{n}$ ) reaction cross sections of ${ }^{241} \mathrm{Pu}$


Fig. 7 All kinds of calculated cross sections of ${ }^{244} \mathrm{Pu}$


Fig. 8(b) $\quad(\mathrm{n}, 2 \mathrm{n})(\mathrm{MT}=16)$ outgoing neutron spectra of ${ }^{241} \mathrm{Pu}$


Fig. 8(a) Neutron spectra of continuous inelastic(MT=91) of ${ }^{241} \mathrm{Pt}$


Fig. 8(c) Fisson ( $\mathrm{MT}=18$ ) neutron spectra of ${ }^{241} \mathrm{Pu}$

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# Calculations of Complete Set of Data for $\mathrm{n}+{ }^{242} \mathrm{Pu}$ Reaction up to 20 MeV 

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${ }^{242} \mathrm{Pu}$ is an important fission nucleus. There are quite a lot experimental data for $\sigma_{\mathrm{n}, \mathrm{F}}$ and some experimental data for $\sigma_{\mathrm{to}}, \sigma_{\mathrm{n} .}$ and elastic scattering angular
distributions. All the experimental data are taken from EXFOR library.
The optimal optical potential parameters for neutron channel are automatically obtained by the code APFO96 ${ }^{[1]}$ based on various experimental data. The obtained optimal neutron optical potential parameters in energy region up to 20 MeV are as follows:

$$
\begin{align*}
& V=49.6401-0.7378 E_{\mathrm{n}}+0.04316 E_{\mathrm{n}}^{2}-24(N-Z) / A  \tag{1}\\
& W_{\mathrm{s}}=4.459+0.2464 E_{\mathrm{n}}-12(N-Z) / A  \tag{2}\\
& W_{\mathrm{v}}=1.1246+0.995 E_{\mathrm{n}}-0.2631 E_{\mathrm{n}}^{2}  \tag{3}\\
& V_{\mathrm{so}}=6.2  \tag{4}\\
& r_{\mathrm{r}}=1.2676, \quad r_{\mathrm{s}}=1.3610, \quad r_{\mathrm{v}}=1.3182, \quad r_{\mathrm{so}}=1.2676  \tag{5}\\
& a_{\mathrm{r}}=0.5359, \quad a_{\mathrm{s}}=0.7184, \quad a_{\mathrm{v}}=0.2900, \quad a_{\mathrm{so}}=0.5359 \tag{6}
\end{align*}
$$

where $E_{\mathrm{n}}$ is incident neutron energy in laboratory system and $Z, N, A$ are proton, neutron, mass number of the target nucleus.

The direct inelastic scattering cross sections and angular distributions for 5 excited states belong to ground state rotational band $\left(2^{+}, 4^{+}, 6^{+}, 8^{+}, 10^{+}\right)$were calculated by coupled channel optical model code ECIS95 ${ }^{[2]}$. The coupled channel optical model parameters used are as follows ${ }^{[3]}$ :

$$
\begin{align*}
& V=51.32134-0.57 E_{\mathrm{n}}+0.02 E_{\mathrm{n}}^{2}-24(N-Z) / A  \tag{7}\\
& W_{\mathrm{s}}=5.04567+0.4 E_{\mathrm{n}}+0.001 E_{\mathrm{n}}^{2}  \tag{8}\\
& W_{\mathrm{v}}=0  \tag{9}\\
& V_{\mathrm{so}}=6.0  \tag{10}\\
& r_{\mathrm{r}}=1.256, \quad r_{\mathrm{s}}=1.26, \quad r_{\mathrm{so}}=1.12  \tag{11}\\
& a_{\mathrm{r}}=0.62, \quad a_{\mathrm{s}}=0.58, \quad a_{\mathrm{so}}=0.5  \tag{12}\\
& \beta_{2}=0.218, \quad \beta_{4}=0.046 \tag{13}
\end{align*}
$$

The FUNF ${ }^{[4]}$ is used as the key code in the calculation. The main statistical theory parameters obtained by code $\mathrm{ADFP}^{[5]}$ are as follows:

|  | $(\mathrm{n}, \gamma)$ | $(\mathrm{n}, \mathrm{f})$ | $\left(\mathrm{n}, \mathrm{n}^{\prime}\right)$ | $\left(\mathrm{n}, \mathrm{n}^{\prime} \mathrm{f}\right)$ | $(\mathrm{n}, 2 \mathrm{n})$ | $(\mathrm{n}, 2 \mathrm{nf})$ | $(\mathrm{n}, 3 \mathrm{n})$ |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Level density $(a):$ | 25.0814 | 26.0881 | 24.1178 | 24.1400 | 23.3416 | 26.6445 | 27.7481 |
| Pair correction $(\Delta):$ | 0.4768 | -0.0907 | 0.3367 | -0.2494 | -0.2430 | -0.1168 | -0.1814 |
| Fission barrier $\left(V_{\mathrm{f}}\right)$ : |  | 5.6432 |  | 6.7197 |  | 5.9301 |  |
| Fission curvature $(\hbar \omega)$ : |  | 0.5440 |  | 1.0000 |  | 0.7904 |  |
| Saddle level density factor $\left(K_{1}\right):$ | 3.173 |  | 2.477 |  | 1.0001 |  |  |


| Exciton model parameter: | $C K=4473.9$ |
| :--- | :--- |
| $(\mathrm{n}, \gamma)$ factor: | $C_{\mathrm{E},}=0.4715$ |
| Direct $(\mathrm{n}, \gamma)$ factor: | $\mathrm{DGMA}=0.34$ |

The calculated $\sigma_{\text {tot }}$ and those given in ENDF/B-6 and JENDL-3 libraries as well as its experimental data are given in Fig. 1, from which we can see that our calculated values are in good agreement with the experimental data. Figs. 2(a)~(c) show the comparisons of the elastic scattering angular distributions between the calculated results and the experimental data for incident energies $0.57,1.0,1.5 \mathrm{MeV}$, respectively. They are in better agreement with each other. Fig. 3 presents the comparison of the $\sigma_{\mathrm{n}, \mathrm{F}}$ between the calculated results and the experimental data, the agreement with each other is better. The comparison of $\sigma_{\mathrm{n}, \gamma}$ between our calculated values, the values in ENDFB6 and JENDL3 libraries, and the experimental data is shown in Fig. 4, they are in better agreement with each other. In high energy region our calculated $\sigma_{n, \gamma}$ are more reasonable since they are more closed to the experimental data of ( $n, \gamma$ ) cross sections of other fission nuclei . Figs. 5,6,7 show the comparisons between our calculated values and those of ENDF/B-6 and JENDL-3 libraries for ( $n, i n l$ ), ( $n, 2 n$ ), and ( $n, 3 n$ ), respectively. They are comparable with each other. But our calculated ( $\mathrm{n}, 2 \mathrm{n}$ ) cross section above 16 MeV is too high and unreasonable, it should be improved in the future. Fig. 8 shows the calculated inelastic scattering excitation functions of 5 discrete levels (their excited energies are $0.04454,0.1473,0.3064,0.5181,0.7787 \mathrm{MeV}$ ) by statistical theory and coupled channel theory. Figs. 9 and 10 are the comparisons between our calculated values and those of ENDF/B-6 and JENDL-3 libraries of the first and second excited states, they are comparable with each other.

The authors would like to thank Prof. Zhang Jingshang for his helpful discussions.


Fig. $1 \quad{ }^{242} \mathrm{Pu}$ total cross sections


Fig.2(b) ${ }^{242} \mathrm{Pu}$ elastic scattering angular distributions for $E_{\mathrm{n}}=1.0 \mathrm{MeV}$


Fig.2(a) ${ }^{242} \mathrm{Pu}$ elastic scattering angular distributions for $E_{\mathrm{n}}=0.57 \mathrm{MeV}$


Fig.2(c) ${ }^{242} \mathrm{Pu}$ elastic scattering angular distributions for $E_{\mathrm{n}}=1.5 \mathrm{MeV}$

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Fig. $3{ }^{242} \mathrm{Pu}$ fission cross sections


Fig. $5 \quad{ }^{242} \mathrm{Pu}$ (n,inl) cross sections


Fig. $4{ }^{242} \mathrm{Pu}(\mathrm{n}, \gamma)$ cross sections


Fig. $6{ }^{242} \mathrm{Pu}(\mathrm{n}, 2 \mathrm{n})$ cross sections


Fig. $7 \quad{ }^{242} \mathrm{Pu}(\mathrm{n}, 3 \mathrm{n})$ cross sections


Fig. $9{ }^{242} \mathrm{Pu}$ first excited state inelastic scattering cross sections


Fig. $8 \quad{ }^{242} \mathrm{Pu}$ discrete level inelastic scattering cross sections


Fig. $10 \quad{ }^{242} \mathrm{Pu}$ second excited state inelastic scattering cross sections

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# Comprehensive Calculations of Neutron Data for Reactions of $n+{ }^{237} \mathrm{~Np}$ in $E_{\mathrm{n}}=0.01 \sim 20 \mathrm{MeV}$ 

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${ }^{237} \mathrm{~Np}$ is an important nucleus in application. However, there are sufficient experimental data only for $\sigma_{f}$ (below 10 MeV ) and $\sigma_{\mathrm{n}, \mathrm{\gamma}}$, some experimental data for $\sigma_{n, 2 n}$. There are no experimental data for all other reaction cross sections, secondary neutron spectra and elastic scattering angular distributions. Therefore, in order to obtain a complete set of neutron data, comprehensive theoretical calculation is necessary.

## 1 Optical Potential Parameters

Because there are no experimental data of the total, nonelastic cross sections and elastic scattering angular distributions for ${ }^{237} \mathrm{~Np}$, its data of ENDF/B-6 are used
as reference to adjust the optical potential parameters for neutron channel with the code CAPFO ${ }^{[1]}$. The final optimum set of optical potential parameters we obtained is

$$
\begin{array}{lcc}
V_{0}=49.14486, & V_{1}=-0.04022, & V_{2}=-0.01523, \\
W_{0}=9.20597, & W_{1}=0.03729, & \\
U_{0}=0.13511, & U_{1}=0.29322, & U_{2}=-0.00868, \\
a_{\mathrm{r}}=0.56509, & a_{\mathrm{s}}=0.59167, & a_{\mathrm{v}}=0.59142, \\
r_{\mathrm{r}}=1.27785, & r_{\mathrm{s}}=1.12218, & r_{\mathrm{v}}=1.22169 .
\end{array}
$$

## 2 Direct Inelastic Scattering

For direct inelastic scattering, the coupled channel optical model code $\mathrm{CUC}^{[2]}$ is used to calculate the cross sections and angular distributions of 3 lower levels in the rotational band. The excited energies are $0.0,0.0332,0.0759$ and 0.1300 MeV , spins are $2.5,3.5,4.5$ and 5.5 for the ground state and these 3 excited states, respectively, and the parity is +1 for all of them.

## 3 The Optimum Fission Parameters

In order to get an optimal set of fission parameters, based on the kernel calculation program $\mathrm{FUNF}^{[3]}$, we wrote a code $\mathrm{ADFP}^{[4]}$ which can automatically search for an optimum set of fission parameters for first, second and third plateau, respectively. The parameters used in statistical theory calculation are: exciton model parameter $C K$, the multiplying factor $C_{\mathrm{E} 1}$ of height of giant resonance in $\sigma_{\mathrm{n}, \mathrm{r}}$ calculation, DGMA(a parameter for adjusting the value of direct $\sigma_{\mathrm{n}, \gamma}$ near $13 \sim 14$ MeV ); level density parameters $a_{\mathrm{n}, \gamma}$ and $a_{\mathrm{n}, \mathrm{n}^{\prime}}$, pair energy corrections $\Delta_{\mathrm{n}, \gamma}, \Delta_{\mathrm{n}, \mathrm{n}^{\prime}}$ and $\Delta_{\mathrm{n}, \mathrm{r}}$, the height of fission barrier $V_{\mathrm{f}}(1)$, the curvature parameter of fission barrier $\hbar \omega(1)$ and the multiplying factor of fission level density $c k_{f}(1)$ for the first plateau; level density parameter $a_{n, 2 n}$, pair energy corrections $\Delta_{n, 2 n}$ and $\Delta_{n, n f}$, the height of fission barrier $V_{f}(2)$, the curvature parameter of fission barrier $\hbar \omega(2)$ and the multiplying factor of fission level density $c k_{f}(2)$ for the second plateau; level density parameter $\mathrm{a}_{\mathrm{n}, 3 \mathrm{n}}$, pair energy corrections $\Delta_{\mathrm{n}, 3 \mathrm{n}}$ and $\Delta_{\mathrm{n}, 2 \mathrm{nf}}$, the height of fission barrier $V_{\mathrm{f}}(3)$, the curvature parameter of fission barrier $\hbar \omega(3)$ and the multiplying factor of fission level density $c k_{f}(3)$ for the third plateau.

With the code ADFP, we can obtain the optimum set of adjustable fission parameters to make $\sigma_{\mathrm{f}}, \sigma_{\mathrm{n}, \mathrm{y}}$ and $\sigma_{\mathrm{n}, 2 \mathrm{n}}$ in optimum accordance with experimental data.

The optimal fission parameters we got are: $C K=3500.0, C_{E l}=0.375$, DGMA $=0.16 ; a_{\mathrm{n}, \mathrm{y}}=27.4792, \Delta_{\mathrm{n}, \mathrm{y}}=0.4141, a_{\mathrm{n}, \mathrm{n}}=28.5044, \Delta_{\mathrm{n}, \mathrm{r}}=0.3565, \Delta_{\mathrm{n}, ~}=-0.0341$, $V_{\mathrm{f}}(1)=5.9641, \hbar \omega(1)=0.3500, c k_{\mathrm{f}}(1)=9.6745$ for $\sigma_{\mathrm{n}, \mathrm{f}}$ in the first plateau, $a_{\mathrm{n}, 2 \mathrm{n}}=28.7369$, $\Delta_{\mathrm{n}, 2 \mathrm{n}}=-0.1143, \Delta_{\mathrm{n}, \mathrm{nf}}=-0.0169, V_{\mathrm{f}}(2)=5.9752, \hbar \omega(2)=1.1000, c k_{\mathrm{f}}(2)=1.8993$ for $\sigma_{\mathrm{n}, \mathrm{nf}}$ in the second plateau, $a_{n, 3 n}=28.4421, \Delta_{n, 3 n}=-0.2183, \Delta_{n, 2 n f}=-0.1360, V_{\mathrm{f}}(3)=5.5695$, $\hbar \omega(3)=0.9195, c k_{\mathrm{f}}(3)=4.4474$ for $\sigma_{\mathrm{n}, 2 \mathrm{nf}}$ in the third plateau.

## 4 Calculated Results and Discussion

Above direct inelastic scattering data obtained with the code CUC, the optimum set of optical potential parameters got with the code CAPFO and the optimal fission parameters got with the code ADFP are the input data of the kernel program FUNF. We calculate the complete set of neutron data of ${ }^{237} \mathrm{~Np}$ with FUNF. All results are given in ENDF/B-6 format.

The calculated $\sigma_{\mathrm{tot}}, \sigma_{\mathrm{non}}$ and $\sigma_{\mathrm{el}}$ and those from ENDF/B-6 library are given in Fig. 1, from which we can see that there is a little difference with our calculated values and the data of


Fig. 1 Total elastic and non-elastic cross sections of ${ }^{237} \mathrm{~Np}$ ENDF/B-6. The calculated and experimental $\sigma_{\mathrm{f}}$ are given in Fig. 2(a) and Fig. 2(b), from which we can clearly see that our calculated $\sigma_{\mathrm{f}}$ are in very good agreement with experimental data, except in $0.6 \sim 1.0 \mathrm{MeV}$ and below 0.25 MeV energy regions, our calculated values are obviously lower than experimental $\sigma_{\mathrm{f}}$. The calculated and experimental $\sigma_{\mathrm{n}, \gamma}$ are given in Fig. 3, from which we can see that our calculated $\sigma_{n, y}$ are in accordance with experimental data and with reasonable shape and values in higher energy region.

The calculated total and continuous $\sigma_{\mathrm{n}, \mathrm{n}^{\prime}}$ as well as the discrete level $\sigma_{\mathrm{n}, \mathrm{n}^{\prime}}$ which included direct reaction components are given in Fig. 4(a) and Fig. 4(b), respectively, from which we can see that our calculated values are physically reasonable. The calculated $\sigma_{n, 2 n}$ and $\sigma_{n, 3 n}$ are given in Fig. 5 , from which we can see that the calculated $\sigma_{\mathrm{n}, 2 \mathrm{n}}$ are in good agreement with experimental data and the calculated $\sigma_{\mathrm{n}, 3 \mathrm{n}}$ are physically reasonable. All kinds of calculated cross sections are given in Fig. 6, in which those with charged outgoing particles are directly calculated with the universal parameters. The calculated secondary neutron spectra of continuous inelastic ( $\mathrm{MT}=91$ ), $(\mathrm{n}, 2 \mathrm{n})$ reaction ( $\mathrm{MT}=16$ ) and fission $(\mathrm{MT}=18)$ at $E_{\mathrm{n}}=8$ and 14 MeV are given in Fig. 7(a), Fig. 7(b) and Fig. 7(c), respectively, from which we can see that our calculated values are physically reasonable.


Fig. 2(a) Fission cross sections of ${ }^{237} \mathrm{~Np}$


Fig. 2(b) Fission cross sections of ${ }^{237} \mathrm{~Np}$

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Fig. 3 Radiative capture cross sections of ${ }^{237} \mathrm{~Np}$


Fig. 4(b) Discrete level inelastic cross sections of ${ }^{237} \mathrm{~Np}$


Fig. 4(a) Total and continuous inelastic cross sections of ${ }^{237} \mathrm{~Np}$


Fig. $5(n, 2 n)$ and $(n, 3 n)$ reaction cross sections of ${ }^{237} \mathrm{~Np}$


Fig. 6 All kinds of calculated cross sections of ${ }^{237} \mathrm{~Np}$


Fig. 7(b) (n,2n) outgoing neutron spectra of ${ }^{237} \mathrm{~Np}$


Fig. 7(a) Neutron spectra of continuous inelastic $(M T=91)$ of ${ }^{237} \mathrm{~Np}$


Fig. 7(c) Fission (MT=18) neutron spectra of ${ }^{237} \mathrm{~Np}$

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# Progress on Theoretical Calculations of Neutron Induced Reaction on ${ }^{174,176,178,180} \mathrm{Hf}$ in the Energy Region from 0.01 MeV to 20 MeV 

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The natural element Hf and its isotopes are important construction materials and its complete neutron nuclear reaction data are very important both for the basic science research and for the nuclear engineering as well as other science and technical domains.

The natural Hf has 6 stable isotopes: ${ }^{174} \mathrm{Hf},{ }^{176} \mathrm{Hf},{ }^{177} \mathrm{Hf},{ }^{178} \mathrm{Hf},{ }^{179} \mathrm{Hf}$ and ${ }^{180} \mathrm{Hf}$, the abundance of them are $0.2 \%, 5.2 \%, 18.5 \%, 27.2 \%, 13.8 \%$ and $35.1 \%$ respectively. There are a small amount of experimental data both for the natural element and for its isotopes. They are mainly the total cross sections for ${ }^{176} \mathrm{Hf},{ }^{177} \mathrm{Hf},{ }^{178} \mathrm{Hf},{ }^{180} \mathrm{Hf}$ and ${ }^{\mathrm{Na}} \mathrm{Hf}$, the ( $\mathrm{n}, \gamma$ ) reaction cross sections for the natural element and its all isotopes, the $(\mathrm{n}, 2 \mathrm{n})$ reaction cross sections for ${ }^{174} \mathrm{Hf}$ and ${ }^{176} \mathrm{Hf}$, the ( $\mathrm{n} . \mathrm{p}$ ) reaction cross sections for ${ }^{179} \mathrm{Hf}$ and ${ }^{180} \mathrm{Hf}$, the ( $\mathrm{n}, \alpha$ ) reaction cross sections for ${ }^{178} \mathrm{Hf}$ and the angular distributions of the elastic scattering for the natural element. Besides the total cross sections for the natural element, all the experimental data mentioned above are only in narrow energy regions or even at individual points. The experimental data are all taken from EXFOR. As the experimental data are very insufficient to practical application, the theoretical calculations of the complete nuclear reaction data are indispensable.

The theoretical calculations for ${ }^{174} \mathrm{Hf},{ }^{176} \mathrm{Hf},{ }^{178} \mathrm{Hf}$ and ${ }^{180} \mathrm{Hf}$ have been completed with program NUNF ${ }^{[1]}$. In this paper, the calculation method and the calculated results for them are discussed. As the complete reaction data both for the natural Hf and for its isotopes are required to give in ENDF/B-6 format respectively, the consistence of the data of the isotopes with the ones of the natural element should be considered. As in the calculations of the natural element the same optical potential parameters are used for all isotopes, but in the calculations of the isotopes, each isotope has its own optical potential parameters, therefore the consistence between the natural element and its isotopes is not easily to be obtained generally. In this work, some attentions in the adjustment of the parameters have been given to improve this consistence.

In the calculations, the parameters of the discrete levels were taken from Nuclear Data Sheets. the optical potential parameters of all charged particles, the level density parameters and the giant dipole resonance parameters have been adjusted in the calculations. Their original values were taken from references [2], [3], [4] and [5]. The program APOM $94^{[6]}$ has been used to automatically get the optimal parameters of the optical potential for neutron channel. As mentioned above, because it is only for the natural Hf that there are abundant experimental data of the
total cross sections and some experimental data of angular distributions of the elastic scattering, only one set of the neutron channel optical potential parameters has been obtained and it has been used to calculate the cross sections and the angular distribution data of the direct inelastc scattering for all isotopes in terms of the program DWUCK $4^{[7]}$. In the calculations of the isotopes using NUNF, they were slightly adjusted to get the better coincidence of the total cross sections with the experimental values and to obtain one set of the neutron optical potential parameters which are available for both the natural element and its isotopes. This ensures the consistence for the total cross sections between the natural element and its isotopes. For each kind of the charged particles (proton, alpha etc.), only one set of optical potential parameters are kept for all isotopes and the natural element too. In the calculations, the level density parameters and the giant dipole resonance parameters were adjusted first whenever physically possible to obtain the coincidence of the calculated results with the experimental data. If the optical potential parameters have to be adjusted for some isotopes, the calculated results of the isotopes which had been calculated before should be modified by using the adjusted optical potential parameters and by adjusting their level density parameters and giant dipole resonance parameters again. This will ensure the consistence between the natural element and its isotopes. For each isotope, the level density parameters of the residual nuclei and the exiton model parameters were adjusted first to obtain the better coincidence of the calculated neutron data with the experimental values. Then the optical potential parameters of the charged particles and the level density parameters of the corresponding residual nucleus were adjusted to obtain the better coincidence of the calculated results with the experiments. Finally the level density parameters and the giant dipole resonance parameters of the compound nucleus were adjusted to obtain the better coincidence of the calculated results of the ( $\mathrm{n}, \gamma$ ) reaction data with the experimental values. The calculated results of the $\gamma$ production data of the residual nucleus can be improved by adjusting its giant dipole resonance parameters.

The optical potential parameters for neutron, proton and alpha are:

## For neutron,

| $V_{0}=51.9946$ | $V_{1}=-0.30055$ | $V_{2}=0.055773$ | $V_{3}=-24.0$ | $V_{4}=0.0$ |
| :--- | :--- | :--- | :--- | :--- |
| $U_{0}=-2.1469$ | $U_{1}=0.2275$ | $U_{2}=0.0076$ |  |  |
| $W_{0}=12.1872$ | $W_{1}=-0.54899$ | $W_{2}=-12.0$ |  |  |
| $V_{\mathrm{so}}=6.2$ |  |  |  |  |
| $r_{\mathrm{r}}=1.148 ?$ | $r_{\mathrm{v}}=1.626$ | $r_{\mathrm{s}}=1.306 ?$ | $r_{\mathrm{so}}=1.2423$ | $r_{\mathrm{c}}=1.25$ |
| $a_{\mathrm{r}}=0.7687$ | $a_{\mathrm{v}}=0.7755$ | $a_{\mathrm{s}}=0.5295$ | $a_{\mathrm{so}}=0.6525$ |  |

For proton,

| $V_{0}=47.52$ | $V_{1}=-0.32$ | $V_{2}=0.0$ | $V_{3}=0.0$ | $V_{4}=0.0$ |
| :--- | :--- | :---: | :---: | :---: |
| $U_{0}=-2.7$ | $U_{1}=0.22$ | $U_{2}=0.0$ |  |  |
| $W_{0}=10.62$ | $W_{1}=-0.25$ | $W_{2}=0.0$ |  |  |
| $V_{\mathrm{so}}=6.2$ |  |  |  |  |
| $r_{\mathrm{r}}=1.17$ | $r_{\mathrm{v}}=1.32$ | $r_{\mathrm{s}}=1.32$ | $r_{\mathrm{so}}=1.01$ | $r_{\mathrm{c}}=1.25$ |
| $a_{\mathrm{r}}=0.75$ | $a_{\mathrm{v}}=0.51$ | $a_{\mathrm{s}}=0.51$ | $a_{\mathrm{so}}=0.75$ |  |

For alpha,

| $V_{1}=110.0$ | $V_{1}=-0.25$ | $V_{2}=0.0$ | $V_{3}=0.0$ | $V_{4}=0.0$ |
| :--- | :--- | :--- | :--- | :--- |
| $U_{0}=3.75$ | $U_{1}=-0.16$ | $U_{2}=0.0$ |  |  |
| $W_{0}=0.0$ | $W_{1}=0.0$ | $W_{2}=0.0$ |  |  |
| $V_{\mathrm{sc}}=0.0$ |  |  |  |  |
| $r_{\mathrm{r}}=1.15$ | $r_{\mathrm{v}}=1.4$ | $r_{\mathrm{s}}=1.4$ | $r_{\mathrm{so}}=1.62$ | $r_{\mathrm{c}}=1.3$ |
| $a_{\mathrm{r}}=0.75$ | $a_{1}=0.84$ | $a_{\mathrm{s}}=0.84$ | $a_{1}=0.75$ |  |

Fig. 1, Fig. 2 and Fig. 3 show the comparisons of the calculated results of the total cross sections with the experimental data and the evaluated results of ENDF/B6 and JENDL- 3 for ${ }^{180} \mathrm{Hf},{ }^{178} \mathrm{Hf},{ }^{176} \mathrm{Hf}$ respectively. Fig. 4 shows the comparisons of the calculated results of the ( $\mathrm{n}, \alpha$ ) cross sections with experimental data and the evaluated values of JENDL-3 for ${ }^{178} \mathrm{Hf}$. Fig. 5 shows the comparisons of the calculated results of the ( $n, p$ ) cross sections with the experimental data and the evaluated results of ENDF/B-6 and JENDL-3 for ${ }^{180} \mathrm{Hf}$. It can be seen that the calculated results are coincident better with the existing experimental data. Fig. 6 throuth Fig. 8 show the comparisons of calculated results of the ( $n, \gamma$ ) reaction cross sections with the experimental data and the evaluated results of ENDF/B-6 and

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Fig. $1{ }^{180} \mathrm{Hf}$ total cross section


Fig. $3{ }^{176} \mathrm{Hf}$ total cross section


Fig. $2{ }^{178} \mathrm{Hf}$ total cross section


Fig. $4{ }^{178} \mathrm{Hf}(\mathrm{n}, \mathrm{\alpha})$ cross section


Fig. $5{ }^{180} \mathrm{Hf}(\mathrm{n}, \mathrm{p})$ cross section


Fig. $6 \quad{ }^{180} \mathrm{Hf}(\mathrm{n}, \gamma)$ reaction cross section


Fig. $7{ }^{178} \mathrm{Hf}(\mathrm{n}, \gamma)$ reaction cross section


Fig. $8 \quad{ }^{176} \mathrm{Hf}(\mathrm{n}, \gamma)$ reaction cross section

JENDL-3 for ${ }^{180} \mathrm{Hf},{ }^{178} \mathrm{Hf}$ and ${ }^{176} \mathrm{Hf}$ respectively. It can be seen that When the neutron incident energies are larger than 3 MeV , the differences among the calculated results, ENDF/B-6 and JENDL-3 evaluated values are very obvious. It is possible that ENDF/B-6 has overestimated the contributions of the compound nucleus statistical processes and JENDL- 3 has eliminated the contributions of the direct-semidirect processes.

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## III DATA EVALUATION

# Evaluation of Complete Neutron Data of $\mathbf{n}+{ }^{240} \mathrm{Pu}$ from $10^{-5} \mathrm{eV}$ to 20 MeV 

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#### Abstract

A complete set neutron nuclear data including cross sections, angular distributions, double differential cross section and gamma production data of $n+{ }^{240} \mathrm{Pu}$ from $10^{-5} \mathrm{eV} \sim 20 \mathrm{MeV}$ were evaluated based on the experimental data and theoretically calculated results in ENDF/B-6 format.


## Introduction

The complete neutron data of ${ }^{240} \mathrm{Pu}$ play an important role for the fuel cycles of all fast and height-burnup reactor systems. A complete set of neutron nuclear data of ${ }^{240} \mathrm{Pu}$ was evaluated from $10^{-5} \mathrm{eV} \sim 20 \mathrm{MeV}$ for CENDL-3, based on the experimental data and calculated results, except for the resonance parameters which were taken from ENDF/B-6. In this work, the direct inelastic scattering cross sections for first 7 levels were calculated with the coupled channel code ECIS-95 and the charged particle emission cross sections were given. The comparison of our evaluated data with ENDF/B-6 and JENDL-3 was performed.

## 1 Resonance Parameters

The resonance parameters and $v$ value of ENDF/B-6 were adopted in this work. The energy range of resolved resonance is from $10^{-5} \mathrm{eV}$ to 5.7 keV and the unresolved one from 5.7 to 40 keV .

The total neutron number per fission is the sum of prompt and delayed neutron number. The delayed neutron number and spectra were evaluated by S.A.Cox ${ }^{[1]}$. The evaluated prompt neutron number relys heavily on the prompt neutron number of ${ }^{252}$ Cf measured by J.Frehaut ${ }^{[2]}$, which assumed as 3.741 .

## 2 Smooth Cross Sections

### 2.1 Total and Elastic Cross Section

There are lot of experimental data above resonance region up to 20 MeV . These data are mainly measured by A.B. Smith ${ }^{[3]}$ in energy region of $0.116 \sim 1.467$ MeV , W.P. Poenitz ${ }^{[4]} 0.48 \sim 4.807 \mathrm{MeV}$ and W.P. Poenitz ${ }^{[5]} 1.818 \sim 21.9 \mathrm{MeV}$, respectively.

The two sets data measured by W.P. Poenitz ${ }^{[4,5]}$ are more important and are in good agreement with each other within errors in energy region of 0.04 to 20 MeV . The measured data below 1.5 MeV were also given by A.B. Smith ${ }^{[3]}$, which are consistent with the data by W.P. Poenitz ${ }^{[4]}$. The recommended total cross section were obtained by fitting experimental data ${ }^{[3-5]}$ and compared with other evaluated data from ENDF/B-6 and JENDL-3 as shown in Fig. 1 .

For elastic scattering angular distributions, there are some measured data from 0.5 MeV to 1.2 MeV , which were carried out by A.B. Smith ${ }^{[3]}$.

### 2.2 Fission Cross Section

The available experimental data of fission cross sections were measured by using absolute and ratio measurement techniques. The measured data were collected up to 1999. The mainly measured data ${ }^{[6-17]}$ from 1970 up to now were analyzed, evaluated and shown in Table 1. For the early measured data, there exists discrepancy beyond the quoted experimental errors. The data measured by Frehaunt ${ }^{[6]}$ have large fluctuations and the difference with others is more than $15 \%$.

| Year | Author | $E_{\mathrm{n}} / \mathrm{MeV}$ | Sample | Detector | Measured Quantity | Method |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1974 | J.Frehaut | 1.87~14.7 | Enriched puity $98.4 \%{ }^{246} \mathrm{Pu}$ | STANK | ${ }^{240} \mathrm{Pu}{ }^{235} \mathrm{U}$ | 12MV <br> tandem |
| 1977 | J.W.Behrens | $0.34 \sim 33.9$ | Enriched puity $98.48 \%{ }^{240} \mathrm{Pu}$ | FISCH | ${ }^{240} \mathrm{Pu}{ }^{2335} \mathrm{U}$ | Flight 15.7 M 100 MV LINAC |
| 1978 | K.Kari | 1~21 | Isotopes purity | SCIN | Absolute | $42 \mathrm{MV}$ <br> Cyclotron |
| 1979 | K.Wisshak | $0.049 \sim 0.213$ | Enriched puity $98.3 \%{ }^{240} \mathrm{Pu}$ | SCIN | ${ }^{244} \mathrm{Pu}^{/ 235} \mathrm{U}$ |  |
| 1979 | V.M.Kuprijanov | 0.127~7.4 | Enriched puity $99.46 \%{ }^{244} \mathrm{Pu}$ | 10 CH | ${ }^{246} \mathrm{Pu} \mathbf{V}^{233} \mathrm{U}$ |  |
| 1981 | J.W.Meadows | 0.335~9.5 | Isotopes purity | IOCH | ${ }^{244} \mathrm{Pu}^{2}{ }^{233} \mathrm{U}$ | 8 MV <br> Dynamitron |
| 1981 | C.Budtz-Jorgensen | $0.151 \sim 0.296$ | Isotopes purity | 1 CCH | ${ }^{240} \mathrm{Pu} /{ }^{233} \mathrm{U}$ | 7 MV <br> Van De Graaff |
| 1982 | M.Cance | 2.5 | Isotopes purity | FISCH | Absolute |  |
| 1983 | L.W.Weston | 0.005~20 | Isotopes purity | Multiple FISCH | ${ }^{246} \mathrm{Pu} /{ }^{234} \mathrm{Pu}$ | Flight 19 M <br> LINAC at ORELA |
| 1983 | J.W.Behrens | 0.0055~0.368 | Enriched puity $98.48 \%{ }^{240} \mathrm{Pu}$ | FISCH | ${ }^{246} \mathrm{Pu} /{ }^{235} \mathrm{U}$ | Flight 15.7 M at LINAC |
| 1990 | T.Iwasaki | 0.6~7 | Isotopes purity | $\begin{gathered} \text { Back-Back } \\ \text { IOCH } \end{gathered}$ | ${ }^{240} \mathrm{Pu}^{2 / 35} \mathrm{U}$ | 4.5 MV <br> Dynamitron |
| 1998 | P.Staples | 0.5~400 | Isotopes purity | Multiple <br> FISCH | ${ }^{240} \mathrm{Pu} /{ }^{235} \mathrm{U}$ | LINAC |

FISCH: Ionization Fission Chamber
IOCH: Los Mass Ionization Chamber
SCIN : (Gas) Scintillator Detector
STANK : Gd - loaded liquid scintillator tank

The improvements of the measurement technology were conducted by using ionization fission chamber with the time-of-flight spectrometer at Linac in 1978. The procedure is called "threshold cross section method". The advantage is that it does not require the knowledge of the mass within the high-purity fission chambers and the detector efficiency. Furthermore, the procedure is suitable to the white neutron source. Therefore, the accurate fission cross sections could be obtained in widely energy region. The fission cross sections were measured by J.W. Behrens ${ }^{[7]}$ in energy region from 0.34 MeV to 33.9 MeV , by K. Kari ${ }^{[8]}$ from 0.99 MeV to 21 MeV and by L.W. Weston ${ }^{[44]}$ from 0.005 to 20 MeV , respectively. Their data are consistent with each other within errors. There is significant improvement for the experiment uncertaint, either eliminated or significantly reduced. Therefore, the data measured by by W. Behrens ${ }^{[7]}$, K. Kari ${ }^{[8]}$ and L.W. Weston ${ }^{[14]}$ are given large weight above 7 MeV in this work.

The data measured by W. Behrens ${ }^{[7]}$, K. Kari ${ }^{[8]}$ and L.W. Weston ${ }^{[14]}$ with the white neutron source are consistent with those by V.M. Kuprijanov ${ }^{[10]}$, J.W. Meadows ${ }^{[1]]}$ by using the mono-energetic neutron within errorbar below 6 MeV . T. Iwasaki ${ }^{[16]}$ improved the time resolution of the fast timing back-back fission chamber to reduce the background and increase the signal to background ratio. The data measured by T. Iwasaki ${ }^{[16]}$ are in good agreement with those by V.M. Kuprijanov ${ }^{[10]}$ and J.W. Meadows ${ }^{[11]}$ below 6 MeV . Therefore, the measured data by T. Iwasaki ${ }^{[16]}$, V.M. Kuprijanov ${ }^{[10]}$ and J.W. Meadows ${ }^{[11]}$ were very important for low energy region and were given large weight in the energy region below 6 MeV .

In the evaluation, the difference was found that the data by T . Iwasaki ${ }^{[16]}$ in 6 to 7 MeV is systematic high related to the data by J.W. Behrens ${ }^{[7]}$ and K. Kari ${ }^{[8]}$ using the white source. The cross section from 6 to 7 MeV corresponds to the rise point of the second chance fission of ${ }^{240} \mathrm{Pu}$ and has large change, the determination of energy becomes very important. The resonance peak of carbon at 6.3 MeV was used by J.W. Behrens ${ }^{[7]}$ to scale the energy for white spectrum, therefore, the data were given large weight in this energy region.

The evaluation is based on all available ratio and absolute data of ${ }^{244} \mathrm{Pu}(\mathrm{n}, \mathrm{f})$ and the result is shown in Fig. 2.

### 2.3 Capture Cross Section

For the ${ }^{240} \mathrm{Pu}(\mathrm{n}, \gamma){ }^{241} \mathrm{Pu}$ reaction, there are experimental data available in energy region from 35 to 325 keV , measured by L.W. Weston ${ }^{[18]}$ with liquid NE226 scintillation at Oak Ridge electron linear accelerator in 1972. Based on the calculated and experimental data, the evaluated data were obtained. The evaluated data could reproduce the experimental data very well, as shown in Fig. 3.

## 2.4 ( $n, 2 n$ ) and ( $n, 3 n$ ) Cross Sections

There are no experimental data for ( $\mathrm{n}, 2 \mathrm{n}$ ) and ( $\mathrm{n}, 3 \mathrm{n}$ ) reactions. The calculated data by Shen Qingbiao ${ }^{[19]}$ were adopted, as shown in Fig. 4.

## 3 Theoretical Calculation and Model Parameters Adjusting

### 3.1 Nonelastic Scattering Cross Section

A set of neutron spherical optical potential parameters was obtained with the automatically searching code APFO96 ${ }^{[20]}$ and AUTOFOT ${ }^{[21]}$ Code by fitting the EXFOR Data. There are enough data for total cross sections and some elastic scattering angular distribution (in incident neutron energy region from 0.5 to 1.2 MeV ). Because lack of the measured nonelastic scattering cross section, the evaluated nonelastic scattering cross section was used for adjusting the optical potential parameters.

The theoretical calculation was performed with FUNF code ${ }^{[22]}$, based on the available experimental total cross sections, nonelastic scattering cross sections from ( $n, \gamma),(n, n \prime),(n, f),(n, 2 n)$ etc, evaluated by us in energy region $0.001 \sim 20 \mathrm{MeV}$ as well as some experimental data of elastic angular distributions.

Using adjusted neutron optical potential parameters and adjusted level density and giant dipole resonance parameters as well as fission parameters, the reaction cross sections, secondary neutron spectra and angular distributions were calculated ${ }^{[19]}$.

### 3.2 Inelastic Scattering Cross Section

The inelastic scattering cross sections were evaluated and calculated. The theoretically calculated total inelastic scattering cross section is the sum of partial
inelastic scattering cross sections ( $\mathrm{MT}=51$ to 84 and 91 ), some of which were adjusted based on experimental data ${ }^{[23]}$.

The direct component was calculated with coupled channel optical model code ECIS-9 ${ }^{[24]}$. The direct component calculation belonging to the first 5 levels of the ground state rotational band and neutron inelastic angular distribution to the rotational levels were performed from threshold to 20 MeV . The compound nuclear contributions calculated with $\mathrm{FUNF}^{[22]}$ code were added with direct component.

The experimental data for inelastic scattering cross sections to 1 st , 2nd, 3rd, 4th and 9th to 11 th levels are available ${ }^{[23]}$. The corresponding inelastic scattering cross sections were adjusted based on these data.

The inelastic scattering to other levels were calculated with FUNF code.
The discrete levels were taken from China Nuclear Parameter Library.
The levels scheme used in this work are as following:

| No. | Energy/MeV | Spin | arity | No. | Energy/keV | Spin-Parity |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| G.S. | 0.0 | 0 | + | 18 | 1.0762 | 4 | $+$ |
| 1 | 0.04282 | 2 | + | 19 | 1.0894 | 0 | + |
| 2 | 0.14169 | 4 | + | 20 | 1.1155 | 5 | - |
| 3 | 0.29431 | 6 | + | 21 | 1.1319 | 2 | + |
| 4 | 0.49752 | 8 | + | 22 | 1.1369 | 2 | + |
| 5 | 0.59734 | 1 | -- | 23 | 1.1615 | 6 | - |
| 6 | 0.64885 | 3 | - | 24 | 1.1775 | 3 | + |
| 7 | 0.74233 | 5 | - | 25 | 1.1804 | 2 | + |
| 8 | 0.7478 | 10 | + | 26 | 1.1990 | 3 | + |
| 9 | 0.8607 | 0 | + | 27 | 1.2230 | 2 | + |
| 10 | 0.90032 | 2 | $+$ | 28 | 1.2325 | 4 | + |
| 11 | 0.93806 | 1 | - | 29 | 1.2408 | 2 | - |
| 12 | 0.95885 | 2 | - | 30 | 1.2620 | 3 | + |
| 13 | 0.9924 | 4 | + | 31 | 1.2820 | 3 | - |
| 14 | 1.0019 | 3 | - | 32 | 1.3087 | 5 | - |
| 15 | 1.0305 | 3 | + | 33 | 1.3756 | 14 | + |
| 16 | 1.0375 | 4 | - | 34 | 1.41075 | 0 | + |
| 17 | 1.0418 | 12 | + |  |  |  |  |

Continuum state was assumed above 1.41075 MeV .
Based on the adjusted model parameters including optical potential parameters, levels scheme and other parameters concerned, a complete set of data were calculated. The discrete level cross sections with experimental data are shown in Figs. 5~9, the total inelastic cross section is shown in Fig. 10.


Fig. 1 Comparison of Evaluated and Measured Data for ${ }^{240} \mathrm{Pu}(\mathrm{n}$, tot) Reaction


Fig. 2 Comparison of Evaluated and Measured Data for ${ }^{240} \mathrm{Pu}(\mathrm{n}, \mathrm{f})$ Reaction


Fig. 3 Comparison of Evaluated and Measured Data for ${ }^{240} \mathrm{Pu}(\mathrm{n}, \gamma)$ Reaction


Fig. 4 Comparison of Evaluated Data for ${ }^{240} \mathrm{Pu}(\mathrm{n}, 2 \mathrm{n})$ and ( $\mathrm{n}, 3 \mathrm{n}$ ) Reactions


Fig. 5 Comparison of Evaluated and Measured Data for ${ }^{240} \mathrm{Pu}\left(\mathrm{n}, \mathrm{n}^{\prime}\right) \mathrm{MT}=51$


Fig. 6 Comparison of Evaluated and Measured Data for ${ }^{240} \mathrm{Pu}\left(\mathrm{n}, \mathrm{n}^{\prime}\right) \mathrm{MT}=52$


Fig. 7 Comparison of Evaluated and Measured Data for ${ }^{240} \mathrm{Pu}\left(\mathrm{n}, \mathrm{n}^{\prime}\right) \mathrm{MT}=53$


Fig. 8 Comparison of Evaluated and Measured Data for ${ }^{240} \mathrm{Pu}\left(\mathrm{n}, \mathrm{n}^{\prime}\right) \mathrm{MT}=55$


Fig. 9 Comparison of Evaluated and Measured Data for ${ }^{240} \mathrm{Pu}\left(\mathrm{n}, \mathrm{n}^{\prime}\right) \mathrm{MT}=59-61$


Fig. 10 Comparison of Evaluated Data for ${ }^{240} \mathrm{Pu}\left(\mathrm{n}, \mathrm{n}^{\prime}\right)$ Reaction

## 4 Comprehensive Recommendation

### 4.1 Reaction Cross Sections

The recommended cross sections for ( $\mathrm{n}, \mathrm{n}^{\prime}$ ), ( $\mathrm{n}, 2 \mathrm{n}$ ), ( $\mathrm{n}, 3 \mathrm{n}$ ), ( $\left.\mathrm{n}, \gamma\right),(\mathrm{n}, \mathrm{f}),(\mathrm{n}, \mathrm{x})$, etc. were given based on the measured and theoretically calculated data.

### 4.2 Double Differential Cross Sections

The correlated energy-angle distributions for $(\mathrm{n}, 2 \mathrm{n}),(\mathrm{n}, 3 \mathrm{n}),(\mathrm{n}, \mathrm{f})$ and ( $\mathrm{n}, \mathrm{n}_{\text {continum }}$ ) reactions were calculated with code FUNF.

### 4.3 Photon-Production Data

All photon-production data were calculated with code FUNF, including the files 12 and 14 for $\mathrm{MT}=51 \sim 84$ and 102 , and file 15 for MT=102.

## 5 Check of Evaluated Data

The check including format, consistency between the total and the sum of partial cross sections, physics parameter etc. for complete neutron data was carried out by using ENDF utility codes CHEKR, FIZCOM and PSYCHE. Some problems were found and modified based on these checked results. The complete neutron data were not recommended until passing through all of these checks.

## 6 Summary

Nonelastic scattering cross section were obtained from the evaluated experimental dada of several reaction channels concerned. So the nonelastic scattering cross sections used consist with sum of the all reaction channels data measured. A set of neutron optical potential parameters were obtained, which could reproduce the total, nonelastic cross sections and elastic scattering angular distribution very well.

In present work, recommended total, fission, capture and partial inelastic scattering cross sections are in good agreement with the measured data available. The comparison of our evaluated data with other evaluated libraries were done.

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# Evaluation of Complete Neutron Nuclear Data for ${ }^{206} \mathbf{P b}$ 

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#### Abstract

The following neutron data are given for ${ }^{206} \mathrm{~Pb}$ in the energy range from $10^{-5} \mathrm{eV}$ to 20.0 MeV . The evaluated neutron nuclear data included total, elastic, noelastic, total inelastic, inelastic cross sections to 15 discrete levels, inelastic continuum, $(n, 2 n),(n, 3 n),\left(n, n^{\prime} p\right),(n, p),(n, t),(n, \alpha)$ and capture cross sections. The angular distributions of elastic and discrete in elastic scattering neutron, the double differential cross sections (DDCS) of secondary neutron, the gamma-ray production data and the resonance parameters are also included. The evaluated data will be adopted into CENDL-3 in ENDF/B-6 format.


## Introduction

Lead is a very important structure material in nuclear fusion engineeting. Its complete neutron nuclear data were evaluated based on both experimental data measured up to 1999 and theoretical calculated data with program $\mathrm{UNF}^{[1]}$. The evaluated data will be adopted into CENDL-3 in ENDF/B-6 format[MAT=3822] and will be utilized in the various fields of nuclear engineering.

The level scheme are given in Table 1 , which was selected from the new data presented in Ref.[2]. The binding energy of emitted final particle are given in Table 2.

Table 1 Inelastic discrete levels (Abundance 24.1\%) for ${ }^{206} \mathbf{P b}$

| $E_{1} / \mathrm{MeV}$ | $J^{\pi}$ | $E_{1} / \mathrm{MeV}$ | $J^{\pi}$ | $E_{1} / \mathrm{MeV}$ | $J^{\pi}$ | $E_{1} / \mathrm{MeV}$ | $J^{\pi}$ |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| 0.0 | $0^{+}$ | 1.4668 | $2^{+}$ | 1.9977 | $4^{+}$ | 2.3790 | $4^{+}$ |
| 0.8031 | $2^{+}$ | 1.6840 | $4^{+}$ | 2.1479 | $2^{+}$ | 2.3842 | $6^{-}$ |
| 1.1660 | $0^{+}$ | 1.7035 | $1^{+}$ | 2.2002 | 7 | 2.3914 | $4^{+}$ |
| 1.3405 | $3^{+}$ | 1.7842 | $2^{+}$ | 2.3150 | $0^{+}$ | 2.4240 | $2^{+}$ |

Table 2. Binding energy of emitted final particle( $\mathbf{M e V}$ ) ${ }^{206} \mathbf{P b}$

| reaction | $\mathrm{n}, \gamma$ | $\mathrm{n}, \mathrm{n}^{\prime}$ | $\mathrm{n}, \mathrm{p}$ | $\mathrm{n}, \alpha$ | $\mathrm{n},{ }^{3} \mathrm{He}$ | $\mathrm{n}, \mathrm{d}$ | $\mathrm{n}, \mathrm{t}$ |
| :--- | :---: | :---: | :---: | ---: | :---: | ---: | :---: |
| channels | $\mathrm{n}, 2 \mathrm{n}$ | $\mathrm{n}, \mathrm{n}^{\prime} \mathrm{p}$ | $\mathrm{n}, \mathrm{n}^{\prime} \alpha$ | $\mathrm{n}, \mathrm{pn}^{\prime}$ | $\mathrm{n}, 2 \mathrm{p}$ | $\mathrm{n}, \alpha \mathrm{n}^{\prime}$ | $\mathrm{n}, 3 \mathrm{n}$ |
|  | 0.0 | 6.7414 | 7.4922 | -0.3956 | 12.6913 | 11.7715 | 13.0546 |
|  | 8.0809 | 7.2547 | -1.1445 | 6.5039 | 7.2500 | 5.9925 | 6.73396 |

## 1 Resonance Parameter

The resolved resonance parameters were given from $10^{-5} \mathrm{eV}$ to 0.9 MeV , taken from ENDF/B-6 data. Thermal cross sections of ( $n, t o t$ ), ( $n, n$ ) and ( $n, \gamma$ ) reactions are $11.266 \mathrm{~b}, 11.237 \mathrm{~b}$ and 29.0 mb , respectively.

## 2 Neutron Cross Section

The comparison of experimental data with evaluated ones are shown in Figs. $1 \sim 10$. It can be seen that the present evaluation is in agreement with the experimental data.

### 2.1 Total Cross Section

Above the resolved resonance region, there are still a energy range (0.9~5.0 MeV ) with some small structure and then smooth energy range ( $5.0 \sim 20.0 \mathrm{MeV}$ ). In the energy range from 0.9 to 20.0 MeV , the data were mainly taken from corresponding experimental data of Horen, Benetakij, Foster Jr, Carlson, Bukarevich and Miller ${ }^{[3-8]}$. A plot of these data and the evaluated data is shown in Fig. 1.

### 2.2 Elastic Scattering Cross Section

Above the resolved resonance region, the elastic scattering cross section was obtained by subtracting the sum of cross sections of all the non-elastic processes from the total cross section. In general, the agreement between the evaluated cross section and the available experimental data of Abdel, Elemad, Holmqvist, Bostrorn, Landan and Walt ${ }^{[9-14]}$ is good, as shown in Fig. 2.


Fig. 1 Total cross section for ${ }^{206} \mathrm{~Pb}$


Fig. 2 Elastic cross section for ${ }^{206} \mathrm{~Pb}$

### 2.3 Nonelastic Scattering Cross Section

This cross section is the sum of all cross sections of $\left(n, n^{\prime}\right),(n, 2 n),(n, 3 n)$, $\left(n, n^{\prime} p\right),(n, \gamma),(n, p),(n, t)$ and $(n, \alpha)$ reactions. The agreement between the evaluated cross section and the available experimental data of Haas ${ }^{[15]}$ and Walt is good, as shown in Fig. 3.

### 2.4 Total Inelastic Cross Section

The calculated results were adopted and normalized to the experimental data by Thomson ${ }^{[16]}$ at 7.0 MeV (see Fig. 4).

### 2.5 Inelastic Cross Section to the Discrete Levels and the Continuum

The inelastic scattering cross section to 15 discrete levels were calculated by using UNF code. For $0.8031,1.166,1.3405$ and 1.4668 MeV levels, there are some the experimental data measured by Almen-Ra., Konobeevskij and Cranberg ${ }^{[17 \sim 19]}$. The model calculated results were normalized to these measured data. A plot of these data and the evaluated data is shown in Fig. 4-1 and 4-2. For 1.684~2.4359 MeV levels, respectively.

The continuum part was obtained by subtracting the cross section of inelastic scatteringe to 15 discrete levels from the total inelastic.

## 2.6 ( $\mathbf{n}, \mathbf{2 n}$ ) and ( $\mathrm{n}, \mathbf{3 n )}$ Cross Section

For ( $\mathrm{n}, 2 \mathrm{n}$ ) reaction, the experimental data were measured by Frehaut ${ }^{[20]}$ in the energy range from 8.44 to 14.76 MeV . The evaluated data were obtained by fitting experimental data with spline function. Above 14.76 MeV , calculated data were nomalized to fitting value of the experimental data at 14.0 MeV (see Fig. 5).

For ( $\mathrm{n}, \mathrm{3n}$ ) reaction, the data were taken from the calculated results(see Fig. 6).

## 2.7 ( $\mathrm{n}, \mathrm{p}$ ) and ( $\mathrm{n}, \mathrm{n} \mathbf{\prime}$ ) Cross Section

For ( $\mathrm{n}, \mathrm{p}$ ) reaction, the experimental datum were measured by Belovitckij ${ }^{[21]}$ at 14.5 McV . The calculated data was normalized to this datum (see Fig. 7).

The ( $\mathrm{n}, \mathrm{n}^{\prime} \mathrm{p}$ ) cross section was taken from the model calculation due to lack of the experimental data.

## 2.8 ( $\mathrm{n}, \alpha$ ) Cross Section

The model calculated results were normalized to the experimental data by Filatenkov, Grallert, Maslov and Yu-Wen Yu ${ }^{[22-25]}$ at 14.5 MeV (see Fig. 8).

### 2.9 Capture Cross Section

The evaluated data of capture cross section from $10^{-5} \mathrm{eV}$ to 0.9 MeV were given by the resonance parameters and the background. From this energy up to 20.0 MeV , the cross section was taken from the model calculation due to lack of the experimental data (see Fig. 9).

For elastic scattering, there are some experimental data measured by Schreder, Ferrer, Guenther ${ }^{[26-28]}$. The calculated results are in good agreement with the experimental data and used as recommended data (see Fig. 10-1, 10-2).

The discrete inelastic angular distributions ( $\mathrm{MT}=51 \sim 65$ ) were obtained from theoretical calculation results. the angular distributions for $(n, 2 n),(n, 3 n),\left(n, n^{\prime} p\right)$ and continuum inelastic ( $\mathrm{MT}=16,17,28,91$ ) were assumed to be isotropic.

## 4 The Double Differential Cross Section and $\gamma$-Ray Production Data

The double differential emission cross section ( $\mathrm{MF}=6, \mathrm{MT}=16,17,28,91,103$, 105,107 ) and $\gamma$-ray production data ( $\mathrm{MF}=12,13,14,15$ ) were taken from the calculation results (see Fig. 11).

## 5 Theoretical Calculation

UNF code, including optical model, Hauser-Feshbach statistical model and exciton model, was used to calculate the data for files $3,4,6,12,13,14,15$, which requires following input parameters: optical potential, level density, giant dipole resonance ${ }^{[29]}$ and nuclear level scheme. These patameters were adjusted on the basis of experimental data concerned in the neutron energy range from 1 keV to 20 MeV .

An automatically adjusted optical potential code (APOM) ${ }^{[50]}$ was used for searching a set of optimum neutron spherical optical potential parameters. DWUCK code was used to calculate the direct inelastic scattering cross sectiona for excited levels as the input data of UNF.

### 5.1 Optical Model, Level Density and Giant Dipole Resonance Parameters

Optical potential parameters used are given in Table 3. The level density and pair correction parameters are given in Table 4. The giant dipole resonance parameters are shown in Table 5, the symbols CSG, EE and GG are the peak cross section, resonance energy and full width at half maximum, respectively.


Fig. 3 Non-elastic cross section for ${ }^{206} \mathrm{~Pb}$


Fig. 4-1 Inelastic cross section for ${ }^{206} \mathrm{~Pb}$ excited states


Fig. 4 Inelastic cross section for ${ }^{206} \mathrm{~Pb}$


Fig. 4-2 Inelastic cross section for ${ }^{206} \mathrm{~Pb}$ excited states


Fig. $5(\mathrm{n}, 2 \mathrm{n})$ cross section for ${ }^{206} \mathrm{~Pb}$


Fig. 7 ( $\mathrm{n}, \mathrm{p}$ ) cross section for ${ }^{206} \mathrm{~Pb}$


Fig. $6(\mathrm{n}, 3 \mathrm{n})$ cross section for ${ }^{206} \mathrm{~Pb}$


Fig. 8 ( $\mathrm{n}, \alpha$ ) cross section for ${ }^{206} \mathrm{~Pb}$


Fig. $9 \quad(\mathrm{n}, \gamma)$ cross section for ${ }^{206} \mathrm{~Pb}$


Fig. 10-2 Elastic scatter angular distribution of ${ }^{206} \mathrm{~Pb}$


Fig. 10-1 Elastic scatter angular distribution of ${ }^{206} \mathrm{~Pb}$


Fig. $11(\mathrm{n}, 2 \mathrm{n})$ and ( $\mathrm{n}, \mathrm{n}^{\prime}$ ) continuous neutron spectra for ${ }^{206} \mathrm{~Pb}$ at 20.0 MeV

### 5.2 Direct Inelastic Calculation

The direct elastic scattering to ground state and direct inelastic scattering to excited states were calculated with code DWUCK at 19 energies by Shen Qingbiao in the required input format of UNF.

Table 3 Optical model potential parameters*

|  | Depth/MeV |  | Radius/fm | Diffuseness/fm |
| :--- | :--- | :--- | :--- | :--- |
| Neutron | $V_{\mathrm{o}}=46.945$ | $W_{\mathrm{o}}=3.805$ | $X_{\mathrm{r}}=1.24715$ | $A_{\mathrm{r}}=0.64$ |
|  | $V_{1}=-0.232$ | $W_{1}=0.4151$ | $X_{\mathrm{s}}=1.24$ | $A_{\mathrm{s}}=0.48$ |
|  | $V_{2}=-0.00$ | $W_{2}=0.00$ | $X_{\mathrm{v}}=1.24$ | $A_{\mathrm{v}}=0.48$ |
|  | $V_{3}=0.00$ | $U_{\mathrm{o}}=-0.0$ | $X_{\mathrm{so}}=1.24715$ | $A_{\mathrm{so}}=0.64$ |
|  | $V_{\mathrm{t}}=0.0$ | $U_{1}=0.0$ | $X_{\mathrm{c}}=1.22$ |  |
|  | $V_{\mathrm{so}}=6.0$ | $U_{2}=0.0$ |  |  |

Note: $\quad V_{\mathrm{i}}(\mathrm{E})=V_{0}+V_{1} \mathrm{E}+V_{2} \mathrm{E}(2)+V_{3}(A-2 Z) / \mathrm{A}+V_{4} Z / A(1 / 3)$;
$W_{s}(\mathrm{E})=W_{0}+W_{1} \mathrm{E}+W_{2}(A-2 Z) / A$;
$U_{v}(\mathrm{E})=U_{0}+U_{1} \mathrm{E}+U_{2} \mathrm{E}(2)$.

Table 4 Level density parameters and pair correction values of 11 residual nuclei*

|  | $\mathrm{n}, \gamma$ | $\mathrm{n}, \mathrm{n}^{\prime}$ | $\mathrm{n}, \mathrm{p}$ | $\mathrm{n}, \alpha$ | $\mathrm{n},{ }^{3} \mathrm{He}$ | $\mathrm{n}, \mathrm{d}$ | $\mathrm{n}, \mathrm{t}$ | $\mathrm{n}, 2 \mathrm{n}$ | $\mathrm{n}, \mathrm{n}^{\prime} \alpha$ | $\mathrm{n}, 2 \mathrm{p}$ | $\mathrm{n}, 3 \mathrm{n}$ |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| L | 4.57 | 6.25 | 4.18 | 8.75 | 7.28 | 5.86 | 7.34 | 7.73 | 11.03 | 5.62 | 10.05 |
| P | 0.60 | 1.21 | 0.0 | 0.78 | 1.14 | 0.61 | 0.25 | 0.85 | 1.25 | 0.53 | 1.32 |

[^0]Table 5 The 11 giant dipole resonance parameters(single peak)

| $\mathrm{CSG} / \mathrm{b}$ | $0.481,0.541,0.541,0.645,0.541,0.481,0.541,0.481,0.645,0.541,0.481$, |
| :--- | :--- |
| $\mathrm{EE} / \mathrm{MeV}$ | $13.56,13.72,13.72,13.63,13.72,13.56,13.72,13.56,13.63,13.72,13.56$, |
| $\mathrm{GG} / \mathrm{MeV}$ | $3.96,4.61,4.61,3.94,4.61,3.96,4.61,3.96,3.94,4.61,3.96$, |

## 6 Concluding Remarks

Due to the new experimental data have been available for recent years, the evaluated data have been considerably improved, especially for cross sections of total, ( $\mathrm{n}, 2 \mathrm{n}$ ), elastic angular distributions and inelastic scattering to some discrete levels.

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# The Experimental Data Evaluation for Natural Hf and Its Isotopes 

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Most of the experimental data were retrieved from EXFOR experimental neutron library, the data for natural Hf and its isotopes were evaluated in the incident neutron energy region up to 20 MeV .

## 1 General Method of the Evaluation

### 1.1 The Retrieval of Experimental Data in EXFOR Format

The experimental data were retrieved directly from EXFOR master experimental neutron data library. The retrieval can be done according to the
nuclides, reaction quantities and/or measured years, or access number by using EXFOR management program RETREV and COFFEE-CS on ALPHA Server or RETRV-Pc at CNDC, which was developed by Yu Hongwei et al. ${ }^{[1]}$.

### 1.2 The Pre-processing of Experimental Data in EXFOR Format

Since the EXFOR format is very flexible and complicated, especially the data table, it need to be changed and standardized including adding the new data, exchanging the column of the data table, unit change, energy region selection, error correction and selecting energy points and averaging for some given energy points. For this purpose, the program FORM was used ${ }^{[2]}$.

In some cases. There is no data-error given, the whole information given was read carefully and the error-bar was added according to the measured method, data, and laboratory. The general case is shown in Table 1. If the error given by the author is not in this region, the error, in general case, was adjusted.

Table 1 the error range of experimental data

| Cross Section | Error Range | Methods |
| :---: | :---: | :---: |
| $\sigma_{\text {tot }}$ | 2-5\% | Transmission, Time of Flight. $\Delta t / \mathrm{L}=$ $0.05 \sim 0.5 \mathrm{~ns} / \mathrm{m}(\mathrm{LINAC})$ |
| $\begin{gathered} \sigma_{\mathrm{n}, \mathrm{n}}(E) \\ \sigma_{\mathrm{n}, \mathrm{n}}(\boldsymbol{\theta}) \\ \sigma_{\mathrm{n}, \mathrm{n}}(E) \\ \sigma_{\mathrm{n}, \mathrm{n}^{\prime}}(E) \\ \boldsymbol{\sigma}\left(E, E^{\prime}, \boldsymbol{\theta}\right) \end{gathered}$ | $\begin{aligned} & 5 \sim 10 \% \\ & 5 \sim 20 \% \\ & 5 \sim 15 \% \\ & 8 \sim 20 \% \\ & 8 \sim 30 \% \end{aligned}$ | Time of Flight , $\Delta t / \mathrm{L}=0.2 \sim 0.7 \mathrm{~ns} / \mathrm{m}$ (VOG, Tandem, CCW) |
| $\begin{gathered} \sigma_{\mathrm{n}, 2 \mathrm{n}} \\ \sigma_{\mathrm{n}, \mathrm{p}} \\ \sigma_{\mathrm{n}, \boldsymbol{\alpha}} \\ \sigma_{\mathrm{n}, \gamma} \\ \sigma_{\mathrm{n}, \mathrm{n}} \end{gathered}$ | $\begin{aligned} & \text { 1) } 5 \sim 15 \% \\ & \text { 2) } 2 \sim 10 \% \end{aligned}$ | Activation method <br> 1) NaI (before 1975) <br> 2) GeLi |

### 1.3 The Correction and Evaluation of Experimental Data in EXFOR Format

Code $\mathrm{SIG}^{[2]}$ is a powerful and convenient tool for physical analysis and evaluation of EXFOR experimental data. In this step the data at any point can be changed, including cross section or its error e.g. multiplied by or plus a constant, put into error, and data modifying line by line etc.

In the physical analysis and evaluation of the experimental data, the following things were considered in this work:

1) Experimental methods. For TOF method, the resolution time is more important, which is directly relative to the energy resolution and depends on the flight path and resolution time of the system. So the less the $\Delta t / \mathrm{L}$, the more reliable the method. While the data measured by activation method are more reliable, if the threshold energy of the monitor reaction is nearest to the threshold energy of the reaction to be measured.
2) The experimental year. Generally speaking, the late experimental data are more reliable.
3) Correction. If the necessary corrections have been done, especially whether the background was already reasonably subtracted.
4) Standard. The standards used must be latest or generally accepted ones, if not, the renormalization should be done with new ones. The new standards used in the evaluation were taken from follows in order:
a. The latest internationally recommended one from ENDF/B-6 (Standard) and INDC(SEC)-10'(1992);
b. The latest evaluated data at home;
c. ENDF/B-6 (rather than standards).

### 1.4 The Processing of Experimental Data in EXFOR Format

The evaluated experimental data were processed, in usual case, were fitted by using spline program SPF $^{[3]}$. The program SPF can fit multi-set data with any order spline as base and has the function of knot optimization, so the program is very convenient for the users and makes the fit results less artificialness. Even though the program has the above advantage, something is still to be noticed by the users:

1) Knot selection: The knot should be taken at the peak and valley, and at the peak both sides, if the peak is rather sharp.
2) Spline order choice: The order of spline function is chosen according to the different curve shape, one order for linear line, two order for parabola, three order for peak structure, etc.

## 2 The Evaluation of Some Typical Reactions.

The cross sections of (n,tot), (n,abs), (n,el), (n,inl), (n, $\alpha$ ), ( $n, \gamma),(n, 2 n)$ and (n,p) reactions for Hf were evaluated. Some typical reactions of natural Hf and its isotopes are introduced below.

## 2.1 ${ }^{176} \mathrm{Hf}(\mathrm{n}, \gamma)$ Reaction

The information of the experimental data are collected for ${ }^{176-179} \mathrm{Hf}(\mathrm{n}, \gamma)$ reactions.
In the energy range below 200 keV , two sets of data ${ }^{[5,7]}$ consist with each other within uncertainty. But when the energy increases above 200 keV , the Bokhovko's data ${ }^{[7]}$ are little higher than Beer's ${ }^{[5]}$. Due to the latter was measured later, we let the spline-fit ${ }^{[3]}$ curve goes through near the latter. The experimental data and spline fitting curve are shown in Fig. 1, compared with ENDF/B-6 and JENDL-3.

Table 2 The information of the experimental data for ${ }^{176-179} \mathrm{Hf}(\mathrm{n}, \gamma)$ reaction

| Entry | Inst. | Author | Year | Method | $E_{\mathrm{n}} / \mathrm{keV}$ | $f^{1)}$ | Adj $^{2 /}$ | Isoto. |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 12755 | USAORL | H.Beer | 1982 | TOF 40.12 M | $3.5 \sim 1950$ | 1.0 | NO | ${ }^{178,179} \mathrm{Hf}$ |
| 12880 | USAORL | H.Beer | 1984 | TOF $40-\mathrm{M}$ | $3.5 \sim 650$ | 1.0 | NO | ${ }^{176.177} \mathrm{Hf}$ |
| 30248 | INDAUW | K.Siddappa | 1970 | Activation | 23 | 1.0 | NO | ${ }^{178.179} \mathrm{Hf}$ |
| 41225 | RUSFE1 | M.V.Bokhovko | 1996 | TOF | $18 \sim 450$ | 1.0 | NO | ${ }^{176-179} \mathrm{Hf}$ |
| Note 1) $f$. correction factor. |  |  |  |  |  |  |  |  |
| 2) Adj Ertor adjusted. |  |  |  |  |  |  |  |  |

## 2.2 ${ }^{177} \mathbf{H f}(\mathrm{n}, \gamma)$ Reaction

In the energy range below 0.07 MeV , the Bokhovko's data ${ }^{[7]}$ are higher than Beer's $s^{[5]}$ one, but the low energy limit of Bokhovko's ${ }^{[7]}$ is at 18 keV , and that of Beer's ${ }^{[5]}$ is at 3.5 keV , so in the energy range from 18 keV to 0.07 MeV , the data were from Beer's. At the energies above 0.07 MeV , two sets of data ${ }^{[5,7]}$ were fitted with spline function code ${ }^{[3]}$, and the results are shown in Fig. 2, compared with ENDF/B-6 and JENDL-3.

## $2.3 \quad{ }^{178} \mathbf{H f}(\mathrm{n}, \gamma)$ Reaction

The Siddappa's data ${ }^{[6]}$ were abandoned for they were measured early and are deviated from the others. The standard used by Beer ${ }^{[4]}$ was ${ }^{6} \mathrm{Li}(\mathrm{n}, \mathrm{t})$ cross section from ENDF/B-5, so the data were corrected with the new standard from ENDF/B-6.

Two sets of data ${ }^{[4,7]}$ are the same, but coincident with each other in the high energy region, there is somewhat systematical discrepancy in the low energy region. The data were fitted with spline code $\mathrm{SPF}^{[3]}$ and the results are shown in Fig. 3 compared with the curve of ENDF/B-6 and JENDL-3.

## 2.4 ${ }^{179} \mathbf{H f}(\mathrm{n}, \gamma)$ Reaction

The data of Siddappa ${ }^{[6]}$ were abandoned because they were measured early and are deviated from the others. The data of Bokhovko ${ }^{[7]}$ were also abandoned for they were measured with the facility VAN-DE-GRAAFF accelerator EG-1. The Beer's data ${ }^{[4]}$ were corrected for the standard with the corresponding data from ENDF/B-6. The experimental data were fitted with spline function code ${ }^{[3]}$ and the results are shown in Fig. 4.

## $2.5{ }^{180} \mathrm{Hf}(\mathrm{n}, \gamma)$ Reaction

Table 3 presents the information for the collected experimental data of ${ }^{180} \mathrm{Hf}$ $(\mathrm{n}, \gamma)$ reaction cross section.

Table 3 The information of the experimental data for ${ }^{180} \mathrm{Hf}(\mathrm{n}, \gamma)$ reaction

| Entry | Inst | Author | Year | Method | $E_{\mathrm{n}} / \mathrm{MeV}$ | $f^{\prime}$ | Adj ${ }^{2}$ | Isoto. |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 11399 | USAORL | R.L.Macklin | 1957 | Activation | 0.024 | 0.3164 | NO | ${ }^{180} \mathrm{Hf}$ |
| 12115 | USAANL | J A.Miskel | 1962 | Activation | 0.032~3.97 | $\begin{gathered} \text { From } 5.9794 \\ \text { to } 0.6015 \end{gathered}$ | 10\% | ${ }^{180} \mathrm{Hf}$ |
| 12755 | USAORL | H.Beer | 1982 | TOF 40.12 M <br> Activation PATH | 0.0035~1.85 | See Table 4 | NO | ${ }^{180} \mathrm{Hf}$ |
| 30502 | INDAUW | K.Siddappa | 1974 | Activation | 0.023 | 1.08619 | NO | ${ }^{180} \mathrm{Hf}$ |
| 30685 | CPRAEP | Zhou Zuying | 1984 | Activation | 0.159~1.473 | 1.0 | NO | ${ }^{180} \mathrm{Hf}$ |
| 31482 | CPRBJG | Chen Jinxiang | 1997 | Activation | 0.52~1.60 | 1.0 | NO | ${ }^{186} \mathrm{Hf}$ |
| 40975 | CCPRI | Yu.N.Trofimov | 1987 | Activation | 2 | 1.0 | NO | ${ }^{180} \mathrm{Hf}$ |
| 41001 | CCPRI | Yu.N.Trofimov | 1987 | Activation | 1 | 0.96747 | NO | ${ }^{180} \mathrm{Hf}$ |
| 41225 | RUSFEI | N.V.Bokhovko | 1996 | TOF | $0.018 \sim 0.45$ | 1.0 | NO | ${ }^{180} \mathrm{Hf}$ |

Note 1) $f$ : correction factor.
2) Adj Error adjusted.

The data of Macklin ${ }^{[8]}$ and Siddappa ${ }^{[10]}$ were abandoned only due to the $\mathrm{Sb}-\mathrm{Be}$ neutron source was used. The Miskel's data ${ }^{[9]}$ were also abandoned because they were measured too early and the correction is too large and the corrected data are still deviated from the others. There are 6 sets of Data ${ }^{[4,11-14,7]}$ remained. They were
corrected and then fitted with SPF code ${ }^{[3]}$. The fit curve was taken as recommended one, and is shown in Fig. 5, compared to ENDF/B-6 and JENDL-3.

Table 4 The correction factor of ${ }^{6} \mathrm{Li}(n, t)$ of ENDF/B-5

| $E_{\text {n }}(\mathrm{keV})$ | 3.5 | 5.0 | 7.0 | 9.0 | $12.5-1450$ | 1550 | 1650 | 1750 | 1850 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| B-5(b) | 2.53467 | 2.11728 | 1.78562 | 1.58085 | 1.34916 <br> 0.2143 | 0.2133 | 0.2126 | 0.2121 | 0.21155 |
| B-6(b) | 2.518 | 2.10832 | 1.78454 | 1.57712 | 1.344406 <br> 0.212818 | 0.212587 | 0.21338 | 0.215259 | 0.217158 |
| B-6/B-5 | 0.99342 | 0.99573 | 0.999395 | 0.9977 | 1.0 | 0.9967 | 1.004 | 1.015 | 1.027 |

## 2.6 ${ }^{\mathrm{Nat}} \mathbf{H f}(\mathrm{n}, \gamma)$ Reaction

In Table 5 is shown the information for the measurement of ${ }^{\mathrm{Nat}} \mathrm{Hf}(\mathrm{n}, \gamma)$ cross section.

Table 5 The information of the experimental data for ${ }^{\text {nat }} \mathrm{Hf}(\mathrm{n}, \gamma)$ reaction

| Entry | Inst. | Author | Year | Method | $E_{\mathrm{n}} / \mathrm{MeV}$ | $f^{1)}$ | Adj2 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 11331 | USAORL | R.L.Macklin | 1963 | NO | $0.03 \sim 0.065$ | 1.083 | NO |
| 12832 | USAANL | W.P.Poentz | 1982 | TOF 2.5-M | $0.5 \sim 3.5$ | 1.186 |  |
| 20358 | GERKFK | D.Kompe | 1969 | TOF | $0.0122 \sim 0.151$ | 0.9832 | NO |
| 32506 | CPRSIU | Mu Yunshan | 1988 | TOF | $0.77 \sim 1.61$ | 1.0 | NO |
| 32541 | CPRSIU | Wang | 1990 | TOF | $0.0114 \sim 0.1$ | See | NO |

Note 1) $f$, correction factor.
2) Adj Error adjusted.

Table 6 The correction factor of ${ }^{197} \mathrm{Au}(\mathrm{n}, \boldsymbol{\gamma})$

| $E_{\mathrm{n}} / \mathrm{keV}$ | 11.40 | 13.00 | 14.50 | 15.60 | 16.90 | 18.30 | 19.90 | 21.70 | 23.70 | 26.10 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Ref(b) | 1095 | 995.5 | 920.5 | 875.4 | 830.2 | 787.35 | 746.55 | 707.45 | 671.25 | 633.70 |
| B-6(b) | 1093.59 | 1003.91 | 919.827 | 868.34 | 817.51 | 762.77 | 700.21 | 672.202 | 643.852 | 620.945 |
| Ratio | 0.9987 | 1.008 | 0.9993 | 0.9919 | 0.9847 | 0.9688 | 0.9379 | 0.9502 | 0.9592 | 0.9799 |
|  |  |  |  |  |  |  |  |  |  |  |
| $E_{\mathrm{n}} / \mathrm{keV}$ | 28.90 | 32.10 | 35.90 | 40.40 | 45.80 | 52.00 | 60.50 | 70.60 | 83.50 | 100.0 |
| Ref(b) | 598.65 | 564.10 | 530.85 | 499.4 | 468.1 | 439.6 | 407.4 | 377.56 | 349 | 321 |
| B-6(b) | 596.027 | 568.198 | 535.442 | 496.652 | 453.488 | 426.27 | 394.675 | 365.686 | 333.525 | 309.9 |
| RATIO | 0.9956 | 1.007 | 1.009 | 0.9945 | 0.9688 | 0.9697 | 0.9688 | 0.9686 | 0.9557 | 0.9654 |

Wang's data $\left[{ }^{19]}\right.$ were measured with monitor ${ }^{197} \mathrm{Au}$, and ${ }^{197} \mathrm{Au}(\mathrm{n}, \gamma)$ cross section was taken from (HSJ-7741,7805), so the data were renormalized with the new
international standard ${ }^{197} \mathrm{Au}(\mathrm{n}, \gamma)$ cross section from ENDF/B-6. All of the experimental data ${ }^{[15-19]}$, after they were corrected, are in agreement with each other. They were fitted with code $\mathrm{SPF}^{[3]}$. The results are shown in Fig. 6.

## 2.7 ${ }^{\mathrm{Na}} \mathrm{Hf}$ (n, tot) Cross Section

The measured data for the total cross section of natural hafnium are shown in table 7.

Table 7 the information of the experimental data for ${ }^{\text {nat }} \mathrm{Hf}(\mathrm{n}$, tot) reaction

| Entry | Inst. | Author | Year | Method | $E_{\mathrm{n}} / \mathrm{MeV}$ | $f^{1)}$ | Adj $^{2}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $10007-005$ | USAANL | G.L.Sherwood | 1970 | TOF | $0.1045 \sim 14.977$ | 1.0 | NO |
| $10007-006$ | USAANL | G.L.Sherwood | 1970 | TOF | $0.60667 \sim 1.4032$ | 1.0 | NO |
| 10047 | USABNW | D.G.Foster | 1971 | TOF | $2.255 \sim 14.92$ | 1.0 | NO |
| 10225 | USABET | L.Green | 1973 | TOF 3.7-M | $0.49551 \sim 9.878$ | 1.0 | NO |
| 10523 | USADKE | M.Divadeenam | 1968 | NO | $0.12 \sim 0.64$ | 1.0 | NO |
| 12061 | USAWIS | A.Okazaki | 1954 | NO | $0.50 \sim 2.96$ | 1.0 | $5 \%$ |

Note 1) $f$, correction factor.
2) Adj Error adjusted.

The experimental data listed in the Table 7 are basically in consistent with each other. But Foster's data ${ }^{[21]}$ at last 3 energy points were deviated unreasonably from the others, so they were deleted. The data error was not given by Okazaki ${ }^{[24]}$, it was assigned as $5 \%$ according to the text. The data ${ }^{[20-24]}$ remained were fitted with spline function code ${ }^{[3]}$ and the results are shown in Fig. 7, Fig. 8 and Fig. 9.

## 3 Conclusion Remarks

The cross sections of ( n , tot) reaction for natural hafnium and $(\mathrm{n}, \gamma$ ) for natural Hf and its isotopes ${ }^{176-180} \mathrm{Hf}$ were evaluated the basis of available experimental data up to now. The experimental data were analysed and corrected, and their errors were adjusted. The evaluated experimental data were fitted with spline fit program SPF ${ }^{[3]}$, recommended they will be used as the complete data evaluation of natural Hf and its isotopes for CENDL-3.


Fig. $1{ }^{176} \mathrm{Hf}(\mathrm{n}, \gamma)$ cross section


Fig. $2{ }^{177} \mathrm{Hf}(\mathrm{n}, \gamma)$ cross section


Fig. $3{ }^{178} \mathrm{Hf}(\mathrm{n}, \gamma)$ cross section


Fig. $4{ }^{179} \mathrm{Hf}(\mathrm{n}, \gamma)$ cross section


Fig. $5{ }^{180} \mathrm{Hf}(\mathrm{n}, \gamma)$ cross section


Fig. $6{ }^{\text {Nat }} \mathrm{Hf}(\mathrm{n}, \gamma)$ cross section


Fig. $7{ }^{\text {Nal }} \mathrm{Hf}(\mathrm{n}$, tot $)$ cross section


Fig. $8{ }^{\text {Nat }} \mathrm{Hf}$ ( n ,tot) cross section


Fig. $9{ }^{\mathrm{Nat}} \mathrm{Hf}(\mathrm{n}$, tot) cross section

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# Evaluation of Complete Neutron Data for Fission Product Nuclides ${ }^{129,131,132,134-136} \mathrm{Xe}$ from $10^{-5} \mathrm{eV}$ to 20 MeV 

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## Abstract

Neutron nuclear data in the energy region between $10^{-5}$ and 20 MeV were evaluated for fission product nuclides ${ }^{129,131,132,134-136} \mathrm{Xe}$ for the CENDL-3. This
evaluation provides a complete representation of the nuclear data needed for transport, damage, heating, radioactivity and shielding application. Evaluation was made on the basis of experimental data up to 1999 and nuclear moder calculation. The data were compared with other evaluated data from ENDF/B-6, JENDL-3 and BROND-2 Libraries.

## Introduction

Xe is a gas element and is one of the important fission product nuclides. Its various kinds of reaction cross sections and energy spectra are requisite for activation analysis and estimation of radiation damage in fusion reactor technology. However, there are some discrepancies in several evaluated nuclear data libraries. The cross section for ${ }^{134,136} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})$ reactions were one of activation cross sections for the generation of short-lived important radionuclides in nuclear technology. In this work, the activation cross sections for ${ }^{129,131,132,134-136} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n}),(\mathrm{n}, 3 \mathrm{n}),(\mathrm{n}, \gamma)$ and some emission charged particle ( $\mathrm{n}, \mathrm{x}$ ) reactions below 20 MeV were evaluated on the basis of experimental and theoretical data.

## 1 Resonance Parameter and Evaluated Files

The resonance parameters for 6 isotopes of Xe were taken from JENDL-3 due to the resonance parameter boundary is higher ( 100 keV ). For example, for ${ }^{131} \mathrm{Xe}$ the resolved resonance region is below 2.25 keV and unresolved resonance region is from 2.25 keV to 100 keV . The smooth cross section at boundary should be reasonably conjuncted with the cross section calculated from resonance parameters. When the conjunction between the smooth cross section and resonance region at boundary is not good, the evaluated data were adjusted around boundary region so as to make the smooth cross section consistent with the calculated one from resonance parameters, see Fig. 1. After adjusting, the cross sections at boundary are in good conjunction within fixed error. The comparisons of evaluated reaction channels (MT number) for ${ }^{131} \mathrm{Xe}$ with other nuclear data libraries from ENDF/B-VI, JENDL-3 and BROND-2 are shown in Table 1.


Fig. 1 Comparison of evaluated and measured data for ${ }^{131} \mathrm{Xe}$

Table 1 Comparison of evaluated nuclear data libraries for ${ }^{131} \mathbf{X e}$

| ${ }^{131} \mathrm{Xe}$ | ENDF/B-6 | JENDL-3 | BROND-2 | CENDL-3 |
| :---: | :--- | :--- | :--- | :--- |
| MAT | $5446(1978)$ | $5446(1990)$ | $5431(1985)$ | $3541(1999)$ |
| File 2. | $1.0^{-5} \mathrm{eV} \sim 1 \mathrm{keV}$ | $1.0^{-5} \mathrm{eV} \sim 2.25 \mathrm{keV}$ | $1.0^{-5} \mathrm{eV} \sim 1.0 \mathrm{keV}$ | $1.0^{-5} \mathrm{eV} \sim 2.25 \mathrm{keV}$ |
|  | $1.0 \sim 80 \mathrm{keV}$ | $2.25 \sim 100 \mathrm{keV}$ | $1.0 \sim 80 \mathrm{keV}$ | $2.25 \sim 100 \mathrm{keV}$ |
| Files. 3,4 | $1,2,3,4$ | $51 \sim 56,91$ | $1,2,3,4,22,28$ | $1,2,3,4$ |
|  | $103 \sim 105,107$ | $103 \sim 105,107$ | $51 \sim 56,91$ | $51 \sim 61,91$ |
|  | $16,17,91$ | $16,17,22,28,32,91$ | $16,17,91$ | $103 \sim 105,107$ |

## 2 Evaluation of Smooth Cross Sections

There are 9 isotopes for xenon in nature and the abundance of isotopes is $0.095 \%$ for ${ }^{124} \mathrm{Xe}, 0.089 \%$ for ${ }^{126} \mathrm{Xe}, 1.910 \%$ for ${ }^{128} \mathrm{Xe}, 26.40 \%$ for ${ }^{129} \mathrm{Xe}, 4.071 \%$ for ${ }^{130} \mathrm{Xe}, 21.232 \%$ for ${ }^{131} \mathrm{Xe}, 26.909 \%$ for ${ }^{132} \mathrm{Xe}, 10.436 \%$ for ${ }^{134} \mathrm{Xe}, 8.857 \%$ for ${ }^{136} \mathrm{Xe}$, respectively. In present work, the complete data for 6 isotopes of fission products Xe up to neutron energy of 20 MeV were evaluated including cross
 $(n, t),(n, \alpha), \ldots$, and emission particle spectra for $(n, 2 n),(n, 3 n),(n, n+p),(n, n+\alpha)$, ( $\mathrm{n}, \mathrm{n}$ 'continue). The available experimental data are shown in Table 2.

## $2.1{ }^{134,136} \mathbf{X e}(\mathbf{n}, 2 n){ }^{133,135} \mathbf{X e}$ Reactions

The measured data for most of the lighter isotopes of Xe are poor owing to their low neutron abundance. Main measurements for ( $n, 2 n$ ) reaction were performed
around 14 MeV because of the availability of intense source of mono-energies neutron of this energy from Cockrofe-Walton accelerator. The measured data for ( $\mathrm{n}, 2 \mathrm{n}$ ) reaction around 14 MeV were collected, selected and renomalized to a common set of decay data and reference cross sections. There are 3 sets of measured data since 1968 (total 6 experimental values), with $10 \% \sim 38 \%$ discrepancy, see Table 3. So the evaluations of cross sections are necessary.

Table 2 The available experimental data of isotopes of Xe

|  | $\sigma_{\text {ot }}$ | $\sigma_{\mathrm{n}, 2 \mathrm{n}}$ | $\sigma_{\mathrm{n}, 3}$ | $\sigma_{\mathrm{n}, \mathrm{y}}$ | $\sigma_{\mathrm{n}, \mathrm{p}}$ | $\sigma_{\mathrm{n}, \alpha}$ |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: |
| ${ }^{\mathrm{Nat} \mathrm{Xe}}$ | $0.1 \sim 20 \mathrm{MeV}$ |  |  |  |  | $12.5 \sim 18.0 \mathrm{MeV}$ |
| ${ }^{129} \mathrm{Xe}$ |  |  |  |  |  |  |
| ${ }^{131} \mathrm{Xe}$ |  |  |  |  | $14.4,14.6 \mathrm{MeV}$ |  |
| ${ }^{132} \mathrm{Xe}$ |  |  |  | 25.0 keV | 14.4 MeV |  |
| ${ }^{133} \mathrm{Xe}$ |  |  |  |  |  |  |
| ${ }^{134} \mathrm{Xe}$ |  | 14.7 MeV |  | 25.0 keV | $14.4,14.6 \mathrm{MeV}$ |  |
| ${ }^{139} \mathrm{Xe}$ |  |  |  |  |  |  |
| ${ }^{136} \mathrm{Xe}$ |  | 14.7 MeV |  |  | 14.6 MeV |  |

Table 3. ${ }^{134,136} \mathbf{X e}(\mathrm{n}, \mathbf{2 n})$ cross sections and relative information

| Year | Author | $\begin{gathered} E_{\mathrm{n}} \\ (\mathrm{MeV}) \end{gathered}$ | Reactions | $\sigma / \mathrm{mb}$ | Monitor | Adjusted factors | $\sigma / \mathrm{mb}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1968 | E.Kondaiah | 14.4 | $\begin{aligned} & { }^{134 \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})^{133} \mathrm{Xe}} \\ & { }^{134} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})^{133 \mathrm{~g}} \mathrm{Xe} \\ & { }^{136} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})^{135 \mathrm{~m}} \mathrm{Xe} \\ & { }^{136} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})^{135} \mathrm{Xe} \end{aligned}$ | $\begin{aligned} & 2360 \pm 240 \\ & 665 \pm 80 \\ & 750 \pm 50 \\ & 1700 \pm 100 \end{aligned}$ | $\begin{aligned} & { }^{28} \mathrm{Si}(\mathrm{n}, \mathrm{p}) \\ & { }^{27} \mathrm{Al}(\mathrm{n}, \alpha) \\ & { }^{27} \mathrm{Al}(\mathrm{n}, \alpha) \\ & { }^{27} \mathrm{Al}(\mathrm{n}, \alpha) \end{aligned}$ | $\begin{aligned} & 0.9949 \\ & 0.9801 \\ & 0.9801 \end{aligned}$ | $\begin{aligned} & 169 \pm 170^{*} \\ & 661 \pm 78 \\ & 735 \pm 49 \\ & 1666 \pm 98 \end{aligned}$ |
| 1976 | R.A.Sigg | 14.6 | $\begin{aligned} & { }^{1344} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})^{133 \mathrm{~m}} \mathrm{Xe} \\ & { }^{134} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})^{1338} \mathrm{Xe} \\ & { }^{134} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})^{133} \mathrm{Xe} \\ & { }^{136} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})^{135 \mathrm{~m}} \mathrm{Xe} \\ & { }^{136} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})^{1358 \mathrm{Xe}} \\ & { }^{136} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})^{135} \mathrm{Xe} \end{aligned}$ | $\begin{aligned} & 665 \pm 60 \\ & 805 \pm 90 \\ & 1460 \pm 110 \\ & 788 \pm 60 \\ & 772 \pm 60 \\ & 1560 \pm 100 \end{aligned}$ | $\begin{aligned} & { }^{27} \mathrm{Al}(\mathrm{n}, \alpha) \\ & { }^{27} \mathrm{Al}(\mathrm{n}, \alpha) \\ & { }^{27} \mathrm{Al}(\mathrm{n}, \alpha) \\ & { }^{27} \mathrm{Al}(\mathrm{n}, \alpha) \\ & { }^{27} \mathrm{Al}(\mathrm{n}, \alpha) \\ & { }^{27} \mathrm{Al}(\mathrm{n}, \alpha) \end{aligned}$ | $\begin{aligned} & \hline 0.9690 \\ & 0.9461 \\ & 0.9461 \\ & 0.9862 \\ & 0.9799 \\ & 1.0186 \end{aligned}$ | $\begin{aligned} & 644 \pm 58 \\ & 761 \pm 85 \\ & 1381 \pm 104 \\ & 777 \pm 59 \\ & 756 \pm 78 \\ & 1589 \pm 102 \end{aligned}$ |
| 1982 | A.Reggoug | 14.7 | $\begin{aligned} & { }^{134} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n}){ }^{133 \mathrm{~m}} \mathrm{Xe} \\ & { }^{134} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})^{1338 \mathrm{Xe}} \\ & { }^{136} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})^{133 \mathrm{~m}} \mathrm{Xe} \end{aligned}$ | $\begin{aligned} & 665 \pm 60 \\ & 805 \pm 90 \\ & 750 \pm 50 \end{aligned}$ |  |  |  |

* Origenal author pornt out the previously reported value as $2360 \pm 240 \mathrm{mb}$ due to an error in the photopeak efficie.

The cross sections for ${ }^{134,136} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n}){ }^{133,135} \mathrm{Xe}$ reactions were firstly measured by E. Kondaiah ${ }^{[1]}$ with activation method, mixed-powder sample and $\mathrm{Ge}(\mathrm{Li}) \gamma$-ray detector at USAGIT laboratory in 1968. The mixed-powder sample is consisted of the inert gas quinol-clathrate and monitor, which were well mixed and sealed in a small polyethylene cylinder. In this activation work, the ${ }^{28} \mathrm{Si}(\mathrm{n}, \mathrm{p}){ }^{27} \mathrm{Mg}$ or ${ }^{27} \mathrm{Al}(\mathrm{n}, \alpha)$ ${ }^{24} \mathrm{Na}$ reactions were used as a monitor, depending on the half-life and gamma energy
of the activity under study. When Wen-deh $\mathrm{Lu}^{[2]}$, who was one of same experimental group of E.Kondaiah, researched into activation cross section for ( $n, 2 n$ ) reaction in region $Z=40 \sim 60$, pointed out the previously result ( $2360 \pm 240 \mathrm{mb}$ ) for ${ }^{134} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})$ ${ }^{133} \mathrm{Xe}$ reaction was mistaken due to an error in the photopeak efficiency. The old data were corrected by Wen-deh $\mathrm{Lu}^{[2]}$ to as $1698 \pm 170 \mathrm{mb}$.

According to requirement of the development of reaction systematics and testing nuclear models, the interest in accurate measurements around 14 MeV cross section for $\mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})$ cross section was persistent. The cross sections for ${ }^{134,136} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})$ ${ }^{133,135} \mathrm{Xe}$ reactions were measured by R.A.Sigg ${ }^{[3]}$ with same method using sodium perxenate sample and $\mathrm{Ge}(\mathrm{Li}) \gamma$-ray spectroscopy at the Cockcroft-walton accelerator of Arkansan University in 1976. The sample does not decompose below $365^{\circ} \mathrm{C}$ for the irradiation. And the sample was dehydrated by heating to $120^{\circ} \mathrm{C}$ under a constant weight to make the sample mass constant under irradiated.

The cross sections for ${ }^{134,136} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})^{133,135} \mathrm{Xe}$ reactions were also measured by A.Reggoug ${ }^{[4]}$ with activation method and $\mathrm{Gi}(\mathrm{Li})$ detector using X-ray spectroscopy at 14.7 MeV . The author has not given the sample and concerned measurement information in detail. Only the results of isometric and ground state cross sections for ${ }^{134,136} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})$ reactions were given.

Those cross sections around 14 MeV were calculated to get the cross section at 14.6 MeV , according to the shape of the excitation curve for ${ }^{134,136} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n}){ }^{133,135} \mathrm{Xe}$ reactions. In order to obtain the factors of energy adjustment values, the data of Shen Qingbiao ${ }^{[5]}$ were used. The data around 14 MeV were corrected for nuclear decay schemes, half-life and standard cross section, which were taken from Ref. [6,7] . Some data were rejected due to the larger discrepancies with others.

The evaluated data were got with the weighted average for the remaining data after corrections mentioned above. The weighted factors in the evaluation were based on the given errors by authors and quoted errors by us. Present evaluated data is $1391 \pm 100 \mathrm{mb}$ for ${ }^{134} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n}){ }^{133} \mathrm{Xe}$ reaction and $1627 \pm 96 \mathrm{mb}$ for ${ }^{136} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n}){ }^{135} \mathrm{Xe}$ reaction at 14.6 MeV . The comparison of evaluated data for CENDL-3 with experimental data is shown in Figs. 2~3.


Fig. 2 Comparison of evaluated and measured data for ${ }^{134} \mathrm{Xe}$

## $2.2 \quad{ }^{132,134} \mathrm{Xe}(\mathrm{n}, \gamma){ }^{133,135} \mathrm{Xe}$ Reactions

For ${ }^{132,134} \mathrm{Xe}(\mathrm{n}, \gamma){ }^{133,135} \mathrm{Xe}$ reactions, there are experimental data ${ }^{[8,9]}$ available at thermal energy point and 25.0 keV .

The thermal cross section were measured by E.Kondaiah ${ }^{[8]}$ at USAART Laboratory using activation method in 1968. The measuring method for thermal cross section is same as ( $\mathrm{n}, 2 \mathrm{n}$ ) cross section at 14.4 MeV . But the epithermal neutron contribution must be taken into account, therefore the sample was covered with Cd to obtain the strictly thermal neutron cross sections.

The ${ }^{132,134} \mathrm{Xe}(\mathrm{n}, \gamma)^{133,135} \mathrm{Xe}$ reactions were measured by H.Beer ${ }^{[9]}$ using activation method at 25.0 KeV at GERKFK and ITYBOL laboratories. The evaluated experimental data at thermal energy point and 25.0 keV were only used as reference in the theoretical calculation. The final results of the evaluated data with experimental data are shown in Figs. 4~5.

## $2.3 \quad{ }^{131,132,134,136} \mathrm{Xe}(\mathrm{n}, \mathrm{p})$ and ${ }^{\mathrm{Nat}} \mathrm{Xe}(\mathrm{n}, \alpha)$ reactions

The data were measured for ${ }^{131,132,134} \mathrm{Xe}(\mathrm{n}, \mathrm{p}){ }^{131,132,134} \mathrm{I}$ reactions by E.Kondaiah ${ }^{[2]}$ at 14.4 MeV and for ${ }^{131,134,136} \mathrm{Xe}(\mathrm{n}, \mathrm{p}){ }^{131,134,136} \mathrm{I}$ reactions by R.A.Sigg ${ }^{[3]}$ at 14.6 MeV , respectively. After correcting the energy to 14.6 MeV , two sets of data consist within error. Therefore, the data can be taken to guide the theoretical calculation. Another data for ${ }^{132} \mathrm{Xe}(\mathrm{n}, \mathrm{p}){ }^{132} \mathrm{I}$ reaction measured by E.Kondaiah ${ }^{[2]}$ and for ${ }^{136} \mathrm{Xe}(\mathrm{n}, \mathrm{p}){ }^{136} \mathrm{I}$ reaction measured by R.A.Sigg ${ }^{[3]}$ could be used as reference for calculation. The comparison of evaluated data with experimental data for ${ }^{131,134} \mathrm{Xe}(\mathrm{n}, \mathrm{p}){ }^{131,134} \mathrm{I}$ reactions
are shown in Figs. 6~7.
 to 18.0 MeV . A high pressure gas scintillator filled either with pure natural xenon or with a mixture of xenon and helium was used as both target and detector. The helium served as a monitor. The ( $\mathrm{n}, \alpha$ ) spectra were measured and analyzed. In present work, the values measured by G. Mack ${ }^{[10]}$ are taken as references for theoretically calculation. The comparison of evaluated data for ${ }^{134} \mathrm{Xe}(\mathrm{n}, \alpha)$ reaction and measured data for ${ }^{\mathrm{Nat}} \mathrm{Xe}(\mathrm{n}, \alpha)$ reaction is shown in Fig. 8.
 data, for other ${ }^{129,131 \sim 136} \mathrm{Xe}(\mathrm{n}, \alpha)$ reactions, the cross sections were calculated theoretically.

## 3 Theoretical Calculation and Recommendation

In order to recommend the cross sections for 6 isotopes of $\mathrm{Xe}(\mathrm{n} .2 \mathrm{n}),(\mathrm{n}, 3 \mathrm{n}),(\mathrm{n}, \gamma)$ and ( $\mathrm{n}, \mathrm{x}$ ) reactions, the theoretical calcu'ation were performed with UNF code ${ }^{[1]]}$, based on the available total cross sections of ${ }^{\text {nat }} \mathrm{Xe}$ measured by F.J. Vaughn ${ }^{[12]}$ and B. Leugers ${ }^{[13]}$, nonelastic scattering cross sections evaluated by us from ( $\left.n, \gamma\right),(n, 2 n)$ etc. for natural and isotopes of Xe in energy region $0.001 \sim 14 \mathrm{MeV}$. Because there are no experimental data for elastic angular distributions, the data of neighbor nucleus were used.

A set of neutron optical potential parameters of neighbor nucleus was used as preliminary input data. A set of neutron optical potential parameters for Xe was obtained in the energy region $0.001 \sim 20 \mathrm{MeV}$ by using automatic searching code $\mathrm{APOM}^{[14]}$.

$$
\begin{aligned}
& V=52.91819-0.6317 E+0.02692 E^{2}-28.66(N-2) / A+0.06277 Z / A^{1 / 3} \\
& W_{\mathrm{s}}=3.600086+0.46658 E-11.53(N-Z) / A \\
& W_{\mathrm{v}}=0.3772+0.1455 E-0.00764 E^{2} \\
& W_{\text {so }}=6.2 \\
& r_{\mathrm{r}}=1.2166 \quad r_{\mathrm{r}}=1.2693 \quad r_{\mathrm{v}}=1.838 \quad r_{\mathrm{so}}=1.2166 \\
& a_{\mathrm{r}}=0.7057 \quad a_{\mathrm{s}}=0.2800 \quad a_{\mathrm{v}}=0.2800 \quad a_{\mathrm{so}}=0.7057
\end{aligned}
$$

Using this set of neutron optical potential parameters and adjusted level density and giant dipole resonance parameters, the cross sections of $\operatorname{Xe}(n, 2 n),(n, 3 n),(n, \gamma)$ and ( $n, x$ ) reactions were calculated. The calculated data can reproduce the measured data available very well.

The inelastic scattering crosses sections to some low levels consist of direct and compound inelastic reactions. The direct inelastic scattering cross sections were calculated with the distorted wave Born approximation DWUCK4 code.

The recommended cross sections for ( $n, \gamma$ ) were given on the basis of the measured and model calculation.

The thresholds of the ( $\mathrm{n}, \mathrm{x}$ ) reactions are above $\sim 8 \mathrm{MeV}$. The calculated cross sections are of the order of a few ten mb or less, generally much less. They were in agreements with existing experimental data. For ( $\mathrm{n}, \alpha$ ) and ( $\mathrm{n}, \mathrm{p}$ ) reactions, the calculated curve could close to or pass the data measured around 14 MeV . The calculated results for ( $\mathrm{n}, \mathrm{x}$ ) reactions were recommended.

The cross sections of all reactions induced by neutron on 6 isotopes of Xe were recommended. The evaluated cross sections and neutron secondary spectra for ${ }^{134,135} \mathrm{Xe}$ are shown in Fig. 9~14.

## 4 Benchmark Testing

In order to satisfy the requirement of reactor projects, the benchmark testing of neutron absorption effects were researched for this new evaluation. The evaluated data for ( $\mathrm{n}, \gamma$ ) reaction of Xe were tested by Liu Guisheng ${ }^{[5]}$ using integral foundation data. The integral foundation assembly CFRMF (Coupled Fast Reactivity Measurement Facility) was established at Idaho National Engineering Laboratory of USA. The enrich uranium was located at the center of the assembly and the water was moderator as reflect blanketing. The assembly was mainly used to test the evaluated capture cross section for fission products and actinide nuclei.

The average capture cross section of irradiated samples, located at center of assembly, for many fission products nuclei were measured by C.R.Weishin ${ }^{[16]}$. Using our evaluated fission product data, the average capture cross sections were calculated by Liu Guisheng ${ }^{[15]}$ with NJOY code. The C/E rate between calculated


Fig. 3 Comparison of evaluated and measured data for ${ }^{136} \mathrm{Xe}$


겅 Fig. 5 Comparison of evaluated and measured data for ${ }^{134} \mathrm{Xe}$


Fig. 4 Comparison of evaluated and measured data for ${ }^{132} \mathrm{Xe}$


Fig. 6 Comparison of evaluated and measured data for ${ }^{131} \mathrm{Xe}(\mathrm{n}, \mathrm{p})$ reaction


Fig. 7 Comparison of evaluated and measured data for ${ }^{134} \mathrm{Xe}(\mathrm{n}, \mathrm{p})$ reaction


Fig. 9 Evaluated neutron cross section for ${ }^{134} \mathrm{Xe}$


Fig. 8 Comparison of evaluated and measured data for ${ }^{134} \mathrm{Xe}(\mathrm{n}, \alpha)$ reaction


Fig. 10 Evaluated neutron cross section for ${ }^{133} \mathrm{Xe}$


Fig. 11 Normalized secondary neutron spectra for ${ }^{134} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})$ reaction


Fig. 13 Normalized secondary neutron spectra for ${ }^{135} \mathrm{Xe}(\mathrm{n}, 2 \mathrm{n})$ reaction


Fig. 12 Normalized secondary neutron spectra for ${ }^{134} \mathrm{Xe}(\mathrm{n}, \mathrm{np})$ reaction


Fig. 14 Normalized secondary neutron spectra for ${ }^{135} \mathrm{Xe}(\mathrm{n}, \mathrm{np})$ reaction
value and experimented value was obtained for each product, here C means calculation from evaluated nuclear libraries, while the E means experimental value measured by C.R.Weishin ${ }^{[16]}$.

According to the test results for Xe , our evaluated data for capture cross section of ${ }^{132,134} \mathrm{Xe}$ consist with benchmark testing data within errors, especially the evaluated data for ${ }^{134} \mathrm{Xe}$ are in the best agreement comparing with others from ENDF/B-5, ENDF/B-6, JEF-2.The results are given in Table 4.

Table 4 Comparison of measured and calculated values for ${ }^{132,134} \mathbf{X e}$

|  | ${ }^{132} \mathrm{Xe}$ |  | ${ }^{13+} \mathrm{Xe}$ |  |
| :---: | :---: | :---: | :---: | :---: |
|  | $\sigma_{\mathrm{c}} / \mathrm{mb}$ | $\mathrm{C} / \mathrm{E}$ | $\sigma_{\mathrm{c}} / \mathrm{mb}$ | $\mathrm{C} / \mathrm{E}$ |
| Measured Value | $43.90 \pm 3.38$ |  | $14.6 \pm 1.0$ |  |
| and error |  |  |  |  |
| ENDF/B-5 | 48.28 | 1.100 | 24.9 | 1.705 |
| ENDF/B-6 | 49.17 | 1.120 | 25.24 | 1.729 |
| JEF-2 | 48.63 | 1.108 | 24.78 | 1.697 |
| This Work | 49.168 | 1.120 | 17.115 | 1.172 |

## 5 Check of Evaluated Data

The complete neutron data for ${ }^{129,131,132,134-136} \mathrm{Xe}$ were recommended in ENDF/B-6.
The check for complete neutron data, including format, consistency between the total and the sum of partial cross sections, physical parameters was carried out by using ENDF utility codes CHEKR, FIZCOM and PSYCHE. Some problems were found and modified. After all of checks were finished, the complete neutron data were recommended.

## Summary

The characteristics of the evaluated data for 6 isotopes of Xe are as follows :

1) Based on the experimental data of total and nonelastic scattering cross sections of $n+X e$ reaction and cross sections of ( $n, 2 n$ ), ( $n, \gamma),(n, p)$ and ( $n, \alpha) \ldots$ reactions, a set of neutron optical potential parameter and giant resonance parameters of neutrons for xenon were obtained. Then complete data for Xe were
calculated by using the code SUNF. Since the calculated results for many channels are in pretty agreement with available experimental data, the predicted reaction data without experimental data are reasonable.
2) Based on the benchmark testing for ${ }^{132,134} \mathrm{Xe}$, the evaluated data were reviewed and improved. Our evaluated capture cross section for ${ }^{132,134} \mathrm{Xe}$ consist with benchmark testing data within errors, especially for ${ }^{134} \mathrm{Xe}$.

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## IV ATOMIC AND MOLECULAR DATA

# Effect of the Charge Distribution in Nucleus on the Calculation of Highly Ionized Atoms 

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#### Abstract

Wavelengths of highly stripped ions $\mathrm{Br}^{23+}, \mathrm{S}^{10+} \rightarrow \mathrm{S}^{13+}$ are calculated by means of GRASP code with two types of the charge distribution in nucleus. The results show that there are effects of the charge distribution in nucleus on the calculation of highly charged atoms. The wavelengths calculated are better in close agreement with experimental data with Fermi two-parameter distribution than the waclengths calculated with point charge distribution in nucleus .


## Introduction

The spectroscopic studies of highly stripped ions are important for testing basic atomic theory, because they sensitively probe interelectron correlations, relativistic corrections, and effects due to the nuclear structure. Also, such ions have important application in the development of X-ray lasers, the diagnostics of thermonuclear plasmas, biomedicine, and the interpretation of spectra from space.

GRASP (General-purpose Relativistic Atomic Structure Program) presented by I.P. Grant ${ }^{[1]}$ extends the previously published program which solved the atomic
orbital wavefunctions and energy levels. Two types of the charge distribution (point charge distribution and Fermi two-parameter distribution) in nucleus were adopted to calculate wavelengths of highly stripped ions. From the results calculated we can analyse the effects of the charge distribution in nucleus on the calculation of highly ionized atoms.

## 1 Theory

Relativistic atomic structure theory is ultimately based on quantum electrodynamics. The GRASP approximation for the calculation of atomic stationary states and transitions among them has been described in the literature ${ }^{[2-4]}$. Only a brief outline of the theory is given in this paper.

As described more fully in Ref. [5] we construct atomic state functions (ASF) from a linear combination of configuration state functions (CSF) which are eigenfunctions of $J^{2}, J_{2}$ and parity. These in turn are built from single-electron Dirac equation.

All the dominant interactions in the highly stripped ion are included in the Dirac-Coulomb Hamiltonian,

$$
\begin{equation*}
\mathrm{H}^{\mathrm{DC}}=\sum_{i=1}^{N} \mathrm{H}_{i}+\sum_{i=1}^{N-1} \sum_{j=i+1}^{N}\left|r_{i}-r_{j}\right|^{-1} \tag{1}
\end{equation*}
$$

in the first term (in atomic units),

$$
\begin{equation*}
\mathrm{H}=c \sum_{i=1}^{3} \alpha_{i} p_{i}+(\beta-1) c^{2}+V_{\mathrm{nuc}}(r) \tag{2}
\end{equation*}
$$

is the one-body contribution for an electron due to its kinetic energy and interaction with the nucleus-the rest energy, $\mathrm{c}^{2}$, has been subtracted out, $r$ is the position vector of the electron, $c$ is the velocity of light, $p \equiv-i \nabla$ is the momentum operator. The operator $\alpha_{i}$ and $\beta$ have their conventional representations

$$
\alpha_{i}=\left(\begin{array}{ll}
0 & \sigma_{i}  \tag{3}\\
\sigma_{i} & 0
\end{array}\right), i=1,2,3, \quad \beta=\left(\begin{array}{ll}
I & 0 \\
0 & -I
\end{array}\right)
$$

where $I$ is the $2 \times 2$ unit matrix and the $\sigma_{i}$ are the usual Pauli matrices. The twobody instantaneous Coulomb interactions between the electrons comprise the second term in (1). Higher-order (QED) modifications to (1) and (2) due to the transverse electromagnetic interaction and the radiative corrections are treated via perturbation theory. The nuclear potential energy, $V_{\text {nuc }}(r)$, takes the two types of the charge distribution in nucleus. First, it takes the Coulomb form or point charge distribution in nucleus, $V_{\text {nuc }}=-Z / r$ (where $Z$ denotes the atomic number of the system); second, takes the Fermi two-parameter distribution,

$$
\begin{equation*}
\rho_{\mathrm{nuc}}(r)=\frac{\rho_{0}}{1+\mathrm{e}^{\left(r-c_{1}\right) / a}}, t=(4 \ln 3) a \tag{4}
\end{equation*}
$$

the parameter $c_{1}$ is the "half-charge radius", the value of $r$ for which $\rho_{\text {nuc }}(r)=0.5 \rho_{0}$; it thus provides a measure of the nuclear radius. The surface thickness $t$, which measures the distance over which the density falls from $0.9 \rho_{0}$ to $0.1 \rho_{0}$. For $A$ (nuclear numbers of system) $>12$, there is a central region of fairly uniform charge density given by $\rho_{0}=0.17 \mathrm{fm}^{-3}, a=0.54 \mathrm{fm}^{[6]}$. The nuclear potential may be calculated from the identity ${ }^{[1]}$

$$
-r V_{\mathrm{nuc}}(r)=4 \pi\left(\int_{0}^{r} \rho(s) s^{2} \mathrm{~d} s+r \int_{r}^{\infty} \rho(s) s \mathrm{~d} s\right)
$$

The oscillator strength for the transition from ASF $\Gamma_{\mathrm{i}}$ to ASF $\Gamma_{\mathrm{j}}$ induced by a multipole radiation field operator $O_{M}^{(L)}$ of order L is ${ }^{[3]}$

$$
f_{i \rightarrow j}=\frac{\pi c}{(2 L+1) \omega^{2}}\left|\left\langle\Gamma_{i} P_{i} J_{i}\left\|O^{(L)}\right\| \Gamma_{j} P_{j} J_{j}\right\rangle\right|^{2}
$$

where we use the Brink and Satchler ${ }^{[7]}$ definition of the reduced matrix element.

## 2 Results and Discussion

From Ref.[8] we know that GRASP is an available program for researching the atomic structure. Wavelengths of highly ionized atoms $\mathrm{Br}^{23+}, \mathrm{S}^{10+} \rightarrow \mathrm{S}^{13+}$ are computed by means of GRASP code with two types of the charge distribution in nucleus. Table 1~5 give out the comparison of transition wavelengths between
theoretical calculation performed by us and experimental data taken from experimentation performed in the Department of CIAE ${ }^{[9,10]}$. Model 1 for point charge distribution in nucleus, Model 2 for Fermi two-parameter distribution in nucleus.

From Table $1 \sim 5$ we can see that there are effects of the charge distribution in nucleus on the calculation of highly charged atoms. The wavelengths calculated are better in close agreement with experimental data with Fermi two-parameter distribution than calculated ones with point charge distribution in nucleus. These results show that Fermi two-parameter distribution in nucleus is better for interpreting atomic structure experimental data than point charge distribution in nucleus. So, the research of nuclear structure may improve the calculation of highly stripped ions and the research of atomic structure may test the theoretical models of nuclear structure.

Table 1 Wavelength comparison between calculated and measured data for Bromine XXIV ( $\mathbf{B r}^{23+}$ )

| Configuration | Term | $J \sim J$ | Wavelerigth( in $\AA^{\prime \prime}$ ) |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | Exp.(CIAE) | Model 1 | Model 2 |
| $3 \mathrm{~s} 3 \mathrm{p}-3 \mathrm{p}^{2}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{P}$ | 0-1 | $172.58{ }^{*}$ | 171.20 | 171.28 |
| $3 \mathrm{~s} 3 \mathrm{p}-3 \mathrm{p}^{2}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{P}$ | 1~1 | $179.03^{*}$ | 177.80 | 177.84 |
| $3 \mathrm{~s} 3 \mathrm{p}-3 \mathrm{p}^{2}$ | ${ }^{1} \mathrm{P}-{ }^{1} \mathrm{~S}$ | 1~0 | 184.45* | 183.81 | 183.87 |
| $3 \mathrm{~s} 3 \mathrm{p}-3 \mathrm{p}^{2}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{P}$ | 1~0 | 200.76* | 197.92 | 198.00 |
| $3 \mathrm{~s} 3 \mathrm{p}-3 \mathrm{p}^{2}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{P}$ | 2~1 | 203.69** | 201.51 | 201.77 |
| $3 \mathrm{~s} 3 \mathrm{p}-3 \mathrm{~s} 3 \mathrm{~d}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{D}$ | 0~1 | $133.40^{*}$ | 133.11 | 133.22 |
| $3 \mathrm{~s} 3 \mathrm{p}-3 \mathrm{~s} 3 \mathrm{~d}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{D}$ | 1~1 | $137.20^{*}$ | 137.10 | 137.16 |
| $3 \mathrm{~s} 3 \mathrm{p}-3 \mathrm{~s} 3 \mathrm{~d}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{D}$ | 2~3 | 147.68 | 147.40 | 147.44 |
| $3 \mathrm{~s} 3 \mathrm{p}-3 \mathrm{~s} 3 \mathrm{~d}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{D}$ | 2~2 | 149.87* | 149.69 | 149.74 |
| $3 \mathrm{~s} 3 \mathrm{p}-3 \mathrm{~s} 3 \mathrm{~d}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{D}$ | 2~1 | 151.14* | 150.90 | 150.97 |
| $3 \mathrm{p}^{2}-3 \mathrm{p} 3 \mathrm{~d}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{P}$ | 1~0 | 137.20* | 137.79 | 137.79 |
| $3 \mathrm{p}^{2}-3 \mathrm{p} 3 \mathrm{~d}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{D}$ | 0~1 | 138.42* | 139.05 | 139.03 |
| $3 \mathrm{p}^{2}-3 \mathrm{p} 3 \mathrm{~d}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{D}$ | 1~2 | 144.11* | 144.79 | 144.75 |
| $3 \mathrm{p}^{2}-3 \mathrm{p} 3 \mathrm{~d}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{D}$ | 1~1 | $151.14^{\circ}$ | 151.85 | 151.82 |
| $3 \mathrm{p}^{2}-3 \mathrm{p} 3 \mathrm{~d}$ | ${ }^{3} \mathrm{P}-\mathrm{C}^{3} \mathrm{D}$ | 1~2 | 157.58* | 158.87 | 158.80 |
| 3s3d-3p3d | ${ }^{3} \mathrm{D}-{ }^{3} \mathrm{P}$ | 2~2 | $179.03^{*}$ | 178.59 | 178.64 |
| 3s3d-3p3d | ${ }^{3} \mathrm{D}-{ }^{3} \mathrm{P}$ | 2~1 | 180.69* | 180.14 | 180.20 |
| 3s3d-3p3d | ${ }^{3} \mathrm{D}-{ }^{3} \mathrm{D}$ | 2-3 | 182.85* | 181.00 | 181.06 |
| 3s3d-3p3d | ${ }^{3} \mathrm{D}-{ }^{3} \mathrm{P}$ | 3-3 | 185.72* | 184.50 | 184.55 |
| $3 \mathrm{p} 3 \mathrm{~d}-3 \mathrm{~d}^{2}$ | ${ }^{3} \mathrm{~F}-{ }^{3} \mathrm{D}$ | 3-2 | 151.14* | 150.09 | 150.17 |
| $3 \mathrm{p} 3 \mathrm{~d}-3 \mathrm{~d}^{2}$ | ${ }^{3} \mathrm{~F}-{ }^{3} \mathrm{~F}$ | 4~4 | $149.87^{\circ}$ | 149.11 | 149.20 |
| $3 \mathrm{p} 3 \mathrm{~d}-3 \mathrm{~d}^{2}$ | ${ }^{3} \mathrm{D}-{ }^{3} \mathrm{~F}$ | 1~2 | $152.07^{\circ}$ | 151.84 | 151.91 |

Table 2 Wavelength comparison between calculated and measured data for Sulphur X1( $\mathrm{S}^{10+}$ )

| Configuration | Term | $J \sim J$ | Wavelength( in $\AA$ ) |  |  |
| :--- | :--- | :--- | :---: | :---: | :---: |
|  |  |  | Exp.(ClAE) | Model 1 | Model 2 |
| $2 \mathrm{~s}^{2} 2 \mathrm{p}^{2}--2 \mathrm{~s} 2 \mathrm{p}^{3}$ | ${ }^{1} \mathrm{D}-{ }^{1} \mathrm{P}$ |  | 189.54 | 188.17 | 188.23 |
| $2 \mathrm{~s}^{2} 2 \mathrm{p}^{2}--2 \mathrm{~s} 2 \mathrm{p}^{3}$ | ${ }^{3} \mathrm{P}-\mathrm{B}^{3} \mathrm{P}$ | $2 \sim 1$ | 247.18 | 246.33 | 246.41 |
| $2 \mathrm{~s}^{2} 2 \mathrm{p}^{2}--2 \mathrm{~s} 2 \mathrm{p}^{3}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{D}$ | $0 \sim 1$ | 281.85 | 279.59 | 279.76 |
| $2 \mathrm{~s}^{2} 2 \mathrm{p}^{2}-2 \mathrm{~s} 2 \mathrm{p}^{3}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{D}$ | $1 \sim 1$ | 285.58 | 283.82 | 283.91 |
| $2 \mathrm{~s}^{2} 2 \mathrm{p}^{2}-2 \mathrm{~s} 2 \mathrm{p}^{3}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{D}$ | $2 \sim 3$ | 291.58 | 290.03 | 290.11 |

Table 3 Wavelength comparison between calculated and measured data for Sulphur XII (S11+)

| Configuration | Term | $J \sim J$ | Wavelength( in $\AA$ ) |  |  |
| :--- | :--- | :---: | :---: | :---: | :---: |
|  |  |  | Exp.(ClAE) | Model 1 | Model 2 |
| $2 \mathrm{~s}^{2} 2 \mathrm{p}-2 \mathrm{~s} 2 \mathrm{p}^{2}$ | ${ }^{2} \mathrm{P}-{ }^{2} \mathrm{P}$ |  | 212.45 | 211.89 | 211.96 |
| $2 \mathrm{~s}^{2} 2 \mathrm{p}-2 \mathrm{~s} 2 \mathrm{p}^{2}$ | ${ }^{2} \mathrm{P}-{ }^{2} \mathrm{~S}$ | $1 / 2 \sim 1 / 2$ | 227.59 | 224.76 | 224.85 |
| $2 \mathrm{~s}^{2} 2 \mathrm{p}-2 \mathrm{~s} 2 \mathrm{p}^{2}$ | ${ }^{2} \mathrm{p}-{ }^{2} \mathrm{~S}$ | $3 / 2 \sim 1 / 2$ | 234.33 | 231.58 | 231.68 |
| $2 \mathrm{~s} 2 \mathrm{p}^{2}-2 \mathrm{p}^{3}$ | ${ }^{2} \mathrm{P}-{ }^{2} \mathrm{~S}$ | $1 / 2 \sim 3 / 2$ | 240.08 | 238.01 | 238.12 |
| $2 \mathrm{~s} 2 \mathrm{p}^{2}-2 \mathrm{p}^{3}$ | ${ }^{2} \mathrm{P}-{ }^{2} \mathrm{~S}$ | $3 / 2 \sim 3 / 2$ | 243.08 | 240.78 | 240.86 |
| $2 \mathrm{~s} 2 \mathrm{p}^{2-2}-2 \mathrm{p}^{3}$ | ${ }^{2} \mathrm{P}-{ }^{2} \mathrm{~S}$ | $5 / 2 \sim 3 / 2$ | 247.18 | 244.70 | 244.81 |

Table 4 Wavelength comparison between calculated and measured data for Sulphur XIII(S12 ${ }^{+}$)

| Configuration | Term | $J \sim J$ | Wavelength(in $\AA$ ) |  |  |
| :--- | :--- | :---: | :---: | :---: | :---: |
|  |  |  | Exp.(ClAE) | Model 1 | Model 2 |
| $2 \mathrm{~s} 2 \mathrm{p}-2 \mathrm{p}^{2}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{P}$ | $1 \sim 2$ | 298.99 | 298.09 | 298.18 |
| $2 \mathrm{~s} 2 \mathrm{p}-2 \mathrm{p}^{2}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{P}$ | $0 \sim 1$ | 303.64 | 301.52 | 301.64 |
| $2 \mathrm{~s} 2 \mathrm{p}-2 \mathrm{p}^{2}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{P}$ | $1 \sim 1$ | 307.22 | 305.51 | 305.60 |
| $2 \mathrm{~s} 2 \mathrm{p}-2 \mathrm{p}^{2}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{P}$ | $2 \sim 2$ | 309.00 | 306.92 | 307.03 |
| $2 \mathrm{~s} 2 \mathrm{p}-2 \mathrm{p}^{2}$ | ${ }^{3} \mathrm{P}-{ }^{3} \mathrm{P}$ | $1 \sim 0$ | 312.92 | 310.79 | 310.80 |
| $2 \mathrm{~s}^{2}-2 \mathrm{~s} 2 \mathrm{p}$ | ${ }^{1} \mathrm{~S}-{ }^{3} \mathrm{P}$ | $0 \sim 1$ | 492.49 | 488.88 | 489.00 |

Table 5 Wavelength comparison between calculated and measured data for Sulphur $\operatorname{XIV}\left(\mathbf{S}^{13+}\right)$

| Configuration | Term | $J \sim J$ | Wavelength( in $\dot{A})$ |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | Exp.(CIAE) | Model1 | Model2 |
| $1 \mathrm{~s}^{2} 2 \mathrm{~s}-2 \mathrm{~s}^{2} 2 \mathrm{p}$ | ${ }^{3} \mathrm{~S}^{2}{ }^{2} \mathrm{P}$ | $1 / 2 \sim 1 / 2$ | 445.74 | 443.19 | 443.36 |

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## V DATA PROCESSING

# Construction of Covariance Matrix for Measured Relative Fission Yield Data 

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## Introduction

Fission yield dada are widely used in the decay heat calculation, burn-up credit study, radio intensity estimation of fission product and etc. For these applications, their covariance data are necessary. And also for evaluators and experimenters, only the covariance matrix is given out, the information is given completely, because the error, as traditional given, is only the diagonal elements of the covariance matrix and only describes the accuracy of the data, nothing about the correiation.

The purpose of this work is to provide a method for experimenters and evaluators to conveniently construct the covariance of relative fission yield measurement based on the information of the experiment. The formulas to calculate the yield are given for absolute, ratio, and $R$-value measurements in the sections $1,2,3$ respectively. The formulas to calculate the covariance matrix are derived in the section 4 based on the parameter analysis method. In the 5 th section, a practical program is introduced, and finally, in the section 6, some examples are given.

## 1 The Calculation Formula for Absolute Fission Yield Measurement

The fission yield can be calculated ${ }^{[1]}$ for absolute measurement with $\operatorname{Ge}(\mathrm{Li})$ method:

$$
\begin{equation*}
Y=N \lambda /\left[\sum_{i=1} n_{\mathrm{fi}}\left(1-\mathrm{e}^{-\lambda T_{i}}\right) \mathrm{e}^{-\lambda T_{c i}}\right]\left(\mathrm{e}^{-\lambda_{1}}-\mathrm{e}^{-\lambda t_{2}}\right) \varepsilon p_{\gamma} k_{\mathrm{s}} k_{\Omega} k_{\tau} \tag{1}
\end{equation*}
$$

Where
$N$ is the total count of $\gamma$ radioactivity, e.g. the area under peak measured;
$\lambda$ is the radio decay constant of the nuclide to be measured;
$n_{\mathrm{fi}}$ is the fission rate in the $i$-th time interval;
$T_{i}$ is the $i$-th time interval of irradiation;
$T_{\mathrm{c} i}$ is the time from $i$-th irradiation time interval to the end of irradiation;
$t_{l}$ is the cooling time, namely the time from the end of irradiation to the beginning of the measurement;
$t_{2}$ the time from the end of irradiation to the end of measurement;
$\varepsilon$ is the efficiency of the detector;
$p_{\gamma}$ is the branch ratio
$k_{s}$ is the correction factor for self-absorption;
$k_{\Omega}$ is the correction factor for geometry;
$k_{\tau}$ is the correction factor for pulses pile.
It should be paid attention to that $p=p\left(r_{i}\right), \varepsilon=\varepsilon\left(E_{\gamma}\right), k_{s}=k_{s}\left(E_{\gamma} \Omega\right), k_{\Omega}=k_{\Omega}(\Omega)$, $k_{\tau}=k_{\tau}(N)$.

The equation can be simplified for different cases, and can be written in the unified form:

$$
\begin{equation*}
Y=N / F(\lambda) N_{\mathrm{f}} P_{\gamma} k_{\mathrm{s}} k_{\Omega} k_{\mathrm{r}} \tag{2}
\end{equation*}
$$

where $N_{\mathrm{f}}=n_{\mathrm{f}} T$ is the total fission count, $T$ is the radiation time, and

$$
f(\lambda)=\left\{\begin{array}{l}
\left(1-\mathrm{e}^{-\lambda T}\right)\left(\mathrm{e}^{-\lambda_{1}}-\mathrm{e}^{-\lambda_{1}}\right) / \lambda T  \tag{3.1}\\
\left(\mathrm{e}^{-\lambda_{1}}-\mathrm{e}^{-\lambda \lambda_{1}}\right) \\
\lambda t
\end{array}\right.
$$

case $1, n_{f}$ is a constant; case $2, n_{f}$ is a constant and radiation time is much less than $T_{12}$; case $3, n_{\mathrm{f}}$ is a constant, and radiation time, cooling time $t_{1}$ and measured time $t_{2}$ are all much less than $T_{12}$.

## 2 Ratio Measurement

In the case that the ratio relative to a standard product nuclide is measured, the ratio

$$
R o=Y / Y_{\mathrm{s}}=\left\{\begin{array}{l}
\frac{N}{N_{\mathrm{s}}} \frac{F_{\mathrm{s}}(\lambda)}{F(\lambda)} \frac{\varepsilon_{\mathrm{s}}}{\varepsilon} \frac{p_{\gamma_{\mathrm{s}}}}{p_{\gamma}} \frac{M_{\mathrm{s}} \sigma_{\mathrm{fs}}}{M} \frac{\sigma_{\mathrm{f}}}{\sigma_{\mathrm{f}}}  \tag{4.1}\\
\frac{N}{N_{\mathrm{s}}} \frac{F_{\mathrm{s}}(\lambda)}{F(\lambda)} \frac{\varepsilon_{\mathrm{s}}}{\varepsilon} \frac{p_{\gamma_{\mathrm{s}}}}{p_{\gamma}}
\end{array}\right.
$$

where

$$
R(\lambda)=\frac{F_{\mathrm{s}}(\lambda)}{F(\lambda)}=\left\{\begin{array}{l}
\frac{\lambda}{\lambda_{\mathrm{s}}} \frac{\left(1-\mathrm{e}^{-\lambda_{s} T}\right)\left(\mathrm{e}^{-\lambda_{s} t_{1}}-\mathrm{e}^{-\lambda_{\mathrm{s}} t_{2}}\right)}{\left(1-\mathrm{e}^{-\lambda T}\right)\left(\mathrm{e}^{-\lambda t_{1}}-\mathrm{e}^{-\lambda t_{2}}\right)}  \tag{5.1}\\
\frac{\left(\mathrm{e}^{-\lambda_{s} t_{1}}-\mathrm{e}^{-\lambda_{s} t_{2}}\right)}{\left(\mathrm{e}^{-\lambda_{1}}-\mathrm{e}^{-\lambda_{2}}\right)} \\
\frac{\lambda_{\mathrm{s}}}{\lambda}
\end{array}\right.
$$

The yield is easily to obtained from the ratio and standard:

$$
Y=R o Y_{\mathrm{s}}=\left\{\begin{array}{l}
\frac{N}{N_{\mathrm{s}}} \frac{F_{\mathrm{s}}(\lambda)}{F(\lambda)} \frac{\varepsilon_{\mathrm{s}}}{\varepsilon} \frac{p_{\gamma \mathrm{s}}}{p_{\gamma}} \frac{M_{\mathrm{s}}}{M} \frac{\sigma_{\mathrm{fs}}}{\sigma_{\mathrm{s}}} Y_{\mathrm{s}}  \tag{6.1}\\
\frac{N}{N_{\mathrm{s}}} \frac{F_{\mathrm{s}}(\lambda)}{F(\lambda)} \frac{\varepsilon_{\mathrm{s}}}{\varepsilon} \frac{p_{\gamma \mathrm{s}}}{p_{\gamma}} Y_{\mathrm{s}}
\end{array}\right.
$$

The equations (4.1), (6.1) are for the case that the yields to be measured and standard ones are from different fission nuclides, and equations (4.2) and (6.2) are for the case that they are from the same one. The equations (5.1), (5.2) and (5.3) are for the cases $1,2,3$ as given above, respectively.

For the relative measurement, the yield is independent from the fission counts in the case that the products to be measured and as standard one are from the same fission nuclide or independent from the neutron flux in the case that both are different and irradiated at the same time. The effects of the difference from the corrections for geometry, self-absorption and pulse pile is also can be neglected. The systematical error in the efficiency calibration can be offset. If the $\gamma$ energy of two products is nearby, the effect of efficiency can also be neglected. But the yield is dependent on the decay characters (branch ratio, decay constant) and standard yield. If the fission nuclides are different, the yield also depends on the quantification of fission material and fission cross section. If the products are the same (at different energy points), then the yield is independent from the decay characters and the efficiency, and only depends on the $\gamma$ counts and the neutron flux.

## $3 R$-value Measurement

$R$-value is the ratio of ratios. There are two kinds of cases.

### 3.1 Different Fission Nuclide at Same Energy Point

In the case that the fission nuclides are different for the yield to be measured and for the standard but at the same energy points, the $R$-value

$$
\begin{equation*}
R v=\frac{Y_{\mathrm{XM}} / Y_{\mathrm{xM}_{0}}}{Y_{\mathrm{SM}} / Y_{\mathrm{SM}_{0}}}=\frac{Y_{\mathrm{xM}} / Y_{\mathrm{SM}}}{Y_{\mathrm{m}_{0}} / Y_{\mathrm{SM}}^{0}}{ }_{0}=\frac{Y_{\mathrm{XM}} Y_{\mathrm{SM}_{0}}}{Y_{\mathrm{M}_{0}} Y_{\mathrm{SM}}} \tag{7.1}
\end{equation*}
$$

where " $M$ " means the fission nuclide to be measured (e.g. ${ }^{238} \mathrm{U}$ ), " $\mathrm{M}_{0}$ " means the fission nuclide as standard (e.g. ${ }^{235} \mathrm{U}$ ), " X " means the product nuclide to be measured, and " S " means product nuclide as standard.

In this case, the $R$-value is a ratio of " $A$ " to " $B$ ". " $A$ " is a ratio of the yield of the product to be measured from the fission nuclide to be measured to the yield of product to be measured from fission nuclide as standard, and " $B$ " is the ratio of the yield of product nuclide as standard from fission nuclide to be measured to the yield of product as standard from fission nuclide as standard.

### 3.2 Same Fission Nuclide at Different Energy Point

In the case that the fission nuclides are the same for the yield to be measured and for the standard but at different energy points, the $R$-value

$$
\begin{equation*}
R v=\frac{Y_{\mathrm{XE}} / Y_{\mathrm{xE}_{0}}}{Y_{\mathrm{SE} / Y_{\mathrm{SE}_{0}}}=\frac{Y_{\mathrm{XE}} / Y_{\mathrm{SE}}}{Y_{\mathrm{XE}_{0}} / Y_{\mathrm{SE}_{0}}}=\frac{Y_{\mathrm{xE}} Y_{\mathrm{SE}_{0}}}{Y_{\mathrm{XE}_{0}} Y_{\mathrm{SE}}}, \text {. }} \tag{7.2}
\end{equation*}
$$

where " $X$ " means the product nuclide to be measured, " S " means the product nuclide as standard, $E$ means the energy point to be measured, $E_{0}$ means the energy point as standard. In this case, the $R$-value is also a ratio of " $A$ " to " $B$ ". But here " $A$ " is ratio of the yield of the product to be measured at the energy to be measured to the yield of product to be measured at the energy as standard (e.g. thermal energy point), and " $B$ " is the ratio of the yield of product nuclide as standard at energy point to be measured to the yield of product as standard at the energy as standard.

Put equation (6.1) into equation (7.1), it is obtained that

$$
\begin{align*}
R v & =\frac{N_{\mathrm{XM}} / N_{\mathrm{xM}_{0}} \times F_{\mathrm{s}}(\lambda) / F(\lambda) \times \varepsilon_{\mathrm{S}} / \varepsilon \times P_{\gamma \mathrm{S}} / P_{\gamma} \times M_{0} / M \times \sigma_{\mathrm{f} 0} / \sigma_{\mathrm{f}}}{N_{\mathrm{SM}} / N_{\mathrm{SM}_{0}} \times F_{\mathrm{S}}(\lambda) / F(\lambda) \times \varepsilon_{\mathrm{s}} / \varepsilon \times P_{\gamma \mathrm{S}} / P_{\gamma} \times M_{0} / M \times \sigma_{\mathrm{f} 0} / \sigma_{\mathrm{f}}} \\
& =\frac{N_{\mathrm{xM}} / N_{\mathrm{xM}_{0}}}{N_{\mathrm{SM}} / N_{\mathrm{SM}_{0}}}=\frac{N_{\mathrm{xM}} / N_{\mathrm{SM}_{0}}}{N_{\mathrm{SM}} / N_{\mathrm{xM}_{0}}} \tag{8.1}
\end{align*}
$$

Put equation (6.2) into equation (7.2), it is obtained that

$$
\begin{align*}
& R o=\frac{N_{\mathrm{XE}} / N_{\mathrm{XE}_{0}} \times F_{\mathrm{s}}(\lambda) / F(\lambda) \times \varepsilon_{\mathrm{S}} / \varepsilon \times P_{\gamma \mathrm{S}} / P_{\gamma}}{N_{\mathrm{SE}} / N_{\mathrm{SE}_{0}} \times F_{\mathrm{S}}(\lambda) / F(\lambda) \times \varepsilon_{\mathrm{S}} / \varepsilon \times P_{\gamma \mathrm{S}} / P_{\gamma}} \\
& =\frac{N_{\mathrm{XE}} / N_{\mathrm{XE}_{0}}}{N_{\mathrm{SE}} / N_{\mathrm{SE}_{0}}}=\frac{N_{\mathrm{XE}} / N_{\mathrm{SE}_{0}}}{N_{\mathrm{SE}} / N_{\mathrm{XE}_{0}}} \tag{8.2}
\end{align*}
$$

From the equations (8.1) and (8.2), it can be seen that the $R$ value is independent on the decay characters ( $\lambda, P_{\gamma}$ ), detector efficiency $(\varepsilon)$ as well as the number and cross section of the fission nuclide $\left(M, \sigma_{\mathrm{f}}\right)$, either for the same or different fission nuclide. It only depends on the measured counts ( $N_{\mathrm{XE}}, N_{\mathrm{SE}^{\prime}}, N_{\mathrm{XE}_{0}}, N_{\mathrm{SE}_{0}}$ or $N_{\mathrm{XM}}, N_{\mathrm{SM}}, N_{\mathrm{XM}_{0}}, N_{\mathrm{SM}_{0}}$. However, three standard yield $Y_{\mathrm{XE}_{0}}, Y_{\mathrm{SE}_{0}}, Y_{\mathrm{SE}}$ or $Y_{\mathrm{XM}_{0}}, Y_{\mathrm{SM}_{0},}, Y_{\mathrm{SM}}$ must be given to get the yield to be measured:

$$
\begin{equation*}
Y(E)=R v \times Y_{\mathrm{xM}_{0}} \times \frac{Y_{\mathrm{SM}}}{Y_{\mathrm{SM}_{0}}}=\frac{N_{\mathrm{xM}} N_{\mathrm{SM}_{0}}}{N_{\mathrm{SM}^{2}} N_{\mathrm{XM}_{0}}} \times Y_{\mathrm{xM}_{0}} \times \frac{Y_{\mathrm{SM}}}{Y_{\mathrm{SM}_{0}}} \tag{9.1}
\end{equation*}
$$

or

$$
\begin{equation*}
Y(E)=R v \times Y_{\mathrm{XE}_{0}} \times \frac{Y_{\mathrm{SE}}}{Y_{\mathrm{SE}_{0}}}=\frac{N_{\mathrm{XE}^{2}} N_{\mathrm{SE}_{0}}}{N_{\mathrm{SE} N_{\mathrm{XE}_{0}}} \times Y_{\mathrm{XE}_{0}} \times \frac{Y_{\mathrm{SE}}}{Y_{\mathrm{SE}_{0}}}, \frac{r^{2}}{}} \tag{9.2}
\end{equation*}
$$

## 4 Covariance Matrix

According to the parameter analysis method ${ }^{[2]}$.

$$
\begin{equation*}
\operatorname{Cov}\left(f_{i}, f_{j}\right)=\left.\left.\sum_{k} \frac{\partial f}{\partial x_{k}}\right|_{i} \frac{\partial f}{\partial x_{k}}\right|_{j} \sigma_{k i} \sigma_{k j} \rho_{i j}^{k} \tag{10}
\end{equation*}
$$

Let us define the relative covariance matrix as

$$
\begin{equation*}
V_{i j}^{\mathrm{R}}=\frac{\operatorname{Cov}\left(f_{i}, f_{j}\right)}{Y_{i} Y_{J}} \tag{11}
\end{equation*}
$$

and the relative error of variable as

$$
\begin{equation*}
\delta_{x_{k}}=\Delta x_{k} / x_{k} \tag{12}
\end{equation*}
$$

From equation (6), it can be obtained that the covariance of ratio measurement

$$
\begin{align*}
V_{i j}^{\mathrm{Ro}} & =\delta_{\mathrm{Ro}_{i}} \delta_{\mathrm{Roj}} \rho_{i j}^{\mathrm{Ro}}+\delta_{\mathrm{Y}_{\mathrm{S} i}} \delta_{\mathrm{Y}_{\mathrm{s} j}} \rho_{i j}^{\mathbf{Y}_{\mathrm{s}}} \\
& =f_{i}(\lambda) f_{j}(\lambda) \delta_{\lambda i} \delta_{\lambda j} \rho_{i j}^{l}+f_{\mathrm{si} i}(\lambda) f_{\mathrm{s} j}(\lambda) \delta_{\mathrm{s} \lambda i} \delta_{\mathrm{s} \lambda j} \rho_{i j}^{\mathrm{s} \backslash}  \tag{13}\\
& =\sum \delta_{\mathrm{x}_{k i}} \delta_{\mathrm{x}_{\mathrm{k} j}} \rho_{i j}^{\mathrm{x}_{\mathrm{k}}}
\end{align*}
$$

where

$$
\begin{gather*}
x_{k}=\left\{\begin{array}{l}
N, N_{\mathrm{s}}, \varepsilon, \varepsilon_{\mathrm{s}}, P_{\gamma}, P_{\mathrm{ys}}, M, M_{\mathrm{s}}, \sigma_{\mathrm{f}}, \sigma_{\mathrm{fs}}, Y_{\mathrm{s}} \\
N, N_{\mathrm{s}}, \varepsilon, \varepsilon_{\mathrm{s}}, P_{\gamma}, P_{\mathrm{ys}}, Y_{\mathrm{s}}
\end{array}\right.  \tag{14.1}\\
f(\lambda)=\left\{\begin{array}{l}
\frac{\lambda T}{\left(1-\mathrm{e}^{-\lambda T}\right)}+\frac{\lambda t}{\left(\mathrm{e}^{-\lambda t_{1}}-\mathrm{e}^{-\mu_{2}}\right)}-1 \\
\frac{\lambda t}{\left(\mathrm{e}^{-\lambda \lambda_{1}}-\mathrm{e}^{-\lambda \lambda_{2}}\right)} \\
1
\end{array}\right.
\end{gather*}
$$

The equation (14.1) is for different fission nuclide, and equation (14.2) is for the same fission nuclide.

From equation (9), it can be obtained that the covariance matrix of R-value measurement

$$
\begin{equation*}
V_{i j}^{R v}=\sum \delta_{x_{k i}} \delta_{\mathrm{x}_{k j}} \rho_{i j}^{\mathrm{x}_{k}} \tag{16}
\end{equation*}
$$

where

$$
x_{\mathrm{k}}=\left\{\begin{array}{l}
R v, Y_{\mathrm{xM}_{0}}, Y_{\mathrm{SM}_{,},} Y_{\mathrm{SM}_{0}}  \tag{17.1}\\
R v, Y_{\mathrm{xE}_{0}}, Y_{\mathrm{SE}^{2},} Y_{\mathrm{SE}_{0}}
\end{array}\right.
$$

or

$$
x_{k}=\left\{\begin{array}{l}
N_{\mathrm{M}}, N_{\mathrm{M}_{0}}, N_{\mathrm{SM}_{0}}, N_{\mathrm{SM}_{0}}, Y_{\mathrm{xM}_{0}}, Y_{\mathrm{SM}_{0}}, Y_{\mathrm{SM}}  \tag{18.1}\\
N_{\mathrm{E}}, N_{\mathrm{E}_{0}}, N_{\mathrm{SE}, N_{\mathrm{SE}_{0}}, Y_{\mathrm{XE}_{0}}, Y_{\mathrm{SE}_{0}}, Y_{\mathrm{SE}}} .
\end{array}\right.
$$

The equations (17.1) or (18.1) are for the different fission nuclide at same energy points and the equations (17.2) or (18.2) are for same fission nuclides at different energy points.

## 5 The Program FYCOVR

A program FYCOVR was developed to practically construct the covariance matrix for relative measurement, including ratio Ro measurement (equation (13)) and $R$ value measurement $R v$ (equation (16)). The positive definition of output matrix is checked and verified by the program.

The input parameters required are as shown in the equations (14) for Ro measurement and (18) for $R$-value measurement. The outputs of the program are absolute covariance matrix, relative covariance matrix, correlation coefficient matrix and absolute uncertainty of the yield.

Correlation coefficient $\rho$ is the key point for calculating the matrix. It is not familiar with for experimenters or evaluators. The correlation coefficients $\rho$ used in the absolate measurement are given in the Ref. [2]. In addition, the Correlation coefirients specially used in the relative measurement are given in the Table 1.

Table 1 The correlation coefficients specially used in the relative measurement

| Quantity | I, ${ }^{\text {d }}$ | $\mathrm{I}, \mathrm{i}^{2)}$ | comment |
| :---: | :---: | :---: | :---: |
| $Y_{5}$ standard yield <br> $Y_{S F}$ standard yield at energy point to be measured <br> $Y_{\mathrm{xI}}$ yield of product to be measured at standard $E_{0}$ <br> $Y_{\mathrm{SE}_{s}}$ standard yield at standard $E_{0}$ <br> $Y_{S M}$ standard yield of product to be measured <br> $Y_{\mathrm{XM}}$ yield of product to be measured from fission nuclide as standard <br> $Y_{\mathrm{sm}}$ standard yield of standard fission nuclide | $\begin{gathered} 1.0(1) \\ \\ 1.0 \\ 0 \text { (or } x \text { ) } \\ 1.0 \end{gathered}$ | $\begin{gathered} 0 \text { or } x(2) \\ 1.0 \\ 0 \text { (or } x) \\ 1.0 \end{gathered}$ | (1) <br> (3) <br> (1) <br> (1) <br> (3) |
| Notes: 1) Different product nuclides at same energy point, <br> 2) The same product nuclide at different energy points. <br> (1) The yield is same for same nuclide at same energy point; <br> (2) If two standard yield were measured independently, $\rho=0$, otherwise. $\rho$ depends on the actual conditions; <br> (3) The yields of different nuclides at same energy point, in general, are independent from each other. But they may be correlative in some cases. |  |  |  |

## 6 Example

An example was taken from Ref. [2](suppose that the yield of ${ }^{95} \mathrm{Zr}$ was taken as the standard).

The errors of the required parameters concerned are given in Table 2.

Table 2 The errors of the parameters concerned ")

| Product | ${ }^{95} \mathrm{Zr}$ | ${ }^{103} \mathrm{Ru}$ | ${ }^{131} \mathrm{I}$ | ${ }^{132} \mathrm{I}$ | ${ }^{140} \mathrm{Ba}$ |
| :--- | :---: | :---: | :---: | :---: | :---: |
| $\Delta P_{r}(\%)$ | 1.2 | 3.4 | 5.0 | 6.0 | 5.0 |
| $\Delta \varepsilon(\%)$ | 1.5 | 3.5 | 2.3 | 3.0 | 1.2 |
| $\Delta \lambda(\%)$ | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| $\Delta N_{7}(\%)$ | 0.98 | 1.05 | 0.57 | 1.56 | 0.92 |
| $\Delta N_{\mathrm{F}}(\%)$ | 1.02 | 0.89 | 0.72 | 1.67 | 0.47 |
| $\Delta Y_{t}(\mathrm{PC} / \mathrm{F})$ | 0.22 | 0.19 | 0.20 | 0.30 | 0.39 |
| $\Delta Y_{\mathrm{F}}(\mathrm{PC} / \mathrm{F})$ | 0.22 | 0.22 | 0.26 | 0.34 | 0.37 |
| $Y_{Y}(\mathrm{PC} / \mathrm{F})$ | 6.37 | 3.08 | 3.18 | 3.55 | 6.20 |
| $Y_{\mathrm{F}}(\mathrm{PC} / \mathrm{F})$ | 6.31 | 3.66 | 4.04 | 3.97 | 6.34 |

Note: 1) the definition of the parameters is given in section 1 .
The correlation coefficients required are given in Table 3.
Table 3 The correlation coefficients required

| Quantity | $\rho_{i j}{ }^{\prime \prime}$ | $\left.\rho_{i j}{ }^{2}\right)$ | Explanation |
| :---: | :---: | :---: | :---: |
| $N$ count | 0 | 0 | Statistical independence <br> $\varepsilon$ decay constant |
| $P_{\gamma}$ branching ratio | 0 | 1.0 | The same for same product nuclide; <br> Independent for different product nuclide |
| $Y_{\mathrm{S}}$ standard yield | 1.0 | 1.0 | The same for same $\gamma$ energy; middle range correlation <br> for different $\gamma$ energy |

Notes: 1) At same energy point for different product nuclide;
2) For same product nuclide at different energy points.

The covariance matrices were calculated by using the code (equation (13), (14.2)). The results are as follows:

1) At thermal energy point

Relative Covariance matrix

|  | ${ }^{103} \mathrm{Ru}$ | ${ }^{133} \mathrm{I}$ | ${ }^{132} \mathrm{I}$ | ${ }^{140} \mathrm{Ba}$ |
| :---: | :---: | :---: | :---: | :---: |
| ${ }^{103} \mathrm{Ru}$ | $2.9611 \mathrm{E}+01$ | $5.1984 \mathrm{E}+00$ | $6.4234 \mathrm{E}+00$ | $3.2734 \mathrm{E}+00$ |
| ${ }^{131} \mathrm{I}$ | $5.1984 \mathrm{E}+00$ | $3.5314 \mathrm{E}+01$ | $4.6234 \mathrm{E}+00$ | $2.5534 \mathrm{E}+00$ |
| ${ }^{132} \mathrm{I}$ | $6.4234 \mathrm{E}+00$ | $4.6234 \mathrm{E}+00$ | $5.2132 \mathrm{E}+01$ | $2.9734 \mathrm{E}+00$ |
| ${ }^{140} \mathrm{Ba}$ | $3.2734 \mathrm{E}+00$ | $2.5534 \mathrm{E}+00$ | $2.9734 \mathrm{E}+00$ | $3.1985 \mathrm{E}+01$ |

Absolute Covariance matrix

|  | ${ }^{103} \mathrm{Ru}$ | ${ }^{131} \mathrm{I}$ | ${ }^{132} \mathrm{I}$ | ${ }^{140} \mathrm{Ba}$ |
| :---: | :---: | :---: | :---: | :---: |
| ${ }^{103} \mathrm{Ru}$ | $2.8090 \mathrm{E}+02$ | $5.0915 \mathrm{E}+01$ | $7.0233 \mathrm{E}+0 \mathrm{I}$ | $6.2509 \mathrm{E}+01$ |
| ${ }^{\mathrm{i} 31} \mathrm{I}$ | $5.0915 \mathrm{E}+01$ | $3.5711 \mathrm{E}+02$ | $5.2194 \mathrm{E}+01$ | $5.0343 \mathrm{E}+0 \mathrm{I}$ |
| ${ }^{132} \mathrm{I}$ | $7.0233 \mathrm{E}+01$ | $5.2194 \mathrm{E}+01$ | $6.5700 \mathrm{E}+02$ | $6.5445 \mathrm{E}+01$ |
| ${ }^{140} \mathrm{Ba}$ | $6.2509 \mathrm{E}+01$ | $5.0343 \mathrm{E}+01$ | $6.5445 \mathrm{E}+01$ | $1.2295 \mathrm{E}+03$ |

Correlation coefficient matrix

|  | ${ }^{103} \mathrm{Ru}$ | ${ }^{131} \mathrm{I}$ | ${ }^{132} \mathrm{I}$ | ${ }^{140} \mathrm{Ba}$ |
| :---: | :---: | :---: | :---: | :---: |
| ${ }^{103} \mathrm{Ru}$ | $1.0000 \mathrm{E}+00$ | $1.6076 \mathrm{E}-01$ | $1.6349 \mathrm{E}-01$ | $1.0636 \mathrm{E}-01$ |
| ${ }^{131} \mathrm{I}$ | $1.6076 \mathrm{E}-01$ | $1.0000 \mathrm{E}+00$ | $1.0775 \mathrm{E}-01$ | $7.5975 \mathrm{E}-02$ |
| ${ }^{132} \mathrm{I}$ | $1.6349 \mathrm{E}-01$ | $1.0775 \mathrm{E}-01$ | $1.0000 \mathrm{E}+00$ | $7.2816 \mathrm{E}-02$ |
| ${ }^{1+0} \mathrm{Ba}$ | $1.0636 \mathrm{E}-01$ | $7.5975 \mathrm{E}-02$ | $7.2816 \mathrm{E}-02$ | $1.0000 \mathrm{E}+00$ |

Absolute error

| ${ }^{103} \mathrm{Ru}$ | ${ }^{131} \mathrm{I}$ | ${ }^{132} \mathrm{I}$ | ${ }^{140} \mathrm{Ba}$ |
| :---: | :---: | :---: | :---: |
| $1.6760 \mathrm{E}+01$ | $1.8897 \mathrm{E}+01$ | $2.5632 \mathrm{E}+0 \mathrm{I}$ | $3.5064 \mathrm{E}+01$ |

2) At fission spectrum

## Relative Covariance matrix

|  | ${ }^{103} \mathrm{Ru}$ | ${ }^{131} \mathrm{I}$ | ${ }^{132} \mathrm{I}$ | ${ }^{140} \mathrm{Ba}$ |
| :---: | :---: | :---: | :---: | :---: |
| ${ }^{103} \mathrm{Ru}$ | $2.9381 \mathrm{E}-03$ | $5.1984 \mathrm{E}-04$ | $6.4234 \mathrm{E}-04$ | $3.2734 \mathrm{E}-04$ |
| ${ }^{131} \mathrm{I}$ | $5.1984 \mathrm{E}-04$ | $3.5587 \mathrm{E}-03$ | $4.6234 \mathrm{E}-04$ | $2.5534 \mathrm{E}-04$ |
| ${ }^{132} \mathrm{I}$ | $6.4234 \mathrm{E}-04$ | $4.6234 \mathrm{E}-04$ | $5.2568 \mathrm{E}-03$ | $2.9734 \mathrm{E}-04$ |
| ${ }^{140} \mathrm{Ba}$ | $3.2734 \mathrm{E}-04$ | $2.5534 \mathrm{E}-04$ | $2.9734 \mathrm{E}-04$ | $3.1440 \mathrm{E}-03$ |


| Absolute Covariance matrix |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | ${ }^{103} \mathrm{Ru}$ | ${ }^{131} \mathrm{I}$ | ${ }^{132} \mathrm{I}$ | ${ }^{140} \mathrm{Ba}$ |  |
| ${ }^{103} \mathrm{Ru}$ | $3.9357 \mathrm{E}-02$ | $7.6866 \mathrm{E}-03$ | $9.3333 \mathrm{E}-03$ | $7.5957 \mathrm{E}-03$ |  |
| ${ }^{134} \mathrm{I}$ | $7.6866 \mathrm{E}-03$ | $5.8084 \mathrm{E}-02$ | $7.4154 \mathrm{E}-03$ | $6.5402 \mathrm{E}-03$ |  |
| ${ }^{132} \mathrm{I}$ | $9.3333 \mathrm{E}-03$ | $7.4154 \mathrm{E}-03$ | $8.2851 \mathrm{E}-02$ | $7.4840 \mathrm{E}-03$ |  |
| ${ }^{140} \mathrm{Ba}$ | $7.5957 \mathrm{E}-03$ | $6.5402 \mathrm{E}-03$ | $7.4840 \mathrm{E}-03$ | $1.2637 \mathrm{E}-01$ |  |

Correlation coefficient matrix

|  | ${ }^{103} \mathrm{Ru}$ | ${ }^{13!} \mathrm{I}$ | ${ }^{132} \mathrm{I}$ | ${ }^{140} \mathrm{Ba}$ |
| :---: | :---: | :---: | :---: | :---: |
| ${ }^{103} \mathrm{Ru}$ | $1.0000 \mathrm{E}+00$ | $1.6076 \mathrm{E}-01$ | $1.6345 \mathrm{E}-01$ | $1.0770 \mathrm{E}-01$ |
| ${ }^{131} \mathrm{l}$ | $1.6076 \mathrm{E}-01$ | $1.0000 \mathrm{E}+00$ | $1.0689 \mathrm{E}-01$ | $7.6337 \mathrm{E}-02$ |
| ${ }^{132} \mathrm{I}$ | $1.6345 \mathrm{E}-01$ | $1.0689 \mathrm{E}-01$ | $1.0000 \mathrm{E}+00$ | $7.3140 \mathrm{E}-02$ |
| ${ }^{140} \mathrm{Ba}$ | $1.0770 \mathrm{E}-01$ | $7.6337 \mathrm{E}-02$ | $7.3140 \mathrm{E}-02$ | $1.0000 \mathrm{E}+00$ |


| Absolute error |  |  |  |
| :---: | :---: | :---: | :---: |
| ${ }^{103} \mathrm{Ru}$ | ${ }^{131} \mathrm{l}$ | ${ }^{132} \mathrm{l}$ | ${ }^{140} \mathrm{Ba}$ |
| $1.9839 \mathrm{E}-01$ | $2.4101 \mathrm{E}-01$ | $2.8784 \mathrm{E}-01$ | $3.5549 \mathrm{E}-01$ |

The positive definition of the matrices was proved.
It can be seen that the correlation is not so strong (about $10 \%$ either at thermal energy point or at fission spectrum). The reason is that the correlation calculated in the example is for different product nuclides at the same energy point and it mainly comes from the same standard, moreover the error of the standard yield is relatively small.

# VI ONLINE NUCLIDE CHART 

## WWW Chart of the Nuclides

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#### Abstract

WWW chart of the nuclides was established on the basis of the latest evaluations of nuclear structure and decay data. By viewing WWW chart of the nuclides, one can retrieve the fundamental data of nuclide such as atomic mass, abundance, spin and parity; the decay mode, branching ratio, half-life and $Q$-value of radioactive nuclide, energy and intensity of strong $\gamma$-ray, etc. The URL of WWW chart of the nuclides is: http://myhome.py.gd.cn/chart/index.asp.


## 1 Introduction

The chart of the nuclides is very useful to the nuclear scientists. Through the chart, it's very easy and rapid to get the fundamental nuclear data such as atomic mass, abundance, spin and parity; the decay mode, branching ratio, half-life and $Q$-value of radioactive nuclide, energy and intensity of strong $\gamma$-ray, etc. Thus the main nuclear data centers in the world have setup their own chart of the nuclides.

The cooperation in the field of the chart of the nuclides between China and Russia has been starting since 1995. Up to now they have compiled and
recommended lots of nuclear data. On the basis of these researches, we prepared WWW chart of the nuclides.

## 2 Data and WWW server

All the data in the WWW chart of the nuclides are from our recommendations evaluated by China and Russia scientists and from the most recent evaluations in NNDC (by the end of march, 2000).

The contents of chart of the nuclides was tabulated, graphed and published on the Internet. The Windows NT system is adopted and ACCESS is served as the data file language. The New Century of PANG YU (http://myhome.py.gd.cn), China, provided the free space to store the chart of the nuclides.

The URL of WWW chart of the nuclides is: http:// myhome. py.gd.cn /chart /index.asp. In order to protect WWW chart of the nuclides, the homepage was encrypted. You can use the common account (user and password is xxx ) to visit this homepage if you don't want to apply another new user.

The arrangement of this WWW chart is firstly presenting map of all known nuclides. Each horizontal row represents one element. A vertical column represents the nuclides with the same neutron numbers.

This WWW chart of the nuclides is made up about 18 parts. Each part has a size of about 50 kbytes. When you click a region of dot, you may see more detailed chart section. By clicking a cell, you may get property of a nuclide or atom.

The following figure (see Fig.1) is an example of the partial map.

## 3 Application

To find a nuclide, you can click the numbers in the sensitive fig, or enter an atomic number and a mass number of a nuclide and then press the submit box.

Here is an example. When we enter 75 and 184 and press submit, we can get the following nuclear data.


Fig. 1 Partial map of color WWW chart of the nuclides

75-RE-184

| Atomic Mass |  | Mass Excess |  |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: |
| 183.952524646889 amu |  | -44.223 MeV |  |  |  |
| Level energy (MeV) | Spin \& parity | Half-life | Mode of decay | Branch ratio(\%) | Decay energy (MeV) |
| Ground state | $3(-)$ | $38.0 \mathrm{D} \mathrm{0.5}$ | EC | 100 | 1.483 |
| .188 | $8(+)$ | 169 D 8 | IT | 75.4 | .188 |
| .188 | $8(+)$ | 169 D 8 | EC | 24.6 | 1.671 |

Strong Gamma-rays from Decay of RE-184

| Decay mode | Half-life | Gamma-ray energy (keV) | Intensity (\%) |
| :---: | :--- | :--- | :--- |
| EC | 169 D 8 | 55.278 | $2.3+-0.3$ |
| IT | 169 D 8 | 104.729 | $13.4+-0.5$ |
| EC | 169 D 8 | 111.207 | $5.8+-0.4$ |
| EC | 169 D 8 | 161.269 | $6.5+-0.4$ |
| EC | 169 D 8 | 215.326 | $2.78+-0.15$ |
| EC | 169 D 8 | 216.547 | $9.4+-0.5$ |
| EC | 169 D 8 | 226.748 | $1.47+-0.08$ |


| EC | 169 D 8 | 252.845 | $10.7+-0.6$ |
| :--- | :--- | :--- | :--- |
| EC | 169 D 8 | 318.008 | $5.7+-0.3$ |
| EC | 169 D 8 | 384.250 | $3.13+-0.15$ |
| EC | 169 D 8 | 536.674 | $3.30+-0.16$ |
| EC | 169 D 8 | 792.067 | $3.69+-0.19$ |
| EC | 169 D 8 | 894.760 | $2.75+-0.16$ |
| EC | 169 D 8 | 903.282 | $3.74+-0.19$ |
| EC | 169 D 8 | 920.933 | $8.1+-0.4$ |
| EC | 169 D 8 | 1110.08 | $0.58+-0.04$ |
| EC | 169 D 8 | 1173.77 | $1.21+-0.09$ |
| EC | 38.0 D 0.5 | 111.207 | $17.1+-0.8$ |
| EC | 38.0 D 0.5 | 252.845 | $3.0+-0.3$ |
| EC | 38.0 D 0.5 | 641.915 | $1.94+-0.06$ |
| EC | 38.0 D 0.5 | 769.778 | $0.67+-0.03$ |
| EC | 38.0 D 0.5 | 792.067 | $37.5+-1.1$ |
| EC | 38.0 D 0.5 | 894.760 | $15.6+-0.5$ |
| EC | 38.0 D 0.5 | 903.282 | $37.9+-1.1$ |
| EC | 38.0 D 0.5 | 1022.63 | $0.52+-0.04$ |

## 4 Conclusion

The WWW chart of the nuclides was published. By viewing WWW chart of the nuclides, one can retrieve the fundamental data of nuclide such as atomic mass, abundance, spin and parity; the decay mode, branching ratio, half-life and Q-value of radioactive nuclide, energy and intensity of strong $\gamma$-ray, etc. It's very convenient to use WWW chart of the nuclides.

The URL of WWW chart of the nuclides is http://myhome.py.gd.cn/chart/index.asp.
This WWW chart of the nuclides may not be corrected. Whenever you find some mistakes, please let us know (huangxl@iris.ciae.ac.cn). Any valuable comments are always appreciated.

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## CINDA INDEX

| Nuclide | Quantity | Energy/ eV |  | Lab | Type | Documentation |  |  |  |  | Author, Comments |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Min | Max |  |  | Ref | Vol | Page |  | Date |  |
| ${ }^{177} \mathrm{Hf}$ | Evaluation | 1.0-5 | $2.0+7$ | ZHN | Eval | Jour CNDP | 24 | 103 | Dec | 2000 | Wang Tingtai + , SIG, DA, DE |
| ${ }^{178} \mathrm{Hf}$ | Evaluation | 1.0-5 | $2.0+7$ | ZHN | Eval | Jour CNDP | 24 | 103 | Dec | 2000 | Wang Tingtai + , SIG, DA, DE |
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| ${ }^{180} \mathrm{Hf}$ | Calculation | 1.0+3 | $2.0+7$ | ZHN | Theo | Jour CNDP | 24 | 72 | Dec | 2000 | Liu Jianfeng+, SIG, DA, DA/DE |
| ${ }^{\mathrm{Na}} \mathrm{Hf}$ | Evaluation | 1.0-5 | $2.0+7$ | ZHN | Eval | Jour CNDP | 24 | 103 | Dec | 2000 | Wang Tingtai + , SIG, DA, DE |
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| ${ }^{2410} \mathrm{Pu}$ | Evaluation | 1.0-5 | $2.0+7$ | AEP | Eval | Jour CNDP | 24 | 80 | Dec | 2000 | Yu Baosheng +, SIG, DA, DA/DE |
| ${ }^{24} \mathrm{Pu}$ | Calculation | $1.0+3$ | $2.0+7$ | NKU | Theo | Jour CNDP | 24 | 54 | Dec | 2000 | Cai Chonghai +, SIG, DA, DA/DE |
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[^0]:    ' Note: $\quad L=\left[0.00880(s(z)+s(n))+Q_{\mathrm{b}}\right] A ; P=p(n)+P(z)$;
    $Q_{b}=0.142$ or 0.12 (spherical or deformation).

