The excitation functions of ^{187}Re(n,2n) ^{186m,g}Re reactions

Xiao-Long Huang(黄小龙)[1)] Meng-Xiao Kang(康梦霄) Li-Le Liu(刘丽乐)
Ji-Min Wang(王记民) Xiong-Jun Chen(陈雄军)
Science and Technology on Nuclear Data Laboratory, China Institute of Atomic Energy, Beijing 102413, China

Abstract: A new value for the emission probability of 137.144 keV γ-rays from ^{186g}Re decay is recommended to be (9.47±0.03)/%. Using this value the measured cross sections for ^{187}Re(n,2n)^{186m}Re and ^{187}Re(n,2n)^{186g}Re reactions around 14 MeV are analyzed, and the cross section for ^{187}Re(n,2n)$^{186m+g}$Re reaction at 14.8 MeV is (2213±116) mb. The UNF code was adopted to calculate the cross sections for the ^{187}Re(n,2n)$^{186m+g}$Re reaction below 20 MeV, fitting to the value (2213±116) mb at 14.8 MeV using a set of optimum neutron optical potential parameters which were obtained based on the relevant experimental data of rhenium. The isomeric cross section ratio for the ^{187}Re(n,2n)^{186m,g}Re reaction was analyzed using the V-H method based on nuclear statistical theory. Combining these calculated results, the excitation functions for the ^{187}Re(n,2n)^{186m}Re and ^{187}Re(n,2n)^{186g}Re reactions were obtained. The obtained results are in good agreement with the available experimental data.

Keywords: excitation function, isomeric cross section, ^{187}Re(n,2n)^{186m,g}Re reaction

PACS: 21.60.Cs, 21.10.Re, 27.61.+j **DOI:** 10.1088/1674-1137/40/8/084102

1 Introduction

The cross sections of neutron-induced reactions on rhenium are important for nuclear science and technology. The metal rhenium is a fusion reactor material, and the cross section for the ^{187}Re(n,2n)$^{186m+g}$Re reaction is an important datum for the safety and environmental evaluation of fusion reactors. ^{186}Re is also an important medical radioisotope, and is regarded as one of the best radioisotopes for radiotherapy and radioimmunotherapy.

The residual nuclei of the ^{187}Re(n,2n)^{186}Re reaction are the ground state ^{186g}Re and isomeric state ^{186m}Re. The half-life of ^{186g}Re is 3.7186 days and that of ^{186m}Re is 2.0×10^5 years. Up till now, measurements of these cross sections are very scarce and have only been provided by several laboratories in the energy region of 14 MeV[1–6]. There are large discrepancies in these measurements for the ^{187}Re(n,2n)^{186g}Re reaction, and large errors for the ^{187}Re(n,2n)^{186m}Re reaction. The theoretical calculation is therefore necessary and interesting.

The previous evaluations for the ^{187}Re(n,2n)^{186g}Re and ^{187}Re(n,2n)^{186m}Re reactions were done in 1998 and published in INDC(CPR)-045, 1998 [2]. These evaluations were obtained based on the evaluated cross section for the ^{187}Re(n,2n)$^{186m+g}$Re reaction at 14.8 MeV (the emission probability of 137.144 keV γ-rays from ^{186g}Re decay used in the activation measurement is 8.33%, see Table 2) and old UNF code. Since then there have been some new measurements of the emission probability of 137.144 keV γ-rays, and the new evaluated value is quite different from the old one (see Table 1). Thus it is necessary to update these reaction cross sections based on the evaluated cross section for ^{187}Re(n,2n)$^{186m+g}$Re reaction at 14.8 MeV using the new evaluated emission probability of 137.144 keV γ-rays from ^{186g}Re decay.

The aim of this paper is to obtain reliable excitation functions for the ^{187}Re(n,2n)^{186m}Re and ^{187}Re(n,2n)^{186g}Re reactions. For this purpose, the nuclear model calculations were done using UNF[7] code to analyze the cross sections for the ^{187}Re(n,2n)$^{186m+g}$Re reaction below 20 MeV; and the V-H method based on nuclear statistical theory was adopted to analyze the isomeric cross section ratios for the ^{187}Re(n,2n)^{186m,g}Re reaction.

2 Evaluation experimental data

All the cross sections for the ^{187}Re(n,2n)^{186g}Re, ^{187}Re(n,2n)^{186m}Re reactions were measured by the activation method. The experimental data were obtained by measuring the activities of ^{186g}Re decay through 137.144 keV γ-rays. The value used in these measurements for the emission probability of 137.144 keV γ-rays from ^{186g}Re decay are different (P_γ=8.22%∼8.83%),

Received 28 August 2015
1) E-mail: huang@ciae.ac.cn

so the emission probability of 137 keV γ rays is first analyzed.

The measured values of absolute emission probability of 137.144 keV γ-rays per 100 disintegrations of ^{186g}Re decay are listed together with evaluated values in Table 1.

A statistical analysis was carried out on the measured values. Our "best" recommended absolute γ-ray emission probabilities were mainly from the weighted average of all the measurements except Goswamy [8] and Coursey [9]. The recommended emission probability of 137.144 keV γ-rays from ^{186g}Re decay is (9.47± 0.03)/%.

For the ^{187}Re(n,2n)^{186m}Re reaction, there are only two sets of measured data at 14.8 MeV which are in good agreement with each other within large errors. The measured data from Lu Hanlin [14] is (521 ± 125) mb at 14.77 MeV, and this result was revised by Huang Xiaolong [2]. So the independent measurement from the China group is the new published value: (485 ± 116) mb. The experimental data are obtained by measuring the activities of ^{186g}Re decay through 137 keV γ rays, so the branching ratio of 137 keV γ-rays is first corrected and renormalized using present evaluations. The evaluated datum at 14.8 MeV is given based on the two corrected values, which is also listed in Table 2.

For the ^{187}Re(n,2n)^{186g}Re reaction, all the measurements can be divided into two groups. One is the measurements with lower values, and the other is T. Fan [3]'s in 1992 with higher values. After correction by decay data and reference cross sections, this discrepancy still exists. In T. Fan's measurement, the branching ratio of 137 keV γ-rays is taken as 8.5%. After being corrected and renormalized using the present evaluation, their data are still higher than those of the first group, but in agreement with Khurana' measurements. The previous data before 1967 were obtained by measuring β^- activities of residual products, but in T. Fan's work the measurements of the neutron fluence rate were carried out by the absolute (associated particle counting) and relative (relative standard cross section) methods, respectively, and their experimental results are in very good agreement.

The decay data used in Karam [5] and Druzhinin [6] are not given (or clear) in the references, and different monitor reactions are used compared to T. Fan's measurement. Khurana's measurement [4] is not adopted in the evaluation due to the following reasons: (1) the decay data used in his measurements is not clear; (2) the reference reaction is ^{56}Fe(n,p)^{56}Mn, but the threshold for ^{187}Re(n,2n)^{186}Re reaction is about 7.5 MeV. It therefore does not seem good to include it in evaluations. Also, Filatenkov's measurement [15] is not used in the evaluation because there is a discrepancy between his measurement and T. Fan's results. Considering these factors, T. Fan's results seem to be more reasonable and reliable. The present evaluated data at 14.8 MeV are given in Table 3, which is obtained based on T. Fan's measurements.

As there are only measurements concentrated on the 14 MeV energy region, the evaluated cross section for the ^{187}Re(n,2n)$^{186m+g}$Re reaction at 14.8 MeV is (2213±116) mb, which is taken from the above evaluated cross section for ^{187}Re(n,2n)^{186m}Re and ^{187}Re(n,2n)^{186g}Re reactions.

Table 1. Measured and evaluated absolute emission probability of 137.144 keV γ-rays from ^{186g}Re decay .

P_γ(137.144keV)/%	references	comments
8.26 ± 0.15	Goswamy[8]	not used
9.45 ± 0.16	Coursey[9]	same group as Ref. [11], superseded by Ref. [11]
9.39 ± 0.09	Schonfeld[10]	
9.45 ± 0.08	Coursey[11]	
9.49 ± 0.03	Miyahara[12]	
9.35 ± 0.10	Woods[13]	
9.47 ± 0.03		weighted average, χ^2=2.7
9.47 ± 0.03		adopted value

Table 2. Measured and evaluated cross sections for ^{187}Re(n,2n)^{186m}Re reaction.

time	author	E_n /MeV	σ/mb	neutron flux	E_γ/keV	P_γ/%	corrected cross section*/mb
1997	Y.Ikeda [1]	14.80	541±189	^{93}Nb(n,2n)^{92m}Nb	137	8.22	470±166
1998	X.Huang [2]	14.77	485±116	^{93}Nb(n,2n)^{92m}Nb	137	8.83	452±109
present evaluated value at 14.8 MeV: 461±106 mb							

∗: Renormalized for decay data only.

Table 3. Measured and evaluated cross sections for ^{187}Re(n,2n)^{186g}Re reaction.

time	author	E_n/MeV	σ/mb	neutron flux	E_γ/keV	I_γ/%	corrected cross section /mb
1961	Khurana [4]	14.8	1675±168	^{56}Fe(n,p)^{56}Mn			1775±177#
1963	R.A.Karam [5]	14.1	1440±410	^{197}Au(n,2n)^{196}Au*			1449±413#
1967	A.Druzhinin [6]	14.8	1490±160	^{27}Al(n,α)^{24}Na			1490±160
1992	T.Fan [3]	14.1	1966.9±50.3	^{93}Nb(n,2n)^{92m}Nb			1765.4±46.2$
		14.6	1967.1±44.7		137	8.5	1765.5±41.3$
		14.8	1952.0±50.7				1752.1±46.3$
		15.0	1903.0±50.3				1708.1±46.8$
1997	A.Filatenkov [15]	14.85	1670±100	^{93}Nb(n,2n)^{92m}Nb	137	8.6	1517±91$
	present evaluated value at 14.8 MeV : (1752±46) mb						

*: $T_{1/2}$=5.3 d. #: renormalized for reference cross sections only. $: renormalized for decay data only.

3 Model calculation

In order to recommend the excitation functions for the ^{187}Re(n,2n)^{186g}Re and ^{187}Re(n,2n)^{186m}Re reactions, a theoretical calculation was performed. The cross sections for the ^{187}Re(n,2n)$^{186m+g}$Re reaction below 20 MeV were analyzed using the UNF code and fitted to the recommended value (2213±116) mb at 14.8 MeV. The isomeric cross section ratio for the ^{187}Re(n,2n)^{186m,g}Re reaction was analyzed using the V-H method based on nuclear statistical theory. Combining these calculated results, the excitation functions for ^{187}Re(n,2n)^{186m}Re and ^{187}Re(n,2n)^{186g}Re reactions were obtained.

3.1 Optical model and optical potential parameters

The optical model is used to calculate the total, nonelastic, elastic scattering cross sections and elastic scattering angular distribution, and the transmission coefficients of the compound nucleus. The optical potentials considered here are Woods-Saxon form for the real part, Woods-Saxon and derivative Woods-Saxon form for the imaginary parts corresponding to the volume and surface absorption, respectively, and the Thomas form for the spin-orbit part.

The code APOM, by which the best neutron optical potential parameters can be searched automatically by fitting the relevant experimental data of the total, nonelastic scattering cross sections and elastic scattering angular distributions, is used to obtain a set of optimum neutron optical potential parameters of ^{187}Re. Because there are no experimental data of elastic scattering angular distributions for Re, the neutron elastic scattering angular distributions of W, which is a neighbor nucleus of Re, is used. A set of optimum neutron optical potential parameters of Re is obtained, and shown in Table 4.

Table 4. Neutron optical potential parameters in the B-G form.

a_R	a_S	a_V	a_{SO}	r_R	r_S	r_V	r_{SO}	r_c	U_0
0.5243	0.4500	0.8999	0.4000	1.1177	1.4127	1.6919	1.1061	1.25	−0.0782
U_1	U_2	V_0	V_1	V_2	V_3	V_{SO}	W_0	W_1	W_2
0.1901	−0.0030	57.4536	0.1689	−0.0213	−24	5.8768	7.6697	−0.3920	−12

Figure 1 compares the theoretical values and experimental data for neutron total cross sections for natural Re in the energy region 0.01–20 MeV. The calculated results are in good agreement with experimental data for the energy range $E_n > 2$ MeV. The comparison of calculated results and experimental data of elastic scattering angular distributions for the n+ ^{Nat}Re reaction is given in Fig. 2 and the theoretically calculated result is reasonable.

In the view of the analysis shown above, this set of neutron optical potential parameters can be used for the theoretical calculation of n+^{187}Re.

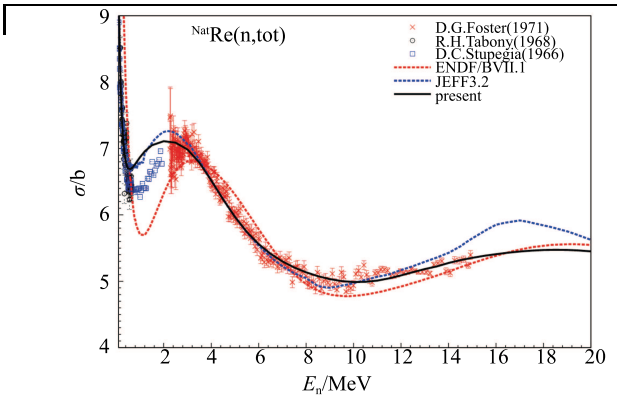

Fig. 1. The total cross section of n+^{Nat}Re reaction.

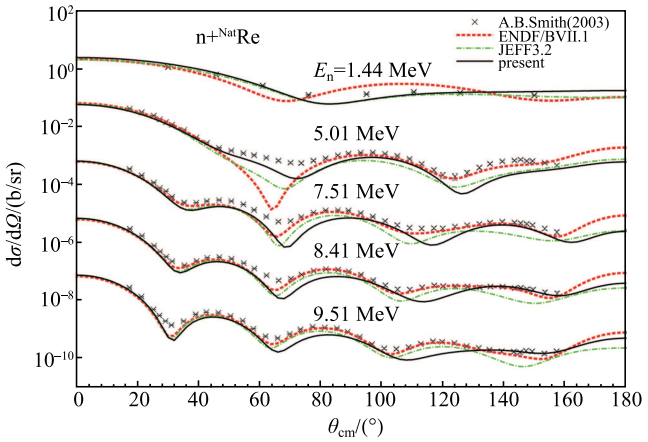

Fig. 2. Elastic scattering angular distributions of the n+$^{\rm Nat}$Re reaction.

3.2 Calculations using UNF

All the reaction cross sections, angular distributions, double differential cross sections, and neutron energy spectrum for n+^{187}Re at incident neutron energies below 20 MeV were calculated and analyzed by the semi-classical theory code UNF. The optical potential parameters, level densities and giant dipole resonance parameters were adjusted to make the calculations consistent with the available measurements around 14 MeV, especially with the present evaluations for the (n,2n) reaction at 14.8 MeV.

The UNF code consists of the optical model, the semi-classical model of multi-step nuclear reaction processes. The semi-classical model of multi-step nuclear reaction processes, in which the discrete level effect in multi-particle emissions as well as the pre-equilibrium phenomenon combining with parity conservation and angular momentum conservation are included, is used to describe the nuclear reaction pre-equilibrium and equilibrium decay processes. This semi-classical model includes both the Hauser-Feshbach theory and the exciton model, and the exact Pauli exclusion effect in the exciton state densities is taken into account. The pick-up mechanism is used to describe the composite particle emission processes. The pre-equilibrium and direct reaction mechanisms of γ emission were also included in this code. The recoil effect was taken into account in the UNF code in order to keep energy conservation for the whole reaction processes.

3.3 Calculation of the isomeric cross section ratio

Of all the methods of calculating the isomeric cross section ratio for (n,2n) reactions, the V-H method [16], based on statistical theory, is a frequently used method. The calculation is done within the framework of the spin-dependent statistical theory of nuclear reactions. Usually the important factors which determine the isomeric cross section ratio for (n,2n) reactions are: (1) the spins of the compound system; (2) the angular momentum carried away at each step; (3) the probability of forming states of different spins during each step of the cascade; and (4) the spins of the isomeric state and ground state. The compound nuclei for a given excitation energy are formed with a variety of spins. The emitted particle leads to residual nuclei with a variety of spins. When the particle emission is not energetically possible, further de-excitation occurs by γ-ray emission and again changes the spin distributions. Ultimately the γ-ray cascade leads to the isomeric state or ground state.

(1) Initial compound nucleus spin distribution

The cross section for the formation of a compound nucleus with spin $J_{\rm c}$ at a bombarding energy E is given by

$$\sigma(J_{\rm c},E)=\pi\lambda^2\sum_{S=|I-s|}^{I+s}\sum_{l=|J_{\rm c}-S|}^{J_{\rm c}+S}\frac{2J_{\rm c}+1}{(2s+1)(2I+1)}T_l(E), \tag{1}$$

where λ is the de Broglie wavelength of the incoming projectile, s is the spin of the projectile, I is the spin of the target nucleus, S is the entrance channel spin, and $T_l(E)$ is the transmission coefficient of the incident particle of energy E and orbital angular momentum l. Then the normalized initial compound nucleus spin distribution can be written as the following form:

$$P(J_{\rm c})=\frac{\sigma(J_{\rm c},E)}{\sum\limits_{J_{\rm c}}\sigma(J_{\rm c},E)}. \tag{2}$$

(2) Spin distribution following neutron emission

A particular state with spin $J_{\rm c}$ can decay by particle emission to final states with a variety of spin values, each of which are denoted by $J_{\rm f}$. The relative probability from an initial state $J_{\rm c}$ to a final state spin $J_{\rm f}$ is given by

$$P(J_{\rm c}\to J_{\rm f})\propto\rho(J_{\rm f})[D(2J_{\rm f}+1)+(1-D)]\cdot\sum_{j=|J_{\rm f}-s|}^{J_{\rm f}+s}\sum_{l=|J_{\rm c}-j|}^{J_{\rm c}+j}T_l(E_{\rm n}), \tag{3}$$

where $T_l(E_{\rm n})$ is the transmission coefficient of the emission neutron with angular momentum l and energy $E_{\rm n}$, D is the contribution from preequilibrium emission as determined by the UNF code, and $\rho(J_{\rm f})$ is the residual nucleus level density,

$$\rho(J_{\rm f})=\frac{2J_{\rm f}+1}{\sqrt{2\pi^2}\sigma^2}\exp\left\{-\frac{(J_{\rm f}+0.5)^2}{2\sigma^2}\right\}, \tag{4}$$

where σ^2 is the spin cutoff factor with

$$\sigma^2=0.146atA^{2/3}=0.073\left(1+\sqrt{1+4aU}\right)A^{2/3}. \tag{5}$$

In these formulae, A is the mass number, a is the level density parameter, $U=E-\Delta$, and Δ is the pairing energy correction. a and Δ are taken from Ref. [3].

To sum over all values of $J_{\rm c}$, one can easily obtain the normalized spin distribution at state $J_{\rm f}$ following a neutron emission

$$P(J_{\rm f})=\sum_{J_{\rm c}}P(J_{\rm c})\cdot\frac{\rho(J_{\rm f})\sum\limits_{j=|J_{\rm f}-s|}^{J_{\rm f}+s}\sum\limits_{l=|J_{\rm c}-j|}^{J_{\rm c}+j}T_l(E_{\rm n})}{\sum\limits_{J_{\rm F}}\rho(J_{\rm F})\sum\limits_{j=|J_{\rm F}-s|}^{J_{\rm F}+s}\sum\limits_{l=|J_{\rm c}-j|}^{J_{\rm c}+j}T_l(E_{\rm n})}. \quad (6)$$

The calculation of spin distribution following second neutron emission is repeatedly done by the steps mentioned above, in which case the normalized spin distribution following the emission of the first neutron becomes the initial spin distribution.

(3) Spin distribution following γ-ray emission

After the second neutron is emitted, the residual nucleus is de-excited by emitting one or a cascade of γ-rays if the energy of the residual nucleus is not enough to emit a neutron. The relative probability from state $J_{\rm i}$ to state $J_{\rm f}$ by γ emission is assumed to be simply proportional to the density of final states with spin $J_{\rm f}$. Thus the normalized probability of $J_{\rm f}$ can be given by the following formula:

$$F(J_{\rm f})=\sum_{J_{\rm i}=|J_{\rm f}-l|}^{J_{\rm f}+l}\frac{F(J_{\rm i})\rho(J_{\rm f})\delta_{J_{\rm i},J_{\rm f}}}{\sum\limits_{J_{\rm F}=|J_{\rm i}-l|}^{J_{\rm i}+l}\rho(J_{\rm F})}, \quad (7)$$

where l is the multipolarity of γ emission and $F(J_{\rm i})$ is the initial spin distribution. For the first γ-ray emission, $F(J_{\rm i})=P(J_{\rm f})$, where $P(J_{\rm f})$ is the spin distribution following the second neutron emission. Considering the pure dipole radiation during γ de-excitation, the multipolarity l can be taken as 1.

The number of γ-rays in the γ-cascade is approximately estimated by

$$N=(l+1)^{-1}\sqrt{aE}=0.5\sqrt{aE} \quad (8)$$

and the mean energy of γ-ray emission at each step can be calculated by

$$E_\gamma=4(E/a-5/a^2)^{1/2}, \quad (9)$$

where E is the excitation energy and a is the level density parameter.

The last γ-ray to be emitted is assumed to lead the excited nucleus to the isomeric state or ground state depending upon which transition has the smaller spin change. Thus of all possible values of $J_{\rm f}$, one can find a separate spin $I_{\rm d}$, which makes the state with higher spin than $I_{\rm d}$ de-excite to the high-spin product and the state with lower than $I_{\rm d}$ de-excite to low-spin product. We define $I_{\rm d}$ as the separate spin value

$$I_{\rm d}=\frac{I_{\rm h}+I_{\rm l}}{2}, \quad (10)$$

where $I_{\rm h}$ is the spin at high spin state and $I_{\rm l}$ is the spin at low spin state.

If $I_{\rm d}$ is a possible spin value of a final state, the ratio can be expressed as

$$r=\frac{\sigma_{\rm h}}{\sigma_{\rm l}}=\frac{1-\sum\limits_{J_{\rm f}\langle I_{\rm d}}F(J_{\rm f})}{\sum\limits_{J_{\rm f}\langle I_{\rm d}}F(J_{\rm f})}. \quad (11)$$

If $I_{\rm d}$ is not a possible spin value of a final state, the ratio can be expressed as

$$r=\frac{\sigma_{\rm h}}{\sigma_{\rm l}}=\frac{1-\left[\sum\limits_{J_{\rm f}\langle I_{\rm d}}F(J_{\rm f})+\frac{2J_{\rm f}+1}{4I_{\rm d}+2}F(J_{\rm f}=I_{\rm d})\right]}{\sum\limits_{J_{\rm f}\langle I_{\rm d}}F(J_{\rm f})+\frac{2J_{\rm f}+1}{4I_{\rm d}+2}F(J_{\rm f}=I_{\rm d})}, \quad (12)$$

where $\sigma_{\rm h},\sigma_{\rm l}$ represent the cross section of high spin and low spin state, respectively.

So the isomeric cross section ratio R, which is the ratio of isomeric cross section to the sum of isomeric cross section and ground cross section, can be written as follows:

$$R=\frac{r}{r+1}, \quad \text{if } I_{\rm m}>I_{\rm g} \quad (13)$$

$$R=\frac{1}{r+1}, \quad \text{if } I_{\rm m}<I_{\rm g} \quad (14)$$

where $I_{\rm m}$ and $I_{\rm g}$ represent the spin of isomeric and ground state, respectively.

(4) Neutron emission energy

After introducing the pairing energy and shell energy correction δ, the maximum energy of the outgoing neutron is given by

$$\varepsilon_{\rm n}=E-S_{\rm n}-\Delta, \quad (15)$$

where E is the excitation energy and $S_{\rm n}$ is the neutron separate energy. Defining

$$X_{\max}=a^{-1}[(a\varepsilon_{\rm n}+0.25)^{\frac{1}{2}}-0.5] \quad (16)$$

the neutron emission energy distribution then becomes

$$f(X)=\frac{X}{X_{\max}}\exp\{aX_{\max}-[a(\varepsilon_{\rm n}-X)]^{\frac{1}{2}}\}, \quad (17)$$

where a is the level density parameter. $f(X)$ satisfies the relationship $f(X_{\max})=1$.

The actual selection of a value of X involves the consecutive drawing of two random numbers between 0 and 1. The first random number, ξ_1, is used to choose a value of X between 0 and ε_n.

$$X = \xi_1 \varepsilon_n. \tag{18}$$

The second random number, ξ_2, is used to determine whether the value of X is to be accepted or rejected. If $f(X) > \xi_2$, the value of X is accepted, otherwise redrawing the ξ_1 and ξ_2.

4 Results and discussion

The comparison of different results calculated by the codes UNF, EMPIRE, TALYS, and present evaluated data at 14.8 MeV for the ^{187}Re(n,2n)^{186}Re reaction is given in Fig. 3. The calculated results from EMPIRE, TALYS and UNF model calculation are in good agreement with each other, and fit the present evaluation at 14.8 MeV very well. The theoretically calculated result is reasonable. The model calculations of ^{187}Re(n,2n)^{186}Re in the TALYS and EMPIRE codes used the default values, and the model parameters used in the UNF code for the (n,2n) channel were adjusted according to the experimental data, shown in Table 5. For other reaction channels, the default values were used.

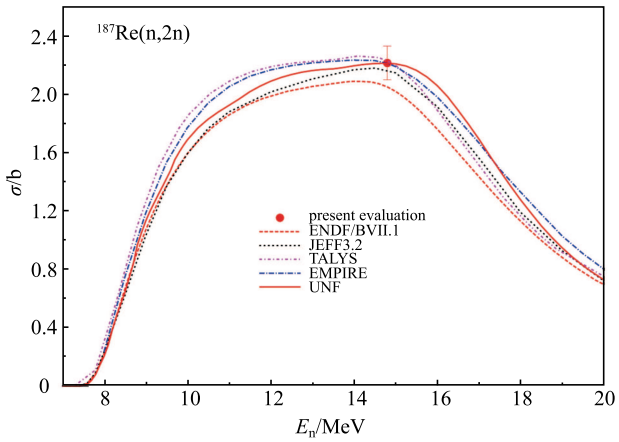

Fig. 3. Cross sections of the ^{187}Re(n,2n)^{186}Re reaction.

Table 5. The level density parameters, pairing correction and giant resonance parameters used in the UNF.

a	Δ	CSGA1	CSGA2	EG1	EG2	GG1	GG2
18.47	0.0	0.2	0.3	12.47	14.63	3.21	5.27

Based on the present evaluated values, the isomeric cross section ratio R ($R = \sigma_m/\sigma_g$) for the ^{187}Re(n,2n)^{186}Re reaction at 14.8 MeV is deduced. The calculated results from the V-H method are compared with these deduced values and the EMPIRE and TALYS calculated results, as shown in Fig. 4. The theoretically calculated isomeric ratios from EMPIRE and TALYS are not in good agreement with each other, especially in the energy region above 15 MeV. The result of the V-H method is very close to the evaluated data at 14.8 MeV. This indicates that the V-H method is a practical method of calculating the isomeric cross section ratios for (n,2n) reactions.

Using the calculated cross sections and isomeric cross section ratios for the ^{187}Re(n,2n)^{186}Re reaction, the cross sections for the ^{187}Re(n,2n)^{186m}Re and ^{187}Re(n,2n)^{186g}Re reactions are deduced, as given in Figs. 5 and 6, respectively. The data plotted in Figs. 5 and 6 are the corrected or adjusted results using new decay data or reference cross sections, etc., not the original measured values. The previous evaluations for the ^{187}Re(n,2n)^{186g}Re and ^{187}Re(n,2n)^{186m}Re reaction in 1998 [2] are also plotted in these figures. The present evaluation has a large improvement compared to the previous evaluations.

Our recommended cross sections for ^{187}Re(n,2n)^{186m}Re and ^{187}Re(n,2n)^{186g}Re reactions are in good agreement with the available experimental data. Of course the results should be further checked by measurements directly in the future because the available experimental data are very scarce and only concentrated on the energy region of 14 MeV.

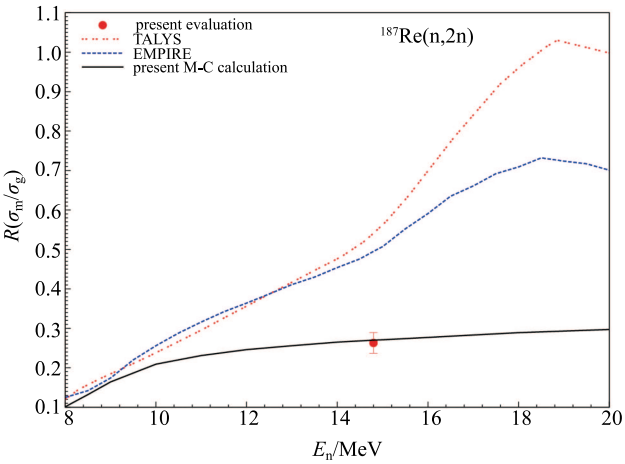

Fig. 4. Isomeric cross section ratio for the ^{187}Re(n,2n)^{186m,g}Re reaction.

There are several factors which may influence the isomeric ratios. The calculations indicate that the most important factor is the spin cutoff factor. Thus it is very important to select the spin cutoff factor accurately in the calculations.

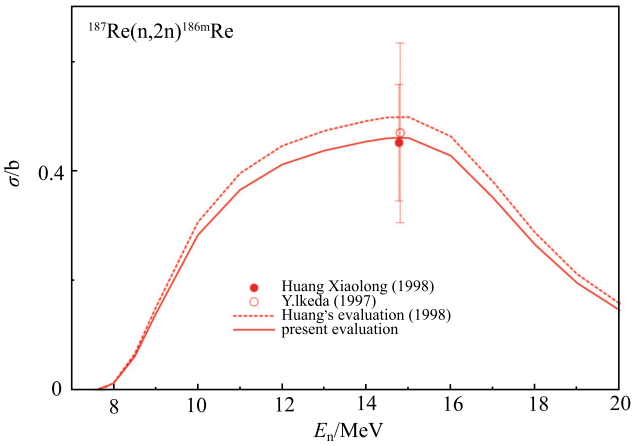

Fig. 5. Cross sections of the ^{187}Re(n,2n)^{186m}Re reaction.

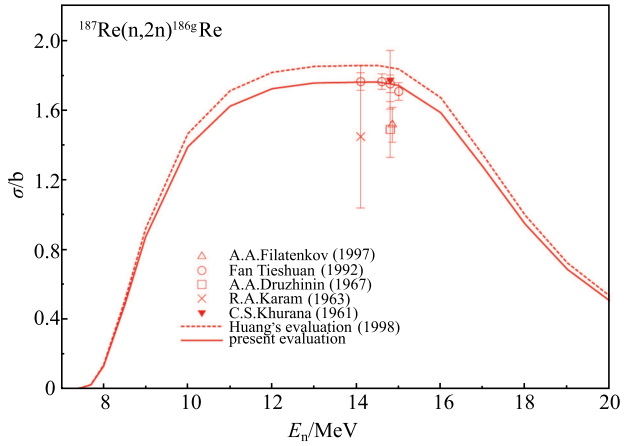

Fig. 6. Cross sections of the ^{187}Re(n,2n)^{186g}Re reaction.

References

1 B. Pashchenko, INDC(NDS)-344, **20**: 23 (1997)
2 X. Huang, H. Lu, W. Zhao et al, INDC(CPR)-045, **17**: 23 (1998)
3 T. Fan, Z. Shi, G. Tang et al, Chin. J. Nucl. Phys., 14, **331**: 337 (1992)
4 C. S. Khurana, H. S. Hans, Nucl. Phys., 28, **560**: 567 (1961)
5 R. A. Karam, T. F. Parkinson, W. H. Ellis. AD-402668, 1963
6 A. A. Druzhinin. YF-5, **18**: 27 (1967)
7 J. S. Zhang, Fast Neutron Physics, 1991
8 J. Goswamy, B. Chand, D. Mehta et al, Appl. Radiat. Isot, 42, **1033**: 1042 (1991)
9 B. M. Coursey, J. Cessna, E. Garcia et al, Appl. Radiat. Isot, 42, **865**: 874 (1991)
10 E. Schonfeld, H. Janssen, U. Schotzig et al, Nucl. Instrum. Methods Phys. Res., A339, **174**: 187 (1994)
11 B. M. Coursey, J. M. Calhoun, J. Cessna et al, Nucl. Instrum. Methods Phys. Res., A339, **26**: 39 (1994)
12 H. Miyahara, G. Wurdiyanto, H. Nagata et al, Appl. Radiat. Isot. 52, **573**: 580 (2000)
13 D. H. Woods, M. Ciocanel, L. J. Husband et al, Appl. Radiat. Isot. 52, **581**: 586 (2000)
14 H. J. Lu, China Nucl. Phys., 19, **35**: 42 (1997)
15 A. A. Filatenkov, INDC(CCP)-402, **47**: 52 (1997)
16 J. R. Hvizenga, Phys. Rev., 120, **1305**: 1328 (1960)