Evaluation of excitation function for ^{186}W(d,2n)^{186}Re reaction

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Abstract. The excitation function of the ^{186}W(d,2n)^{186}Re reaction was evaluated and the thick target yield (TTY) of the therapeutic radioisotope ^{186}Re was calculated. The available experimental data from the EXFOR library and literature were analyzed and corrected with the g-ray branching ratio, radioactive decay constant and standard cross sections. The excitation function of the ^{186}W(d,2n)^{186}Re reaction was recommended below 50 MeV on basis of the least-squares fit with polynomial and the theoretical calculation with TALYS code. The TTY was calculated using the recommended excitation function of the ^{186}W(d,2n)^{186}Re reaction.

1. Introduction

The charged particle excitation functions are the important part of the nuclear data, applied to the activation analysis, nuclear medicine investigation, nuclear theory, calculation of integral thick target yield, and so on.

Rhenium-186 is an important medically radionuclide, and regarded very suitable for radiotherapy and radioimmunotherapy due to its attractive properties which include emission of high-energy β-rays 1.07 MeV, low-abundance (9.42%) gamma emission at 137 keV, and 90.64 h half-life.

The ^{186}Re has been produced using nuclear reactors through ^{185}Re(n,γ)^{186}Re reaction, but the specific activity is medium, not in no-carrier-added form. In order to radiolabel antibodies more efficiently, production of no-carrier-added ^{186}Re with high specific activity is required. There are two major routes for the production of no-carrier-added ^{186}Re by cyclotron, namely ^{186}W(p,n)^{186}Re and ^{186}W(d,2n)^{186}Re.

In the present work, the excitation function of ^{186}W(d,2n)^{186}Re reaction was evaluated. The available experimental data include the latest reports [1,2] that are not considered in previous works [3,4] were analyzed and corrected. The nuclear model calculation was done using TALYS [5]. The TTY of ^{186}Re was calculated using the recommended excitation function of ^{186}W(d,2n)^{186}Re reaction, and compared with the TTY from ^{186}W(p,n)^{186}Re reaction [6].

2. Evaluation of experimental data

The activation method and stacked foil technique are often used in the charged particle excitation functions measurement. The formula [7] of charged particle excitation functions is as follows:

$$\sigma = \frac{M}{n\varepsilon p a N_0} \cdot \frac{c}{t} \cdot \frac{1}{\chi} \cdot \frac{1.6 \times 10^{-19} t_i}{Q} \cdot \frac{e^{\lambda t_d}}{1 - e^{-\lambda t_i}} \cdot 10^{24}\,(b) \quad (1)$$

Where, M is the target molecular weight, $n$is the target nucleus number in a molecule, ε denotes the detection efficiency of detector at full energy peak, p is the g-ray branching ratio, a denotes the isotope abundance, N_0 is the Avogadro constant, $c/t$is the accounting g-ray number at full energy peak in a unit time, χ denotes the target weight in a unit area, t_i denotes the irradiation time, $Q$is the total integrated beam current (in Coulomb), t_d denotes the cooling time (start from stop irradiation) and λ is the radioactive decay constant.

From the mentioned-above formula, the cross sections are proportional to the radioactive decay constant, and inversely proportional to the g-ray branching ratio. Moreover, if the experiment is relative measurement, the cross sections are proportional to the standard cross sections. According to these relations, σ can be corrected by the new p, λ and standard cross sections.

Eight experiments [1,2,7–12] of the ^{186}W(d,2n)^{186}Re reaction were founded in the EXFOR library and literature, listed in Table 1 and shown in Fig. 1.

The experimental data were normalized to 100% enrichment of ^{186}W, considering the given enrichment of the target in the literature and the isotopic composition of natural tungsten, i.e., ^{180}W (0.12%), ^{182}W (26.50%), ^{183}W (14.31%), ^{184}W (30.64%) and ^{186}W (28.43%). In the measurements of F. Tarkanyi et al. [11], K.Ochiai et al. [12], S. Manenti et al. [1] and C. Duchemin et al. [2], the samples were thick natural W-metal foils, so the normalization factor is 3.517. In the measurement of F.W. Pement et al. [8], the sample was WO_3 powder, enriched to 97.2% in ^{186}W, so the normalization factor is 1.0288.

In the measurement of Tao Zhenlan et al. [7], the g-ray branching ratio of 137.16 keV are 0.092, and the new value is 0.0942 [13]. The sample was WO_3 powder, enriched to 99% in ^{186}W, so the corrected factor is 0.9813. The experimental data after normalization and correction are shown in Fig. 2.

3. Nuclear model calculations

Several nuclear model code have been developed, in the evaluation of data are very helpful. In the process of evaluation, the parameters of the nuclear model

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Table 1. Measurements of ^{186}W(d,2n)^{186}Re reaction.

Author	Sample	Method
F.W. Pement et al. [8]	WO_3 enriched to 97.2%	STTA
S.J. Nassiff et al. [9]	—	STTA, ACTIV
Tao Zhenlan et al. [7]	WO_3 enriched to 99%	STTA, ACTIV
N.S. Ishioka et al. [10]	natural	STTA, ACTIV
F. Tarkanyi et al. [11]	natural	STTA, ACTIV
K. Ochiai et al. [12]	natural	STTA, ACTIV
S. Manenti et al. [1]	natural	STTA, ACTIV
C. Duchemin et al. [2]	natural	STTA, BCINT

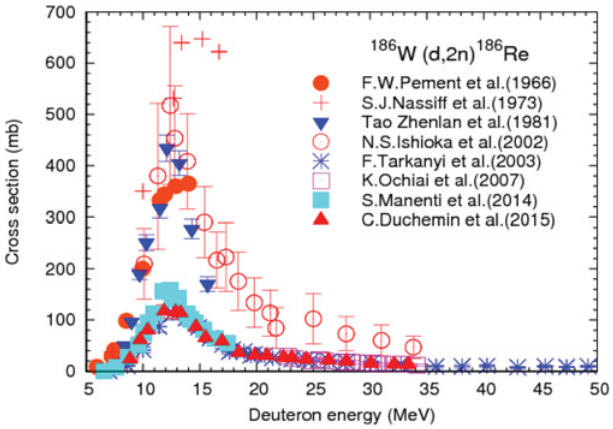

Figure 1. Original experimental data.

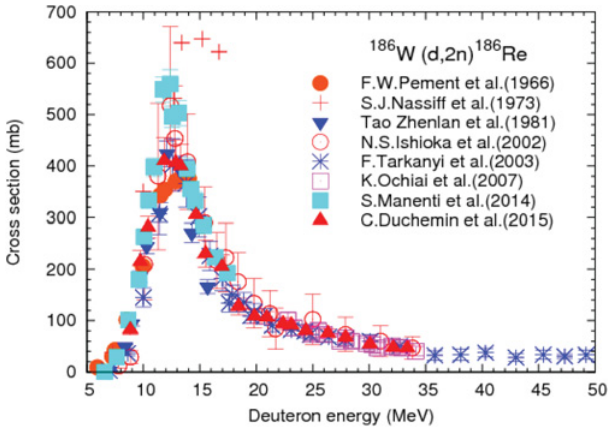

Figure 2. The experimental data after normalization and correction.

code need to be adjusted to reproduce the experimental data.

In this work, the cross sections were calculated using TALYS, a nuclear model code, developed by Koning et al. [5]. The nuclei were considered non-spherical in shape. The compound nucleus contribution was considered in the frame of Moldaner model. The contributions of direct reactions were taken into account by ECIS. The back-shifted Fermi gas model (BFM) was used for level densities (ldmodel 2). The OM parameters were adjusted,

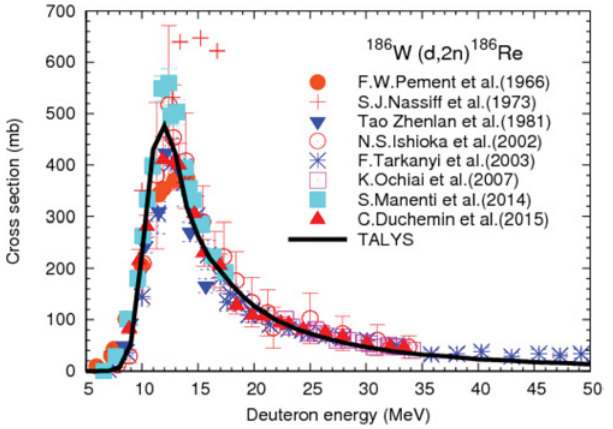

Figure 3. The results of nuclear model calculation using TALYS.

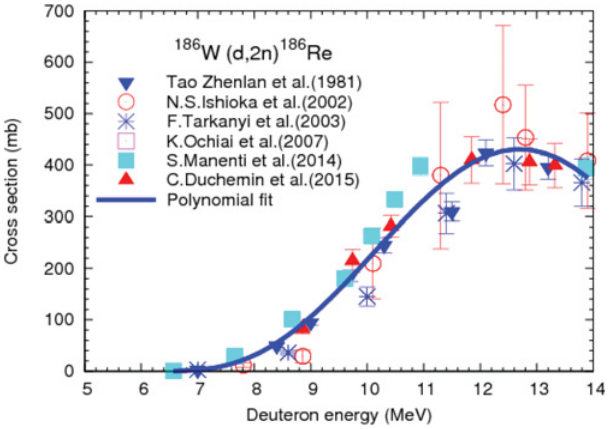

Figure 4. The results of fitting from threshold to 14 MeV.

rvsdjust was set to 1.2. The pairing energy of ^{186}Re was set to 0.0. The theoretical results are shown in Fig. 3.

4. Fitting of experimental data

After normalization and correction, the experimental data are consistent besides the partial data of S.J. Nassiff et al. [9] and S. Manenti et al. [1]. S.J. Nassiff et al. reported six cross section values from 7.3 to 16.7 MeV, but the errors not given. The data are higher than the calculated values using TALYS and those reported by other authors between 10 to 20 MeV. The data of S. Manenti et al. are highter than the results of calculation and other measurements at 11.76, 12.38, 12.54 and 13.14 MeV. F.W. Pement et al. [8] reported nine data points but not given the errors also. So these data were neglected in fitting of experimental data.

On basis of least-squares fit with polynomial, the evaluated experimental data were fitted from threshold to 14 MeV and from 14 to 50 MeV. The curves of fitting are shown in Fig. 4 and Fig. 5.

The function of fitting from threshold to 14 MeV as follws:

$$\sigma_{d,2n} = a - bE_d + cE_d^2 - dE_d^3 \quad (2)$$

Where, $a = 4.2176$, $b = 1.4378$, $c = 0.1555$, $d = 0.0052$.

The function of fitting from 14 to 50 MeV as follws:

$$\sigma_{d,2n} = \exp(a - bE_d + cE_d^2) \quad (3)$$

Where, $a = 1.8248$, $b = 0.2544$, $c = 0.0031$.

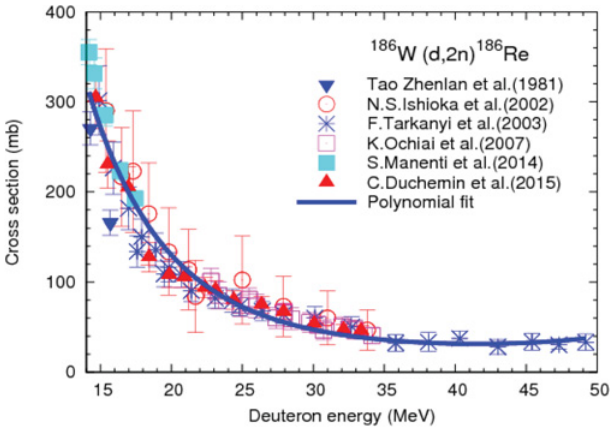

Figure 5. The results of fitting from 14 to 50 MeV.

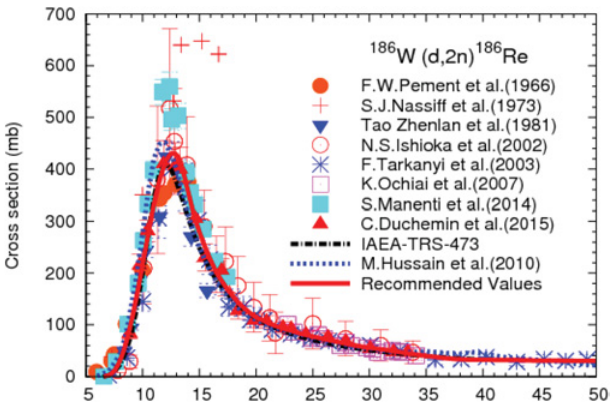

Figure 6. The recommended excitation function for ^{186}W(d,2n)^{186}Re reaction, compared with experimental data and results published earlier.

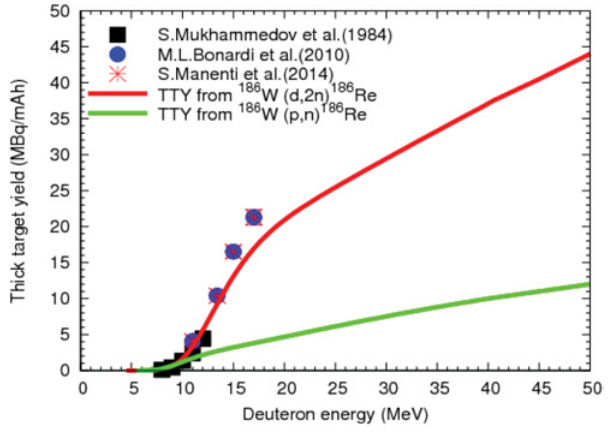

Figure 7. The TTY of ^{186}W(d,2n)^{186}Re reaction, compared with the TTY of ^{186}W(p,n)^{186}Re reaction.

5. Results and discussion

The excitation function for ^{186}W(d,2n)^{186}Re reaction was recommended from threshold energy to 50 MeV after comprehensive evaluation, take into account the results of calculation and fitting. The recommended curve is given in Fig. 6, together with the results of M. Hussain et al. [3] and IAEA TRS 473 [4]. The recommended excitation function of ^{186}W(d,2n)^{186}Re reaction are agree with the experimental data, the maximum value is slightly higher than the value of IAEA TRS 473, and little lower than the value of M. Hussain et al.

The thick target yield (TTY) of ^{186}Re was calculated using the recommended excitation function of ^{186}W(d,2n)^{186}Re reaction, and compared with the TTY from ^{186}W(p,n)^{186}Re reaction [6], together with the measurements [1, 14, 15] are shown in Fig. 7. The TTY of ^{186}W(d,2n)^{186}Re reaction are much higher than the value of ^{186}W(p,n)^{186}Re reaction above 15 MeV. So the ^{186}W(d,2n)^{186}Re reaction may be more suitable for production of no-carrier-added ^{186}Re for medical application, if the deuteron beams are available by cyclotron and the energy is high enough.

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