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Analysis of the total activation cross section of all possible reactions producing the same radioactive nuclide for the same element*

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Abstract: Firstly, according to the regulation of growth and decay of radioactive nuclides produced in reactions, a formula used to calculate the total activation cross section of all possible reactions producing the same radioactive nuclide for the same element is deduced, and it is pointed out that the activation formula given in two references is incorrect. Then, as an example, the so-called total activation cross section in one of the two references is analyzed and the correct results of the cross sections of ^{182}W(n,p)$^{182(m+g)}$Ta, ^{183}W(n,p)^{183}Ta and ^{206}Pb(n,α)^{203}Hg induced by neutrons around 14 MeV calculated with the data given in the literature, the nuclear parameters and some evaluated values are given. Finally, the correct results are compared with other values collected in the literature.

Key words: total activation cross sections, analysis, cross section, tungsten, lead

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1 Introduction

Cross sections are the foundational gist of testing the nuclear theory; they are also the basic data, which can be utilized in nuclear technology and nuclear power and, therefore, accurate measurement of them is very important. However, in practice, cross-section measurements can be influenced by many factors, such as the interactions of all possible reactions, γ-rays with close energies, the interference of an excited state on the ground state, cascade coincidence, self-absorption and so on. All the above problems need to be resolved. As to the interactions of all possible reactions producing the same radioactive nuclide for the same element with several stable nuclei, this can be solved by using the common method of neglecting the effect of the smaller reaction cross section or deducting the effect indirectly when the bigger cross section is calculated. The Refs. [1, 2] reported the total activation cross section of all possible reactions producing the same radioactive nuclide for the same element induced by neutrons around 14 MeV on three elements of nickel, tungsten and lead. The total activation cross section data induced by neutrons around 14 MeV should be useful for the selection of materials and the design of fusion power reactors and related fusion energy devices, but the method of calculating and the result in Refs. [1, 2] are incorrect.

In this paper, firstly, according to the regulation of growth and decay of radioactive nuclides produced in reaction [3, 4], a formula used to calculate the total activation cross section of all possible reactions producing the same radioactive nuclide for the same element is deduced, and it is pointed out that the activation formula given in Refs. [1, 2] is incorrect. Then, as an example, the so-called total activation cross section in Ref. [1] is analyzed and the correct results of the cross sections of ^{182}W(n,p) $^{182(m+g)}$Ta,

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^{183}W(n,p) ^{183}Ta and ^{206}Pb (n,α) ^{203}Hg induced by neutrons around 14 MeV are calculated with the data given in Ref. [1]; the nuclear parameters [5] and some values [6], are given. Finally, the correct results are compared with the other values collected in the literature.

2 The formula used to calculate the total activation cross section and associated discussions

According to the regulation of growth and decay of radioactive nuclides produced in reactions [3, 4], the following formula can be deduced to calculate the cross section [7]:

$$\sigma_x=\frac{[S\varepsilon I_\gamma\eta KMD]_0}{[S\varepsilon I_\gamma\eta KMD]_x}\frac{[\lambda AFC]_x}{[\lambda AFC]_0}\sigma_0, \tag{1}$$

where the subscript 0 represents the term corresponding to the monitor reaction and the subscript x corresponds to the measured reaction, ε is the full-energy peak efficiency of the measured characteristic gamma ray, I_γ is the γ-ray intensity, η is the abundance of the target nucleus, M is the mass of sample, $D=\mathrm{e}^{-\lambda t_1}-\mathrm{e}^{-\lambda t_2}$ is the counting collection factor, t_1, t_2 are the time intervals from the end of the irradiation to the start and end of counting respectively, A is the atomic weight, C is the measured full-energy peak area, λ is the decay constant, F is the total correction factor of the activity: $F=f_\mathrm{s}\times f_\mathrm{c}\times f_\mathrm{g}$, where f_s, f_c and f_g are the correction factors for the self-absorption of the sample at a given gamma energy and the coincidence sum effect of cascade gamma rays in the investigated nuclide and in the counting geometry, respectively, K is the neutron fluence fluctuation factor:

$$K=\left[\sum_i^L\varPhi_i(1-\mathrm{e}^{-\lambda\Delta t_i})\mathrm{e}^{-\lambda T_i}\right]/(\varPhi S)\ ,$$

where L is the number of time intervals into which the irradiation time is divided, Δt_i is the duration of the ith time intervals, T_i is the time interval from the end of the ith interval to the end of irradiation, $\varPhi_i$ is the neutron flux averaged over the sample in Δt_i, $\varPhi$ is the neutron flux averaged over the sample in the total irradiation time T and $S=1$–$\mathrm{e}^{-\lambda T}$ is the growth factor of the nuclide produced.

Suppose η_{1x}, η_{2x}, η_{3x}, $\cdots$ is the abundance of each isotope of one element considered in a natural sample, C_{1x}, C_{2x}, C_{3x}, $\cdots$ is their measured full-energy peak area, respectively. According to Formula (1), we can obtain the following formulas to calculate each of the cross sections of all possible reactions producing the same nuclide for the one investigated element:

$$\begin{aligned}\sigma_{1x}&=\frac{[S\varepsilon I_\gamma\eta KMD\sigma]_0}{[S\varepsilon I_\gamma KMD]_x}\frac{[\lambda AF]_x}{[\lambda AFC]_0}\frac{C_{1x}}{\eta_{1x}},\\ \sigma_{2x}&=\frac{[S\varepsilon I_\gamma\eta KMD\sigma]_0}{[S\varepsilon I_\gamma KMD]_x}\frac{[\lambda AF]_x}{[\lambda AFC]_0}\frac{C_{2x}}{\eta_{2x}},\\ \sigma_{3x}&=\frac{[S\varepsilon I_\gamma\eta KMD\sigma]_0}{[S\varepsilon I_\gamma KMD]_x}\frac{[\lambda AF]_x}{[\lambda AFC]_0}\frac{C_{3x}}{\eta_{3x}}.\\ &\cdots\cdots.\end{aligned}$$

So the total activation cross-section formula of all possible reactions producing the same radioactive nuclide for the one investigated element is:

$$\begin{aligned}\sigma_x&=\sigma_{1x}+\sigma_{2x}+\sigma_{3x}+\cdots\\ &=\frac{[S\varepsilon I_\gamma\eta KMD\sigma]_0}{[S\varepsilon I_\gamma KMD]_x}\frac{[\lambda AF]_x}{[\lambda AFC]_0}\left(\frac{C_{1x}}{\eta_{1x}}\right.\\ &\qquad\left.+\frac{C_{2x}}{\eta_{2x}}+\frac{C_{3x}}{\eta_{3x}}+\cdots\right).\end{aligned} \tag{2}$$

And the total activation cross-section formula given in Refs. [1, 2] is:

$$\sigma_x=\frac{[S\varepsilon I_\gamma KMD]_0}{[S\varepsilon I_\gamma KMD]_x}\frac{[\lambda AFC]_x}{[\lambda AFC]_0}\sigma_0, \tag{3}$$

in the case of $\eta_0=1$, such as the monitor reaction is ^{93}Nb(n,2n) $^{92\mathrm{m}}$Nb or ^{27}Al(n, α)^{24}Na, Formula (3) can be written as:

$$\begin{aligned}\sigma_x&=\frac{[S\varepsilon I_\gamma\eta KMD\sigma]_0}{[S\varepsilon I_\gamma(\eta_1+\eta_2+\eta_3+\cdots)KMD]_x}\frac{[\lambda AF]_x}{[\lambda AFC]_0}(C_{1x}\\ &\quad+C_{2x}+C_{3x}+\cdots)=\frac{[S\varepsilon I_\gamma\eta KMD\sigma]_0}{[S\varepsilon I_\gamma KMD]_x}\frac{[\lambda AF]_x}{[\lambda AFC]_0}\\ &\quad\times\frac{C_{1x}+C_{2x}+C_{3x}+\cdots}{\eta_{1x}+\eta_{2x}+\eta_{3x}+\cdots},\end{aligned} \tag{4}$$

where $\eta_{1x}+\eta_{2x}+\eta_{3x}+\cdots=100\%=1$.

It can be seen from Formula (4) that Formula (3) imported the sum of the abundance of each isotope of the investigated element in a natural sample, instead of without the abundance of the target nuclide, and that the total activation cross section from Formula (3) or (4) is much smaller than that from Formula (2). Furthermore, it can also be seen from Formula (2) that it is impossible that the total activation cross section of all possible reactions producing a certain radioactive nuclide for one element can be obtained by means of single experiment when samples of natural abundance are used.

It must be pointed out that several possible reactions producing the same nuclide rarely happen in an experiment due to the threshold energy and so on. So it is necessary to analyze all sets of circumstances, such as which reactions are possible, which interferences or effects can be avoided, neglected or deducted and so on, in order to gain accurate and credible cross-section values.

3 Results and discussion

The cross sections of ^{82}W(n,p)$^{182(m+g)}$Ta, ^{183}W(n,p)^{183}Ta and ^{206}Pb(n,α)^{203}Hg should be obtained from the those of W(n,x) ^{182}Ta, W(n,x)^{183}Ta and Pb(n,x)^{203}Hg, respectively in Ref. [1].

In samples of natural abundance, the isotopic abundance of tungsten [5]: ^{180}W-0.13%, ^{182}W-26.3%, ^{183}W-14.3%, ^{184}W-30.67%, ^{186}W-28.6%. In fact, the W(n,x) ^{182}Ta reaction is made up of ^{182}W(n,p) $^{182(m+g)}$Ta, ^{183}W(n,d+np) $^{182(m+g)}$Ta and ^{184}W(n,t+nd+2np) $^{182(m+g)}$Ta. The cross sections of ^{182}W(n,p) $^{182(m+g)}$Ta were calculated by Formula (1) deducting the contribution of ^{183}W(n,d+np)$^{182(m+g)}$Ta reaction with the data of Ref. [1] and the evaluated values [6], at the same time neglecting the contribution of ^{184}W(n,t+nd+2np) $^{182(m+g)}$Ta reaction because of its tiny cross sections (μb), and the results are summarized in Table 1 and plotted in Fig. 1 together with the collected partial literature values for comparison.

Table 1. Summary of the cross sections. (mb)

reaction	E_n/MeV		
	13.5±0.2(or±0.3)	14.4±0.2	14.7±0.2
^{182}W(n,p)$^{182(m+g)}$Ta	2.02±0.14	2.72±0.16	3.24±0.19
^{183}W(n,p)^{183}Ta			3.88±0.22
^{206}Pb(n,α)^{203}Hg	0.98±0.07	1.22±0.08	1.38±0.10

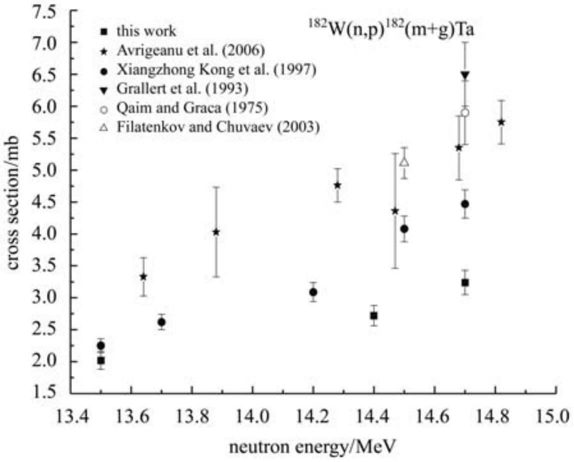

Fig. 1. The cross section of ^{182}W(n,p)$^{182(m+g)}$Ta reaction.

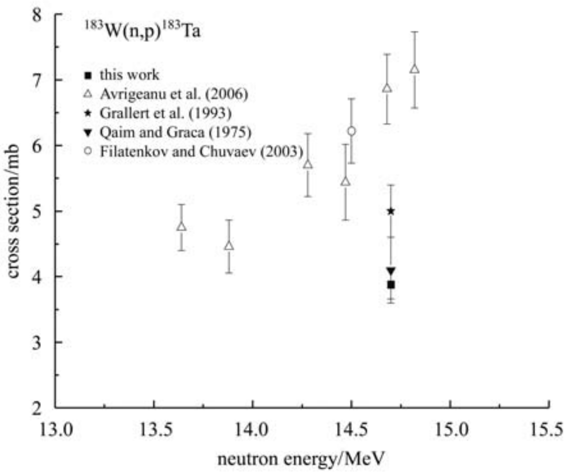

Fig. 2. The cross section of ^{183}W(n,p) ^{183}Ta reaction.

The W(n,x) ^{183}Ta reaction is made up of ^{183}W(n,p) ^{183}Ta and ^{184}W(n,d+np) ^{183}Ta. The cross sections of ^{1183}W(n,p) ^{183}Ta were calculated by Formula (1) deducting the contribution of ^{184}W(n,d+np) ^{183}Ta reaction with the data of Ref. [1] and the evaluated values [6], and the results are summarized in Table 1 and plotted in Fig. 2 together with the collected partial literature values for comparison.

In the natural abundance samples, the isotopic abundance of lead [5]: ^{204}Pb-1.4%, ^{206}Pb-24.1%, ^{207}Pb-22.1%, ^{208}Pb-52.4%. The Pb(n,x)^{203}Hg reaction is made up of ^{204}Pb(n,2p) ^{203}Hg, ^{206}Pb(n,α)^{203}Hg, ^{207}Pb(n,n$'\alpha$)^{203}Hg and ^{208}Pb(n,2nα)^{203}Hg. As mentioned above, it is impossible that all these reactions could be induced by neutrons around 14 MeV due to threshold energy and so on, and the cross sections of ^{204}Pb(n,2p) ^{203}Hg, ^{207}Pb(n,n$'\alpha$) ^{203}Hg and ^{208}Pb(n,2nα) ^{203}Hg are much smaller than those of ^{206}Pb(n,α) ^{203}Hg reaction, the cross sections of ^{206}Pb(n,α) ^{203}Hg reaction were calculated by Formula (1) neglecting the contributions of ^{204}Pb(n,2p) ^{203}Hg, ^{207}Pb(n,n$'\alpha$) ^{203}Hg and ^{208}Pb(n,2nα) ^{203}Hg, and the results are summarized in Table 1 and plotted in Fig. 3 together with the collected partial values from the literature for comparison.

It can be seen from Table 1 and Figs. 1–3 that the cross sections of ^{182}W (n,p) $^{182(m+g)}$Ta reaction are lower than literature values [8–11] except the cross-section value at 13.5 MeV energy point which is in

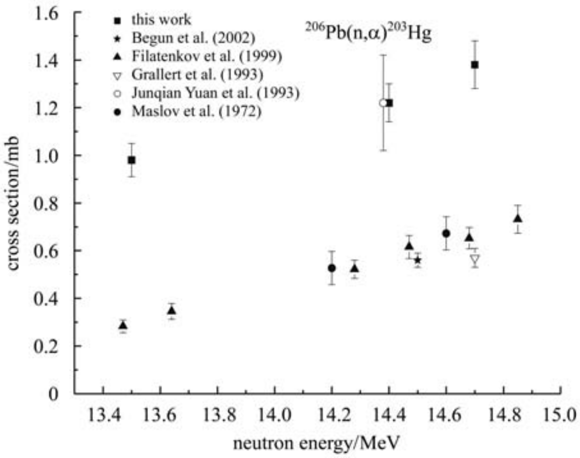

Fig. 3. The cross section of ^{206}Pb(n,α)^{203}Hg reaction.

agreement, within experimental error, with the result of Ref. [12]. Most of the values from the literature were not corrected to account for the possible contribution of ^{183}W(n,d+np) $^{182(m+g)}$Ta reaction. For the cross section of a ^{183}W(n,p) ^{183}Ta reaction, the result is in agreement with that of Ref. [11], but lower than other literature values [8–10]. The results on the cross section of ^{206}Pb(n,α) ^{203}Hg reaction are in agreement with the data of Ref. [13], but higher than other literature values [9, 14–16].

In summary, the so-called total activation cross-section formula given in Refs. [1, 2] is not only that of all possible reactions producing the same radioactive product nuclide for the one investigated element but also the specific cross-section formula of nuclear reactions. As mentioned above, the total activation cross-section formula of all possible reactions producing the same radioactive product nuclide for the one investigated element is Formula (2), but it is impossible that the total activation cross section can be obtained by means of a single experiment when employing samples of natural abundance. The formula for calculating the cross section is Formula (1).

References

1 ZHANG Feng, KONG Xiang-Zhong. HEP&NP, 2003, **27**(1): 28 (in Chinese)
2 FANG Kai-Hong, XU Xiao-San, LAN Chang-Lin, YUAN Ji-Long, KONG Xiang-Zhong. HEP&NP, 2008, **32** (4): 251
3 YANG Fu-Jia, WANG Yan-Sen, LU Fu-Quan. Nuclear Physics (The Second Edition). Shanghei: Fudan University Press, 2002. 102–107 (in Chinese)
4 LU Xi-Ting. Nuclear Physics (Revised Edition). Beijing:Atomic Energy Press, 2000. 22–39(in Chinese)
5 Firestone R B, Shirley V S. Table of Isotopes. New York:Wiley, 1996
6 JEFF-3.1-Evaluated Nuclear Data File (Database Version of March 03, 2009), IAEA Nuclear Data Servic, http://www-nds.iaea.org/exfor/endf.htm
7 WANG Yong-Chang, YUAN Jun-Qian, REN Zhong-Liang et al. HEP & NP, 1990, **14**(10): 919 (in Chinese)
8 Avrigeanu V, Chuvaev S V, Eichin R, Filatenkov A A, Forrest R A, Freiesleben H, Herman M, Koning A J, Seidel K, Nucl. Phys. A, 2006, **76**: 1
9 Grallert A, Csikai J, Buczko CS M, Shaddad I. Report: IAEA Nucl. Data Section report to the I.N.D.C., 1993, **286**: 131
10 Filatenkov A A, Chuvaev S V. Report: Khlopin Radiev. Inst., Leningrad Reports, 2003, 259
11 Qaim S M, Graca C. Nucl. Phys. A, 1975, **242**: 317
12 KONG Xiang-Zhong, HU Shang-Bin, YANG Jing-Kang. Communication of Nuclear Data Progress, 1997, **17**: 9
13 YUAN Jun-Qian, WANG Yong-Chang, YANG Jing-Kang, QIU Jiu-Zi. Nuclear Techniques, 1993, **16**(9): 518
14 Begun S V, Kadenko I M, Maidanyuk V K, Neplyuev V M, Primenko G I, Tarakanov V K. J. Nucl. Science and Technol. Tokyo, Supplement, 2002, **2**(1): 425
15 Filatenkov A A, Chuvaev S V, Aksenov V N, Yakovlev V A, Malyshenkov A V, Vasil'ev S K, Avrigeanu M, Avrigeanu V, Smith D L, Ikeda Y, Wallner A, Kutschera W, Priller A, Steier P, Vonach H, Mertens G, Rochow W, Report: Khlopin Radiev. Inst., Leningrad Reports, 1999, 252
16 Maslov G N, Nasyrov F, Pashkin N F, Report: Yadernye Konstanty, 1972, **9**: 50