

Activation cross-section measurement of a sort of nuclide produced with a target including two isotopes^{*}

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Abstract: Based on a formula used to calculate the activation cross-section sum of two reactions producing a sort of nuclide with a target including two isotopes, the related problems in some references have been analyzed and discussed. It is pointed out that the calculation methods of the cross-section sum of two reactions producing the same radioactive nuclide for two isotopes in some references are improper and usually it is impossible to obtain the correct cross-section sum of two reactions producing the same radioactive nuclide for two isotopes in the case of using natural samples. At the same time, the related concepts are clarified and the correct processing method and representation are given. The comparison with the experimental results show that the theoretical analysis results are right.

Key words: cross section, cross-section sum of two reactions producing the same radioactive nuclide, cross-section measurement

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1 Introduction

Nuclear reaction cross sections are to test the fundamental basis of nuclear theory. They are also the basic data for nuclear technology and nuclear power development. Therefore, the accurate measurement of nuclear reaction cross sections is very important. However, in practice, cross-section measurement induced by neutrons can be influenced by many factors, such as the interactions of all possible reactions, γ -rays with close energies, the interferences from the excited states on the ground state, γ - γ cascade coincidences, γ -ray self-absorption in the sample, and so on. All of these problems need to be resolved. As to the problem of the interactions of all possible reactions, it can usually be resolved by using the solution of isotope separation or a different cooling time according to the different half-life of the product radionuclide. When the target nuclei have many stable isotopes and natural samples are used, it is sometimes difficult to avoid the effects of all possible reactions, such as ${}^a\text{X}(n, p){}^a\text{Y}$ and ${}^{a+1}\text{X}(n, d){}^a\text{Y}$ ($d^* = np + pn + d$) reactions, ${}^a\text{X}(n, 2n){}^{(a-1)m}\text{X}$ and ${}^{a-1}\text{X}(n, n'){}^{(a-1)m}\text{X}$ reactions, and so

on. For these cases, different processing methods or representations are used in different references [1–14] and even the meaning of nuclear reaction cross section is not clear in some references. They are neither conducive to academic exchanges nor conducive for adoption by international or national nuclear data centers. For the effects of ${}^a\text{X}(n, p){}^a\text{Y}$ and ${}^{a+1}\text{X}(n, d){}^a\text{Y}$ reactions or ${}^a\text{X}(n, 2n){}^{(a-1)m}\text{X}$ and ${}^{a-1}\text{X}(n, n'){}^{(a-1)m}\text{X}$ reactions on each other, there are different processing methods or representations in Refs. [1–14].

In this paper, based on a formula used to calculate the activation cross-section sum of two reactions producing a sort of nuclide with a target including two isotopes, the related problems in Refs. [1–14] are analyzed and discussed, and the theoretical analysis results are compared with the experimental results. It is pointed out that the calculation methods of the cross-section sum of two reactions producing the same radioactive nuclide for two isotopes in Refs. [1–8] are improper. At the same time, the related concepts are clarified and the correct processing method and representation are given.

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2 The related formulas

The measured cross sections σ_x were calculated by the following activation formula [15]:

$$\sigma_x = \frac{[S\varepsilon^p I_\gamma \eta KMD]_0 [\lambda AFC]_x}{[S\varepsilon^p I_\gamma \eta KMD]_x [\lambda AFC]_0} \sigma_0, \quad (1)$$

where the subscript 0 represents the term corresponding to the monitor reaction and subscript x corresponds to the measured reaction, ε^p =full-energy peak efficiency of the measured characteristic gamma ray, I =gamma-ray intensity, η = abundance of the target nuclide, M = mass of sample, $D = e^{-\lambda t_1} - e^{-\lambda t_2}$ = counting collection factor, t_1, t_2 = time intervals from the end of the irradiation to the start and end of counting, respectively, A = atomic weight, C = measured full-energy peak area, λ = decay constant, F = total correction factor of the activity: $F = f_s \times f_c \times f_g$, 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 = neutron fluence fluctuation factor:

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

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

Using a similar approach of Ref. [16], the following formula used to calculate the cross-section sum of ${}^aX(n, p){}^aY$ and ${}^{a+1}X(n, d){}^aY$ reactions can be deduced

$$\sigma_x = \sigma_{1x} + \sigma_{2x} = \frac{[M\eta I_\gamma \varepsilon^p KSD]_0 [F\lambda A]_x}{[MI_\gamma \varepsilon^p KSD]_x [FC\lambda A]_0} \sigma_0 \left(\frac{C_{1x}}{\eta_{1x}} + \frac{C_{2x}}{\eta_{2x}} \right), \quad (2)$$

where η_{1x} and η_{2x} are the abundances of aX and ${}^{a+1}X$ respectively, C_{1x} and C_{2x} are the full-energy peak (FEP) counts of the characteristic γ ray of aY from ${}^aX(n, p){}^aY$ and ${}^{a+1}X(n, d){}^aY$ reactions respectively.

The result is also applicable to the cross-section sum of ${}^aX(n, 2n)^{(a-1)m}X$ and ${}^{a-1}X(n, n')^{(a-1)m}X$ reactions.

3 Theoretical analysis and discussion of related problems

It can be seen from Eq. (2) that the FEP counts C_{1x} and C_{2x} of the characteristic γ ray of aY from ${}^aX(n, p){}^aY$ and ${}^{a+1}X(n, d){}^aY$ reactions must be measured separately in order to obtain the cross-section sum of

${}^aX(n, p){}^aY$ and ${}^{a+1}X(n, d){}^aY$ reactions, it is impossible in the case of using natural samples, because the aY from ${}^aX(n, p){}^aY$ and the ${}^{a+1}X(n, d){}^aY$ reactions can not be distinguished. However, Refs. [1–8] obtained the cross-section sum of ${}^aX(n, p){}^aY$ and ${}^{a+1}X(n, d){}^aY$ reactions or ${}^aX(n, 2n)^{(a-1)m}X$ and ${}^{a-1}X(n, n')^{(a-1)m}X$ reactions, it is possible that the so-called cross-section sum is obtained by using one of the following two methods in Refs. [1–8].

The first method: The cross section of the ${}^aX(n, p){}^aY$ reaction or the ${}^aX(n, 2n)^{(a-1)m}X$ reaction was calculated from Eq. (1) and it was regarded as the cross-section sum. While the cross section of the ${}^aX(n, p){}^aY$ reaction or the ${}^aX(n, 2n)^{(a-1)m}X$ reaction was calculated, the FEP count C_x of the characteristic γ ray from aY or ${}^{(a-1)m}X$ (it is $C_{1x} + C_{2x}$ in fact) was regarded as C_{1x} , so the so-called cross-section sum can be given as

$$\sigma'_x = \frac{[M\eta I_\gamma \varepsilon^p KSD]_0 [F\lambda A]_x}{[MI_\gamma \varepsilon^p KSD]_x [FC\lambda A]_0} \frac{C_{1x} + C_{2x}}{\eta_{1x}} \sigma_0. \quad (3)$$

Comparing Eqs. (3) and (2), it can be seen that the cross-section sum from Eq. (3) is in agreement with that from Eq. (2) only when the abundance η_{1x} of aX equals the abundance η_{2x} of ${}^{a+1}X$ (or the abundance η_{1x} of aX equals the abundance η_{2x} of ${}^{a-1}X$). In other words, Eq. (3) is not the formula used to calculate the activation cross-section sum of two reactions producing the same radioactive nuclide for two isotopes in normal cases. The cross-section sum from Eq. (3) is less than that from Eq. (2) when η_{1x} is more than η_{2x} and the cross-section sum from Eq. (3) is more than that from Eq. (2) when η_{1x} is less than η_{2x} .

The second method: The cross section of the ${}^aX(n, p){}^aY$ reaction was calculated from Eq. (1) and it was regarded as the cross-section sum. While the cross section of the ${}^aX(n, p){}^aY$ reaction was calculated, the FEP count C_x of the characteristic γ ray from aY (it is $C_{1x} + C_{2x}$ in fact) was regarded as C_{1x} , and the sum of the abundance η_{1x} of aX and the abundance η_{2x} of ${}^{a+1}X$ was regarded as the abundance η_{1x} of aX , so the so-called cross-section sum can be given as

$$\sigma''_x = \frac{[M\eta I_\gamma \varepsilon^p KSD]_0 [F\lambda A]_x}{[MI_\gamma \varepsilon^p KSD]_x [FC\lambda A]_0} \frac{C_{1x} + C_{2x}}{\eta_{1x} + \eta_{2x}} \sigma_0. \quad (4)$$

Comparing Eqs. (4) and (2), it can be seen that the cross-section sum from Eq. (4) is always less than that from Eq. (2).

Ref. [4] pointed out explicitly that the data value for ${}^*Ni(n, p){}^{61}Co = {}^{61}Ni(n, p){}^{61}Co + {}^{62}Ni(n, n+p){}^{61}Co$ was defined by authors taking the abundance of the first mentioned isotope. It can be seen that the cross-section sum of the ${}^{61}Ni(n, p){}^{61}Co$ reaction and the ${}^{62}Ni(n, n+p){}^{61}Co$ reaction in the Ref. [4] was calculated according to the first method mentioned above. The target nuclear abundance corresponding to the $Ba(n, x){}^{136}Cs$ reaction is

9.009% which exactly equals the sum of the abundance 2.417% of ^{134}Ba and the abundance 6.592% of ^{135}Ba in Table 1 of Ref. [7]. This shows that the cross-section sum was calculated according to the second method mentioned above. A description of how to obtain the cross-section sum was not given in Refs. [1–3, 5, 6, 8], but the cross-section sum calculated according to either method mentioned above is not the true cross-section sum which is calculated from Eq. (2).

When the target nuclei have many stable isotopes and natural samples are used, it is sometimes difficult to avoid the summation of $^a\text{X}(n, p)^a\text{Y}$ and $^{a+1}\text{X}(n, d^*)^a\text{Y}$ reactions, $^a\text{X}(n, 2n)^{(a-1)m}\text{X}$ and $^{a-1}\text{X}(n, n')^{(a-1)m}\text{X}$ reactions. The common methods used are as follows.

If the cross-section difference between the $^{a+1}\text{X}(n, d^*)^a\text{Y}$ reaction and the $^a\text{X}(n, p)^a\text{Y}$ reaction is very small or the effect of the $^{a+1}\text{X}(n, d^*)^a\text{Y}$ reaction on the $^a\text{X}(n, p)^a\text{Y}$ reaction can not be neglected, the cross sections of the $^a\text{X}(n, p)^a\text{Y}$ reaction can be obtained by subtracting the contribution of the $^{a+1}\text{X}(n, d^*)^a\text{Y}$ reaction with the credible experimental or evaluation values of the cross section of the $^{a+1}\text{X}(n, d^*)^a\text{Y}$, and vice versa. The same is true for the $^{a-1}\text{X}(n, n')^{(a-1)m}\text{X}$ reaction on the $^a\text{X}(n, 2n)^{(a-1)m}\text{X}$ reaction. For example, the cross sections of the $^{61}\text{Ni}(n, p)^{61}\text{Co}$ reaction were calculated by Formula (1) deducting the contribution of the $^{62}\text{Ni}(n, d^*)^{61}\text{Co}$ reaction with the evaluated values from ENDF JEFF-3.1 in Ref. [13]. For another example, the cross sections of the $^{46}\text{Ti}(n, p)^{46}\text{Sc}$ reaction, which were obtained by subtracting the effect of the $^{47}\text{Ti}(n, d^*)^{46}\text{Sc}$ reaction with the credible experimental values of the cross sections of the $^{a+1}\text{X}(n, d^*)^a\text{Y}$, were in agreement with the results of using enriched isotope samples in Ref. [14].

If the cross sections of the $^{a+1}\text{X}(n, d^*)^a\text{Y}$ reaction are much smaller than those of the $^a\text{X}(n, p)^a\text{Y}$ reaction, or the abundance of ^{a+1}X is also much smaller than that of ^aX , the cross sections of the $^a\text{X}(n, p)^a\text{Y}$ reaction can be obtained by ignoring the influence of the $^{a+1}\text{X}(n, d^*)^a\text{Y}$ reaction. It is same with the $^{a-1}\text{X}(n, n')^{(a-1)m}\text{X}$ reaction on the $^a\text{X}(n, 2n)^{(a-1)m}\text{X}$ reaction. For example, after calculation we know that the effect of the $^{98}\text{Mo}(n, d^*)^{97}\text{Nb}$ reaction on the $^{97}\text{Mo}(n, p)^{97}\text{Nb}$ reaction was lower than 0.1% in Ref. [12]. For another example, the relative errors of the cross sections for the $^{60}\text{Ni}(n, p)^{60m}\text{Co}$ reaction which neglected the effect of the $^{61}\text{Ni}(n, d^*)^{60m}\text{Co}$ reaction are lower 1.2% than those

which deducted the effect of the $^{61}\text{Ni}(n, d^*)^{60m}\text{Co}$ reaction with the credible experimental values. So the cross sections of the $^{60}\text{Ni}(n, p)^{60m}\text{Co}$ reaction were calculated by Formula (1) neglecting the effects of $^{61}\text{Ni}(n, d^*)^{60m}\text{Co}$ reactions in Ref. [13].

The cross sections of $^{137,136,134}\text{Ba}(n, p)$ reactions in Ref. [9] and the cross sections of $^a\text{X}(n, p)^a\text{Y}$ reaction in Refs. [10, 11] may be calculated by using the first method mentioned above. In fact, the effects of the $^{a+1}\text{X}(n, d^*)^a\text{Y}$ reaction were neglected while the cross sections of the $^a\text{X}(n, p)^a\text{Y}$ reaction were calculated by using Formula (1) in Refs. [9–11].

4 Comparison between the experimental and theoretical results

Two experiments (one by using natural samples, another by using the enriched isotope) should be done to compare the difference between the so-called cross-section sum obtained by using two methods mentioned above and the true cross-section sum calculated from Eq. (2), but we did only the experiment by using natural samples due to the limitation of the experimental conditions. For comparison, the so-called cross-section sum was obtained from Eqs. (3) and (4) respectively with related experimental data in our experiments, and the true cross-section sum was calculated from Eq. (2) with the experimental values reported in Refs. [17, 18] and the evaluation values of ENDF/B-VII.1 [21], respectively.

The experimental conditions, instruments, equipment, samples, experimental process and so on in our experiments can be seen from Refs. [5] and [19]. The natural abundances of the target isotopes are taken from Ref. [20] the so-called cross-section sum calculated from Eq. (3) is expressed by using σ_1 and the so-called cross-section sum calculated from Eq. (4) is expressed by using σ_2 , the cross-section sum σ is calculated from Eq. (2) with the experimental values reported in Refs. [17, 18] and the cross-section sum σ^* is calculated from Eq. (2) with the evaluation values of ENDF/B-VII.1 [21]. They are all listed in Table 1.

It can be seen from Table 1 that the abundance of ^{46}Ti is more than that of ^{47}Ti , so σ_1 is less than σ , but the difference of σ_1 and σ is very small because the abundances of ^{46}Ti and ^{47}Ti are close. The abundance of ^{198}Hg is less than that of ^{199}Hg , so σ_1 is more than σ .

Table 1. Comparison between theoretical and experimental results.

reaction	abundance of target isotope (%)	neutron energy/MeV	σ_1/mb	σ_2/mb	σ/mb	σ^*/mb
$^{46}\text{Ti}(n,p)^{46}\text{Sc}+$	8.0	14.81	305 ± 12	159 ± 7	329.5 ± 5.0 [17]	263.62 [21]
$^{47}\text{Ti}(n,d)^{46}\text{Sc}$	7.3					
$^{198}\text{Hg}(n,p)$	9.97	14.5	5.7 ± 0.3	2.1 ± 0.2	4.9 ± 0.5 [18]	5.81 [21]
$^{198}\text{Au}+$	16.87					
$^{199}\text{Hg}(n,d)^{198}\text{Au}$						

But σ_2 is always less than σ in the two situations. These are in agreement with the theoretical analysis results in Part 3. It shows the theoretical analysis results are very reasonable.

In summary, in this article it is pointed out that the calculation methods of the cross-section sum of two reactions producing the same radioactive nuclide for two isotopes in some references are improper and normally it is impossible to obtain the cross-section sum of two reactions producing the same radioactive nuclide for two isotopes in the case of using natural samples. The activation cross-section sum of two reactions producing the same radioactive nuclide for two isotopes in normal circumstances can be obtained from Eq. (3) when the abundance of ${}^a\text{X}$ equals the abundance of ${}^{a+1}\text{X}$ or the abundance of ${}^a\text{X}$ equals the abundance of ${}^{a-1}\text{X}$. If the cross-

section difference between the ${}^{a+1}\text{X}(\text{n}, \text{d}^*){}^a\text{Y}$ reaction and the ${}^a\text{X}(\text{n}, \text{p}){}^a\text{Y}$ reaction is small or the effect of the ${}^{a+1}\text{X}(\text{n}, \text{d}^*){}^a\text{Y}$ reaction on the ${}^a\text{X}(\text{n}, \text{p}){}^a\text{Y}$ reaction can not be neglected, the cross sections of the ${}^a\text{X}(\text{n}, \text{p}){}^a\text{Y}$ reaction can be obtained by subtracting the effect of the ${}^{a+1}\text{X}(\text{n}, \text{d}^*){}^a\text{Y}$ reaction with the credible experimental or evaluation values of the cross section of the ${}^{a+1}\text{X}(\text{n}, \text{d}^*){}^a\text{Y}$, and vice versa. It is the same with the ${}^{a-1}\text{X}(\text{n}, \text{n}')^{(a-1)\text{m}}\text{X}$ reaction on the ${}^a\text{X}(\text{n}, 2\text{n})^{(a-1)\text{m}}\text{X}$ reaction. If the cross sections of the ${}^{a+1}\text{X}(\text{n}, \text{d}^*){}^a\text{Y}$ reaction are much smaller than those of the ${}^a\text{X}(\text{n}, \text{p}){}^a\text{Y}$ reaction, or the abundance of ${}^{a+1}\text{X}$ is much smaller than that of ${}^a\text{X}$, the cross sections of the ${}^a\text{X}(\text{n}, \text{p}){}^a\text{Y}$ reaction can be obtained by ignoring the influence of the ${}^{a+1}\text{X}(\text{n}, \text{d}^*){}^a\text{Y}$ reaction. The same is true with the ${}^{a-1}\text{X}(\text{n}, \text{n}')^{(a-1)\text{m}}\text{X}$ reaction on the ${}^a\text{X}(\text{n}, 2\text{n})^{(a-1)\text{m}}\text{X}$ reaction.

References

- 1 LU W D, Ranakumar N, Fink R W. *Phys. Rev. C*, 1970, **1**: 350
- 2 Hankla A K, Fink R W. *Nucl. Phys.*, 1972, **180**: 157
- 3 LUO Jun-Hua, HE Guo-Zhu, LIU Zhong-Jie, KONG Xiang-Zhong. *Radiochim. Acta*, 2005, **93**: 381
- 4 Bahal B M, Pepelnik R. Report: GKSS-85-E, 1985, 11
- 5 YUAN Jun-Qian, WANG Yong-Chang, KONG Xiang-Zhong, YANG Jing-Kang. *HEP & NP*, 1992, **16**: 57 (in Chinese)
- 6 ZHENG Wei-Qiang, YUAN Jun-Qian. *J. Lanzhou University*, 1997, **33**: 37 (in Chinese)
- 7 KONG Xiang-Zhong, WANG Yong-Chang, YANG Jing-Kang, YUAN Jun-Qian. *HEP & NP*, 1995, **19**: 781 (in Chinese)
- 8 LU Han-Lin, ZHAO Wen-Rong, YU Wei-Xian, *Chin. Nucl. Phys.*, 1992, **14**: 244
- 9 YUAN Jun-Qian, QIU Jiu-Zi, YANG Jing-Kang, KONG Xiang-Zhong, WANG Yong-Chang. *Trends in Nucl. Phys.*, 1994, **11**: 65 (in Chinese)
- 10 LAN Chang-Lin, XU Xiao-San, FANG Kai-Hong, LIU Gang, KONG Xiang-Zhong, LIU Rong. *An. Nucl. Energy*, 2008, **35**: 2105
- 11 PU Zhong-Sheng, GUAN Qiu-Yun, MA Jun, YAN Dong. *HEP & NP*, 2006, **30**: 1171 (in Chinese)
- 12 KONG Xiang-Zhong, WANG Yong-Chang, YANG Jing-Kang, YUAN Jun-Qian, WANG Xue-Zhi. *J. Lanzhou University*, 1992, **28**: 170 (in Chinese)
- 13 ZHOU Feng-Qun, XIAO Xia-Jie, FANG Kai-Hong, LAN Chang-Lin, KONG Xiang-Zhong. *Nucl. Instrum. Methods Phys. Res., Sect. B*, 2011, **269**: 642
- 14 LU Han-Lin, WANG Da-Hai, CUI Yun-Feng et al. *Nuclear Energy Science and Technology*, 1975, **12**: 113
- 15 KONG Xiang-Zhong, WANG Rong, WANG Yong-Chang, YANG Jing-Kang. *Appl. Radiat. Isot.*, 1999, **50**: 361
- 16 ZHOU Feng-Qun, SONG Yue-Li, KONG Xiang-Zhong, TUO Fei. *CPC (HEP & NP)*, 2011, **35**: 31
- 17 Ribansky I, Gmuca S. *J. Phys.*, 1983, **9**: 1537
- 18 Hankla A K, Fink R W, Hamilton J H. *Nucl. Phys. A*, 1972, **180**: 157
- 19 YUAN Jun-Qian, KONG Xiang-Zhong, YANG Jing-Kang. *China Nuclear Science and Technology Report*, 1995, **S3**: 16. <http://www.cnki.com.cn/Journal/C-C3-ZHBG.htm>
- 20 Firestone R B, Shirley V S. *Table of Isotopes*. New York: Wiley, 1996
- 21 ENDF/B-VII.1, US Evaluated Nuclear Data Library, 2011/12, <http://www-nds.iaea.org/>