A formula used to subtract the effect of gamma-ray of the others to that of measured reaction in measurement of cross section of nuclear reaction and its application*

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Abstract According to the regulation of growing and decay of artificial radioactive nuclide, a formula used to subtract the effect of characteristic γ-ray of the others to that of measured reaction was deduced. And then the cross sections of ^{120}Te (n, 2n)^{119m}Te reaction induced by neutrons around 14 MeV were measured by activation relative to the ^{93}Nb (n, 2n)^{92m}Nb. In the process of the cross sections measured to be calculated, it was subtracted that the effect of characteristic γ-ray of ^{126}Te (n, p)^{126}Sb to that of measured ^{120}Te (n, 2n)^{119m}Te reaction using the formula deduced. The experimental results were (689±37) and (750±41) mb at the neutron energies of (13.5±0.3) and (14.6±0.3) MeV, respectively. Measurements were carried out by γ-detection using a coaxial HPGe detector. As samples, spectroscopically pure tellurium powder has been used. The fast neutrons were produced by the T(d, n)^{4}He reaction. The neutron energies in these measurements were determined by the method of cross-section ratios between ^{90}Zr (n, 2n) $^{89m+g}$Zr and ^{93}Nb (n, 2n) ^{92m}Nb reactions.

Key words formula, tellurium, activation cross sections, neutron-induced reactions, HPGe detector

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1 Introduction

Reaction cross sections are the basic gist of testing the nuclear theory, they are also the basic data which can be utilized in the nuclear technology and nuclear power, and therefore, their accurate measurements are very important. But in the practical work of cross-section measurement, a lot of problems are often encountered, such as the problems of the effects of low energy neutron, γ-γ cascade coincidence, γ-ray self-absorption in the sample, the interactions of all kinds of reactions and γ-rays with close energies, the interferences of excited state on ground state and so on. These problems mentioned above need to be resolved reasonably，if accurate measurement results are gained. As to the problems of the interactions of all kinds of reactions and γ-rays with close energies, they can be resolved by using the solutions of isotope separation or different cooling time of different half-life of product radionuclides. But in some cases, especially in the instances of more target-nuclear isotopes and natural sample used, such as for some reaction not only the half-life of product radionuclide is close with that of the measured reaction but also its energy of characteristic γ-rays is close with that of the measured reaction, its cross section can't be measured usually using characteristic γ-ray of product radionuclide because of the limit of energy resolution of the detector and useless methods of using cooling and so on.

Activation cross section measurements for the reactions of 14 MeV neutrons on tellurium isotopes are difficult because tellurium isotopes are many and γ-ray spectrum is complex after natural sample is

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activated. For the ^{120}Te (n, 2n)^{119m}Te reaction, the measurable characteristic γ-rays of product radionuclide are all affected, the energy of the selected characteristic γ-ray in this work is 1212.73 keV which is also affected by that of 1213.00 keV of product radionuclide of the ^{126}Te (n, p)^{126}Sb + ^{128}Te (n, t)^{126}Sb.

In this paper, first of all, according to the regulation of growing and decay of artificial radioactive nuclide[1—3], a formula used to subtract the effect of characteristic γ-ray of the others to that of the measured reaction was deduced. And then the cross sections of ^{120}Te (n, 2n)^{119m}Te reaction induced by neutrons around 14 MeV were measured by activation relative to the ^{93}Nb (n, 2n)^{92m}Nb. During the cross sections measured were calculated, it was subtracted that the effect of characteristic γ-ray of ^{126}Te (n, p)^{126}Sb to that of measured ^{120}Te (n, 2n)^{119m}Te reaction using the formula deduced above (the effect of ^{128}Te (n, t)^{126}Sb reaction is neglected because its cross section is small in μb order).

2 Deducing procedure of the formula

Two reactions of X_1(n, b_1) Y_1 and X_2(n, b_2) Y_2 with different product radionuclide were induced by neutrons around 14 MeV after the samples were irradiated. In the process of the cross sections of X_2(n, b_2) Y_2 reaction to be measured, the energy of the selected characteristic γ-ray (γ_2) is E_2. The product radionuclide of X_1(n, b_1) Y_1 has a γ_2 whose energy is E_2 or close to E_2, and has a γ_1 whose energy is E_1 and its measurement is not affected. The time of irradiating the sample is T_1, when the γ_1 emitted from Y_1 is detected, the cooling time of the sample is T_{21}, the measuring time is T_{31}, when the γ_2 emitted from Y_2 is detected, the cooling time of the sample is T_{22}, the measuring time is T_{32} (Fig. 1). According

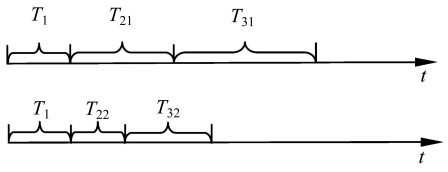

Fig. 1. The sketch map of the time which the sample is irradiated, cooled and detected.

to the rules of artificial radioactive growth and decay[1—3], we can deduce the full-energy peak (FEP) counts of the γ_1 of Y_1 during the measuring time T_{31} (referring to the literature[4] and taking into account the correction factor F_{g1} of the cascade coincidence effect of the characteristic γ-ray) as follows

$$C_1 = \frac{MN_A\eta\phi I_{\gamma1}\varepsilon_1^p K_1 S_1 D_1 \sigma}{F_{c1}F_{s1}F_{g1}\lambda_1 A} , \qquad (1)$$

where M is mass of the sample, N_A is Avogadro constant, η is the abundance of X_1, A is atomic weight of the parent nucleus, ϕ is the mean neutron flux, σ is the cross-section value of X_1(n, b_1) Y_1 reaction. $I_{\gamma1}$, ε_1^p, λ_1, F_{c1}, F_{s1} and F_{g1} are the intensity, FEP efficiency, decay constant, correction factor of the coincidence sum effect of cascade gamma rays, correction factor of the self-absorption in the sample and correction factor of the counting geometry of the γ_1 of Y_1, respectively.

$$D_1 = e^{-\lambda_1 T_{21}} - e^{-\lambda_1 (T_{21}+T_{31})},$$

$$S_1 = 1 - e^{-\lambda_1 T_1},$$

$$K_1 = \frac{\sum_{i=1}^{n} \phi_i (1 - e^{-\lambda_1 T_i}) e^{-\lambda_1 t_i}}{S_1 \phi},$$

where n is number of time intervals into which the irradiation time is divided, T_i is duration of the i-th time intervals, t_i is time interval from the end of the i-th interval to the end of irradiation, ϕ_i is neutron flux averaged over the sample in T_i.

Using similar deducing method, the counts subtracted from the FEP counts of the characteristic γ-ray of Y_2 because of the effect of γ_2 of Y_1 during the measuring time T_{32} can easily be given as

$$C_2 = \frac{MN_A\eta\phi I_{\gamma2}\varepsilon_2^p K_2 S_2 D_2 \sigma}{F_{c2}F_{s2}F_{g2}\lambda_2 A} , \qquad (2)$$

where the meanings of M, N_A, η, A, ϕ and σ are the same as above. $I_{\gamma2}$, ε_2^p, λ_2, F_{c2}, F_{s2} and F_{g2} are the intensity, FEP efficiency, decay constant, correction factor of the coincidence sum effect of cascade gamma rays, correction factor of the self-absorption in the sample and correction factor of the counting geometry of the γ_2 of Y_1, respectively.

$$D_2 = e^{-\lambda_2 T_{22}} - e^{-\lambda_2 (T_{22}+T_{32})},$$

$$S_2 = 1 - e^{-\lambda_2 T_1},$$

$$K_2 = \frac{\sum_{i=1}^{n} \phi_i (1 - e^{-\lambda_2 T_i}) e^{-\lambda_2 t_i}}{S_2 \phi}.$$

Comparing formula (1) with formula (2), we can get

$$C_2 = \frac{I_{\gamma2}\varepsilon_2^p K_2 S_2 D_2}{I_{\gamma1}\varepsilon_1^p K_1 S_1 D_1} \cdot \frac{F_{s1}F_{g1}F_{c1}\lambda_1}{F_{s2}F_{g2}F_{c2}\lambda_2} C_1 , \qquad (3)$$

Formula (3) is the formula used to subtract the effect of characteristic γ-ray of the others to that of the measured reaction.

3 Experiment

Irradiation of the samples was carried out at the ZF-300-Ⅱ Intense Neutron Generator at Lanzhou

University. The neutrons with a yield of about 3×10^{10}— 4×10^{10} n/s were produced by the T(d, n)^{4}He reaction with an effective deuteron beam energy of 135 keV and a beam current of 500 μA. The thickness of the tritium-titanium (T-Ti) target used in the generator was 1.35 mg/cm^2. The small variation of the neutron yield was monitored by the U-fission chamber so that the correction could be made for the fluctuation of the neutron flux during the irradiation. The cross sections for the ^{93}Nb (n, 2n) ^{92m}Nb reaction were selected as the monitor to measure the cross sections of the ^{120}Te (n, 2n)^{119m}Te reaction. The tellurium powder of 99.999% purity was compressed into a disk 20 mm in diameter and 2.16—3.62 mm in thickness which was then sandwiched between two 0.28—0.36 mm thick niobium foils (99.99% purity) of the same diameter.

The groups of samples were irradiated at fixed positions about 2—5 cm away from the center of the T-Ti target and at angles of 0° and 135° relative to the incident deuteron beam direction. The neutron energy in these positions was determined by the method of cross section ratios for ^{90}Zr (n, 2n) $^{89m+g}$Zr and ^{93}Nb (n, 2n) ^{92m}Nb reactions[5].

The γ-ray activities of ^{92m}Nb, ^{119m}Te and ^{126}Sb were determined by a CH8403 coaxial HPGe detector (sensitive volume 110 cm^3) (made in the People's Republic of China) with a relative efficiency of 20% and an energy resolution of 3 keV at 1.33 MeV. The efficiency of the detector was calibrated using a standard γ-ray source (standard reference material 4275 was obtained from the National Institute of Standards and Technology, Washington, DC, USA). An absolute efficiency calibration curve was obtained at 20 cm from the surface of the germanium crystal. At this distance the coincidence summing effects can be considered to be negligible. In our situation, however, we needed to calibrate the efficiency at 2 cm, the actual counting position used because of the weak activity of the sample. Therefore, we selected a set of mono-energetic sources and placed them at two positions (20 and 2 cm) successively to measure their efficiency ratios so that we were able to evaluate the efficiency ratio curve as a function of energy. The absolute efficiency calibration curve at 2 cm was obtained from the calibrated curve at 20 cm and the efficiency ratio curve. The error in the absolute efficiency curve at 2 cm was estimated to be ∼1.5%, while the error of the activity of the standard source was ∼1%.

Table 1. Reactions and associated decay data of activation products.

reaction	abundance of target isotope(%)	$T_{1/2}$/ d	E_γ/ keV	I_γ (%)
^{120}Te (n, 2n)^{119m}Te	0.096	4.70	1212.73	66.2
^{126}Te (n, p)^{126}Sb	18.95	12.46	666.3	99.6
			1213.0	2.39
^{93}Nb (n, 2n) ^{92m}Nb	100	10.15	934.44	99.07

The decay characteristics of the product radionuclides and the natural abundance of the target isotopes in the present investigation are summarized in Table 1[6].

4 Results and discussion

The measured cross sections were calculated by the following formula[7]:

$$\sigma_x = \frac{[S\varepsilon^{\mathrm{p}} I_\gamma \eta K M D]_0}{[S\varepsilon^{\mathrm{p}} I_\gamma \eta K M D]_x} \frac{[\lambda A F C]_x}{[\lambda A F C]_0} \sigma_0 \ , \qquad (4)$$

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

$$K = \left[\sum_i^n \phi_i (1 - \mathrm{e}^{-\lambda T_i}) \mathrm{e}^{-\lambda t_i}\right] \Big/ \phi S \ ,$$

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

The cross sections measured of the ^{120}Te(n, 2n)^{119m}Te and the values given in the literatures are summarized in Table 2 and plotted in Fig. 2, and the cross sections of the ^{93}Nb (n, 2n)^{92m}Nb reaction (obtained by interpolating the values in the report of Wagner et al. (1990)[8]) are also listed in Table 2.

Corrections were made for γ-ray self-absorption in the sample, for γ-γ coincidence summing effects, for fluctuation of the neutron flux during the irradiation and for sample geometry. Especially, during the cross sections measured of the ^{120}Te (n, 2n)^{119m}Te were calculated, it was subtracted that the effect of characteristic γ-ray, whose energy is 1213.0 keV and

Table 2. Cross sections for ^{120}Te (n,2n)^{119m}Te reaction.

reaction	present work		literature values		reference
	E_n/MeV	σ/mb	E_n/MeV	σ/mb	
^{120}Te (n, 2n)^{119m}Te	13.5±0.3	689±37	14.6	673±74	[9]
	14.6±0.3	750±41	14.8±0.2	535±85	[10]
			13.48	403±80	[11]
			13.67	459±46	[11]
			14.46	560±50	[11]
			14.67	586±54	[11]
^{93}Nb (n, 2n)^{92m}Nb			13.5±0.3	456.6±13.7	[8]
			14.6±0.3	459.7±13.8	[8]

the half life of the product radionuclide is 12.46 day, of ^{126}Te (n, p)^{126}Sb to that, whose energy is 1212.73 keV and the half life of the product radionuclide is 4.70 day, of the measured ^{120}Te (n, 2n)^{119m}Te reaction. The major errors in our work result from the errors of counting statistics, detector efficiency, monitor reaction cross sections, weight of samples, self-absorption of γ-ray, coincidence summing effect of cascade γ-rays, sample geometry and the effect of the scattering neutrons.

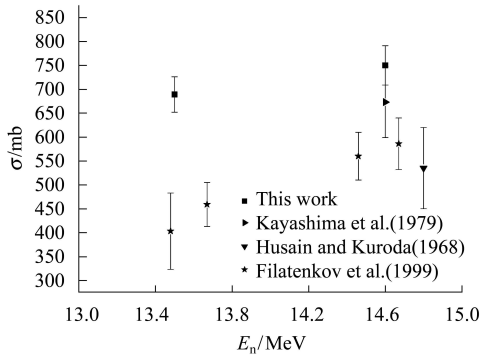

Fig. 2. Cross section of ^{120}Te (n, 2n)^{119m}Te reaction.

It can be seen from Table 2 and Fig. 2 that only three laboratories obtained their results, and our results are in agreement, within experimental error, with those of Kayashima et al. (1979)[9], but higher than those of Husain et al. (1968)[10] and Filatenkov et al. (1999)[11]. The results of Kayashima et al. (1979)[9] were gained by measuring γ-ray with Ge(Li) detector, and those of Husain et al. (1968)[10] and Filatenkov et al. (1999)[11] were gained by measuring γ-ray with NaI(Cr) detector and scanning scintillation detection online with PC, respectively.

In summary, in the present work the HPGe detector was used to increase the energy resolution, the effect of γ-ray of the others to that of the measured reaction ^{120}Te (n, 2n)^{119m}Te was subtracted. Furthermore, the most recent and accurate nuclear data of Firestone and Shirley (1996)[6] and Wagner et al. (1990)[8] were adopted. All these mentioned above should make the results more accurate and reliable.

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