Cross section measurements via residual nuclear decays: Analysis methods

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We develop an approach to calculating the pure cross section of the ground state of artificial radioactive nuclides that subtracts the effect of an excited state on the ground state. We apply a formalism to obtaining pure cross sections by subtracting the effect of excited states in the reactions ^{122}Te$(n,2n)^{121}$Te^g and ^{128}Te$(n,2n)^{127}$Te^g, induced by neutrons of about 14 MeV. The cross sections are measured by an activation relative to the ^{93}Nb$(n,2n)^{92}$Nb^m reaction and are compared with results that take into account the effect of the excited state. Measurements are carried out by γ detection using a coaxial high-purity germanium (HPGe) detector. As samples, spectroscopically pure Te powder is used. The fast neutrons are produced by the ^{3}H$(d,n)^4$He reaction. The neutron energies in these measurements are determined using the method of cross-section ratios between the ^{90}Zr$(n,2n)^{89}$Zr^{m+g} and ^{93}Nb$(n,2n)^{92}$Nb^m reactions.

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I. INTRODUCTION

Cross sections are fundamental observables for testing nuclear theory. They are also among the basic quantities that are utilized in nuclear technology, such as nuclear power generation. Therefore, their accurate measurement is very important. However, in practice, cross-section measurements often encounter many problems, such as taking an accurate account of contributions from various kinds of reactions or processes, for example, γ rays with close energies, interference from excited states on the ground state, cascade coincidences, self-absorption, and so on. All of these problems need to be resolved. As to the problem of interference of the excited state on the ground state [as in Fig. 1, if some radioactive daughter nuclei with the ground state Z^g and the excited state Z^m are produced by some reaction, the excited state may produce electron capture (EC) decay and isomeric transition (IT), which will have an influence on the $X(n,b)Z^g$ reaction cross-section measurements by the ground-state decay]. The common methods used are as follows. When the half-life $T_{m1/2}$ of excited state Z^m is much longer than the half-life $T_{g1/2}$ of ground state Z^g and the branch ratio $X_{\rm it}$ of IT is very small or the cross section of the $X(n,b)Z^m$ reaction is much less than that of the $X(n,b)Z^g$ reaction, the influence of the excited state on the ground state can be ignored; when the half-life $T_{m1/2}$ of Z^m is much shorter than that of Z^g, the samples are measured after having cooled for an adequate period of time, then the total cross sections of $X(n,b)Z^{g+m}$ are calculated. Thus, it can be seen that the two treatments toward the two particular instances mentioned above are approximations.

In this article, first of all, according to the regulation of the growth and decay of artificial radioactive nuclide [1,2], the two formulas used to subtract the effect of the excited state on the ground state in cross-section measurements are deduced. Then, the pure cross sections of the ^{122}Te$(n,2n)^{121}$Te^g and ^{128}Te$(n,2n)^{127}$Te^g reactions induced by neutrons around 14 MeV are measured by the activation relative to the ^{93}Nb$(n,2n)^{92}$Nb^m reaction and are compared with the results that take into account the effect of the excited state. Measurements are carried out by γ detection using a coaxial high-purity germanium (HPGe) detector. As samples, spectroscopically pure Te powder is used. The fast neutrons are produced by the ^{3}H$(d,n)^4$He reaction. The neutron energies in these measurements are determined by the method of cross-section ratios between the ^{90}Zr$(n,2n)^{89}$Zr^{m+g} and ^{93}Nb$(n,2n)^{92}$Nb^m reactions [3].

II. DEDUCING PROCEDURE OF THE FORMULAS

The mass of the sample is M, the atomic weight of the parent nucleus is A, the isotope abundance is θ, the time of irradiating the sample is T_1, the mean neutron flux in neutrons/cm^2/sec is ϕ, and the cross-section value of the $X(n,b)Z^m$ reaction is σ_m. When the characteristic γ ray emitted from the ground state Z^g is detected, the cooling time of the sample is T_{2g}, the measuring time is T_{3g}; when the characteristic γ ray emitted from the excited state Z^m is detected, the cooling time of the sample is T_{2m} and the measuring time is T_{3m} (Fig. 2).

According to the regulation of the growth and decay of the artificial radioactive nuclide we can deduce a formula to calculate the number of the daughter nucleus Z^m at any moment t during the irradiation as follows:

$$N_m(t) = \frac{MN_A\theta\phi\sigma_m}{A\lambda_m}(1 - e^{-\lambda_m t}), \tag{1}$$

where N_A is Avogadro's constant and λ_m is the decay constant of Z^m.

At any moment t during the irradiation, the number of Z^g from the $sZ^m \rightarrow Z^g$ procedure meets the following equation:

$$\frac{dN_g(t)}{dt} = \lambda_m N_m(t) X_{it} - \lambda_g N_g(t). \tag{2}$$

Here, λ_g is the decay constant of Z^g.

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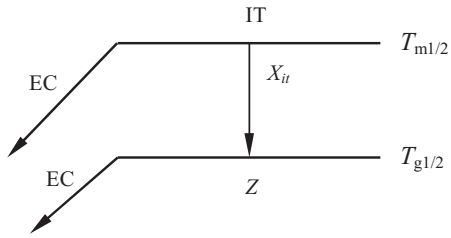

FIG. 1. Sketch map of the decay scheme used to explain the effect of excited state on ground state.

Using Eqs. (1) and (2) and the initial condition: $t = 0$, $N_g = 0$, and working out $N_g(t)$,

$$N_g(t) = \frac{MN_A\theta\phi\sigma_m X_{it}}{A}\left(\frac{1}{\lambda_g} - \frac{1}{\lambda_g - \lambda_m}e^{-\lambda_m t}\right) + \frac{MN_A\theta\phi\sigma_m X_{it}}{A}\left(\frac{1}{\lambda_g - \lambda_m} - \frac{1}{\lambda_g}\right)e^{-\lambda_g t}. \quad (3)$$

At the moment of the end of the irradiation ($t = T_1$), the numbers of Z^m and Z^g from $Z^m \to Z^g$ are $N_m(T_1)$ and $N_g(T_1)$, respectively. They can be obtained by using Eqs. (1) and (3).

At any moment t' after the irradiation, the number of Z^m is

$$N_m(t') = N_m(T_1)e^{-\lambda_m t'} = \frac{MN_A\theta\phi\sigma_m}{A\lambda_m}(1 - e^{-\lambda_m T_1})e^{-\lambda_m t'}. \quad (4)$$

At any moment after the irradiation t', the number of Z^g from $Z^m \to Z^g$ meets the following equation:

$$\frac{dN_g(t')}{dt} = \lambda_m N_m(t')X_{it} - \lambda_g N_g(t'). \quad (5)$$

Using Eqs. (4) and (5) and the initial condition $t' = 0$, $N_g = N_g\,(T_1)$, and working out $N_g(t')$,

$$N_g(t') = \frac{MN_A\theta\phi\sigma_m X_{\rm it}}{A(\lambda_g - \lambda_m)}(1 - e^{-\lambda_m T_1})e^{-\lambda_m t'} - \frac{MN_A\theta\phi\sigma_m X_{\rm it}}{A}\frac{\lambda_m}{\lambda_g(\lambda_g - \lambda_m)}(1 - e^{-\lambda_g T_1})e^{-\lambda_g t'}. \quad (6)$$

Let t' in Eq. (6) equal $t'' + T_{2g}$. We can obtain the number of Z^g from the $Z^m \to Z^g$ procedure at any moment t'' after

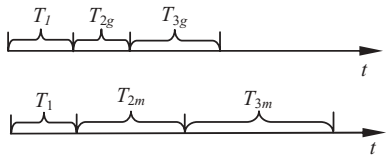

FIG. 2. Sketch map of the time which the sample is irradiated, cooled, and detected.

beginning to detect the characteristic γ ray of Z^g:

$$N_g(t'') = \frac{MN_A\theta\phi\sigma_m X_{\rm it}}{A(\lambda_g - \lambda_m)}(1 - e^{-\lambda_m T_1})e^{-\lambda_m T_{2g}}e^{-\lambda_m t''} - \frac{MN_A\theta\phi\sigma_m X_{\rm it}}{A}\frac{\lambda_m}{\lambda_g(\lambda_g - \lambda_m)} \times (1 - e^{-\lambda_g T_1})e^{-\lambda_g T_{2g}}e^{-\lambda_g t''}. \quad (7)$$

During the period T_{3g} of detecting the characteristic γ ray of Z^g, the full-energy peak (FEP) counts C_g of the characteristic γ ray of Z^g from the $Z^m \to Z^g$ procedure are

$$C_g = \int_0^{T_{3g}} \frac{\lambda_g N_g(t'')}{F_{gs}F_{gg}} I_{\gamma g}\varepsilon_g^p dt'' = \frac{MN_A\theta\phi\sigma_m X_{\rm it} I_{\gamma g}\varepsilon_g^p}{AF_{gs}F_{gg}} \times \frac{\lambda_g}{\lambda_m(\lambda_g - \lambda_m)}(1 - e^{-\lambda_m T_1})e^{-\lambda_m T_{2g}}(1 - e^{-\lambda_m T_{3g}}) - \frac{MN_A\theta\phi\sigma_m X_{\rm it} I_{\gamma g}\varepsilon_g^p}{AF_{gs}F_{gg}}\frac{\lambda_m}{\lambda_g(\lambda_g - \lambda_m)} \times (1 - e^{-\lambda_g T_1})e^{-\lambda_g T_{2g}}(1 - e^{-\lambda_g T_{3g}}), \quad (8)$$

where $I_{\gamma g}$ is the intensity of the characteristic γ ray of Z^g, ε_g^p is its FEP efficiency in the detector, F_{gs} is its self-absorption correction factor in the sample, and F_{gg} is the geometry correction factor of the sample.

It should be pointed out that the cascade coincidence effect of the characteristic γ ray of Z^g has not been corrected in the process of deducing Eq. (8) to avoid the repeated correction. In addition, the neutron flux ϕ is regarded as a constant. However, in the course of actual irradiation, neutron flux varies significantly for various reasons, therefore, the neutron flux ϕ in Eq. (8) should be amended. Hence, the total irradiation time T_1 is divided into n parts; T_i means the time of the ith part and t_i means the time from the end of the ith part to the end of the total irradiation. The mean neutron flux of the ith part is regarded as a constant. At any moment t'' after beginning to detect the characteristic γ ray of Z^g, the number $N_{gi}(t'')$ of Z^g from the $Z^m \to Z^g$ procedure by the irradiation of the ith part can be obtained using a similar method to that of deducing Eq. (7):

$$N_{gi}(t'') = \frac{MN_A\theta\sigma_m X_{\rm it}}{A(\lambda_g - \lambda_m)}\phi_i(1 - e^{-\lambda_m T_i})e^{-\lambda_m t_i}e^{-\lambda_m T_{2g}}e^{-\lambda_m t''} - \frac{MN_A\theta\sigma_m X_{\rm it}}{A}\frac{\lambda_m}{\lambda_g(\lambda_g - \lambda_m)}\phi_i \times (1 - e^{-\lambda_g T_i})e^{-\lambda_g t_i}e^{-\lambda_g T_{2g}}e^{-\lambda_g t''}.$$

So, at the same moment t'', the number $N_g(t'')$ of Z^g from the $Z^m \to Z^g$ procedure by the total irradiation is

$$N_g(t'') = \frac{MN_A\theta\sigma_m X_{\rm it}}{A(\lambda_g - \lambda_m)}e^{-\lambda_m T_{2g}}e^{\lambda_m t''}\sum_{i=1}^{n}\phi_i(1 - e^{-\lambda_m T_i})e^{-\lambda_m t_i} - \frac{MN_A\theta\sigma_m X_{\rm it}}{A}\frac{\lambda_m}{\lambda_g(\lambda_g - \lambda_m)}e^{-\lambda_g T_{2g}}e^{-\lambda_g t''} \times \sum_{i=1}^{n}\phi_i(1 - e^{-\lambda_g T_i})e^{-\lambda_g t_i}.$$

During the period T_{3g} of detecting the characteristic γ ray of Z^g, the FEP counts of the characteristic γ ray of Z^g from the $Z^m \rightarrow Z^g$ procedure are

$$C_g{}' = \int_0^{T_{3g}} \frac{\lambda_g N_g(t'')}{F_{gs}F_{gg}} I_{\gamma g}\varepsilon_g{}^p dt''$$
$$= \frac{MN_A\theta\sigma_m X_{\rm it} I_{\gamma g}\varepsilon_g^p}{AF_{gs}F_{gg}} \frac{\lambda_g}{\lambda_m(\lambda_g-\lambda_m)} e^{-\lambda_m T_{2g}}$$
$$\times (1-e^{-\lambda_m T_{3g}}) \sum_{i=1}^{n} \phi_i (1-e^{-\lambda_m T_i}) e^{-\lambda_m t_i}$$
$$- \frac{MN_A\theta\sigma_m X_{\rm it} I_{\gamma g}\varepsilon_g^p}{AF_{gs}F_{gg}} \frac{\lambda_m}{\lambda_g(\lambda_g-\lambda_m)} e^{-\lambda_g T_{2g}} (1-e^{-\lambda_g T_{3g}})$$
$$\times \sum_{i=1}^{n} \phi_i (1-e^{-\lambda_g T_i}) e^{-\lambda_g t_i}. \quad (9)$$

Comparing Eqs. (8) and (9), we get

$$C_g' = \frac{\lambda_g^2 e^{-\lambda_m T_{2g}}(1-e^{-\lambda_m T_{3g}})\sum_{i=1}^{n}\phi_i(1-e^{-\lambda_m T_i})e^{-\lambda_m t_i} - \lambda_m^2 e^{-\lambda_g T_{2g}}(1-e^{-\lambda_g T_{3g}})\sum_{i=1}^{n}\phi_i(1-e^{-\lambda_g T_i})e^{-\lambda_g t_i}}{\phi\lambda_g^2(1-e^{-\lambda_m T_1})e^{-\lambda_m T_{2g}}(1-e^{-\lambda_m T_{3g}}) - \phi\lambda_m^2(1-e^{-\lambda_g T_1})e^{-\lambda_g T_{2g}}(1-e^{-\lambda_g T_{3g}})} C_g$$
$$= \frac{MN_A\theta\phi\sigma_m X_{\rm it} I_{\gamma g}\varepsilon_g^p K_g}{AF_{gs}F_{gg}} \left[\frac{\lambda_g}{\lambda_m(\lambda_g-\lambda_m)} S_m D_m - \frac{\lambda_m}{\lambda_g(\lambda_g-\lambda_m)} S_g D_g\right], \quad (10)$$

where $S_m = 1-e^{-\lambda_m T_1}$, $S_g = 1-e^{-\lambda_g T_1}$, $D_m = e^{-\lambda_m T_{2g}}(1-e^{-\lambda_m T_{3g}})$, $D_g = e^{-\lambda_g T_{2g}}(1-e^{-\lambda_g T_{3g}})$, and

$$K_g = \frac{\lambda_g^2 D_m \sum_{i=1}^{n}\phi_i(1-e^{-\lambda_m T_i})e^{-\lambda_m t_i} - \lambda_m^2 D_g \sum_{i=1}^{n}\phi_i(1-e^{-\lambda_g T_i})e^{-\lambda_g t_i}}{\phi\left(\lambda_g^2 S_m D_m - \lambda_m^2 S_g D_g\right)}.$$

Using a similar deducing method, the formula of the FEP counts of the characteristic γ ray of Z^m during the period T_{3m} can easily be given as

$$C_m = \frac{MN_A\theta\phi\sigma_m I_{\gamma m}\varepsilon_m^p K_m S_m D_{mm}}{AF_{ms}F_{mg}F_{mc}\lambda_m}, \quad (11)$$

where $K_m = \frac{\sum_{i=1}^{n}\phi_i(1-e^{-\lambda_m T_i})e^{-\lambda_m t_i}}{\phi S_m}$, $S_m = 1-e^{-\lambda_m T_1}$, $D_{mm} = e^{-\lambda_m T_{2m}}(1-e^{-\lambda_m T_{3m}})$, $I_{\gamma m}$ is the intensity of the characteristic γ ray of Z^m, ε_m^p is its FEP detection efficiency in the detector, and F_{ms}, F_{mg}, and F_{mc} are the self-absorption correction factor of the characteristic γ ray in the sample, the geometry correction factor of the sample, and the cascade coincidence correction factor of the characteristic γ ray (here F_{mc} must be taken into account), respectively.

Comparing Eqs. (10) and (11), we get

$$C_g' = \frac{I_{\gamma g}\varepsilon_g^p K_g X_{\rm it}\left(\lambda_g^2 S_m D_m - \lambda_m^2 S_g D_g\right) F_{ms}F_{mg}F_{mc}}{I_{\gamma m}\varepsilon_m^p K_m S_m D_{mm} F_{gs}F_{gg}\lambda_g(\lambda_g-\lambda_m)} C_m, \quad (12)$$

where C_g' in the formula is the part we should deduct from the FEP counts of the characteristic γ ray of Z^g in the cross-section measurement of the $X(n,b)Z^g$ reaction.

In practical cross-section measurements, C_g'' (the measured FEP count of the characteristic γ ray of Z^g) subtracts C_g' calculated from Eq. (12) in the case of the FEP count C_m of any characteristic γ ray of Z^m. C_m can be measured till it meets the request, which means the count deducted the influence of the excited state on the ground state. However, in the case where the FEP count C_m of any characteristic γ ray of Z^m cannot be measured, then Eq. (12) is not available. For this special circumstance, if the half-life of Z^m is much shorter than that of Z^g, then the total cross section of the $X(n,b)Z^{g+m}$ reaction can be calculated by taking the previously mentioned method with which the sample is measured after having cooled for a long enough period of time (commonly, the cooling time is more than seven times the half-life of Z^m); if the half-life of Z^m is much longer than that of Z^g, the following method can be used to deduct the influence of Z^m on Z^g. Any characteristic γ ray of Z^g is measured twice: the first should be done before seven times the half-life of Z^g (without other influence, the earlier the measurement is taken the better); the second should be done after seven times the half-life of Z^g (if the FEP count of any characteristic γ ray meets the request, the later the measurement is taken the better). The FEP count C_{g1} of a characteristic γ ray of Z^g from the $Z^m \rightarrow Z^g$ procedure during the first measurement can be deduced from Eq. (10) as

$$C_{g1} = \frac{MN_A\theta\phi\sigma_m X_{\rm it} I_{\gamma g}\varepsilon_g^p K_{g1}}{AF_{gs}F_{gg}}$$
$$\times \left[\frac{\lambda_g}{\lambda_m(\lambda_g-\lambda_m)} S_{m1} D_{m1} - \frac{\lambda_m}{\lambda_g(\lambda_g-\lambda_m)} S_{g1} D_{g1}\right], \quad (13)$$

where T_{3g1} is the time of the first measurement, T_{2g1} is the cooling time; additionally, T_{3g2} is the time of the second measurement and T_{2g2} is the cooling time.

In the second measurement, the FEP count C_{g2} of a characteristic γ ray of Z^g from the $Z^m \rightarrow Z^g$ procedure [here the FEP count of a characteristic γ ray of Z^g from the $X(n,b)Z^g$ reaction can be ignored, especially when $T_{2g2} \gg 7T_{g\ 1/2}$] also can be derived from Eq. (10) as

$$C_{g2} = \frac{MN_A\theta\phi\sigma_m X_{\mathrm{it}} I_{\gamma g}\varepsilon_g^p K_{g2}}{AF_{gs}F_{gg}} \times \left[\frac{\lambda_g}{\lambda_m(\lambda_g-\lambda_m)}S_{m2}D_{m2} - \frac{\lambda_m}{\lambda_g(\lambda_g-\lambda_m)}S_{g2}D_{g2}\right]. \tag{14}$$

Comparing Eqs. (13) and (14), we get

$$C_{g1} = \frac{\lambda_g^2 D_{m1}\sum_{i=1}^{n}\phi_i(1-e^{-\lambda_m T_i})e^{-\lambda_m t_i} - \lambda_m^2 D_{g1}\sum_{i=1}^{n}\phi_i(1-e^{-\lambda_g T_i})e^{-\lambda_g t_i}}{\lambda_g^2 D_{m2}\sum_{i=1}^{n}\phi_i(1-e^{-\lambda_m T_i})e^{-\lambda_m t_i} - \lambda_m^2 D_{g2}\sum_{i=1}^{n}\phi_i(1-e^{-\lambda_g T_i})e^{-\lambda_g t_i}} C_{g2}, \tag{15}$$

where $D_{m1} = e^{-\lambda_m T_{2g1}}(1-e^{-\lambda_m T_{3g1}})$, $D_{g1} = e^{-\lambda_g T_{2g1}}(1-e^{-\lambda_g T_{3g1}})$, $D_{m2} = e^{-\lambda_m T_{2g2}}(1-e^{-\lambda_m T_{3g2}})$, and $D_{g2} = e^{-\lambda_g T_{2g2}}(1-e^{-\lambda_g T_{3g2}})$.

When disposing the experimental data, we get the FEP count C_{g1} of a characteristic γ ray of Z^g from the $Z^m \rightarrow Z^g$ procedure of the first measurement with the second measured FEP count C_{g2} of a characteristic γ ray of Z^g and Eq. (15). Then the C_{g1} should be subtracted from the first measured FEP count C_g of the characteristic γ ray of Z^g.

III. 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} ns^{-1} were produced by the ^{3}H(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 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 can be made for the fluctuation of the neutron flux during the irradiation. The cross sections for the ^{93}Nb(n,2n)^{92}Nb^m reaction, which are 456.6 ± 13.7, 459.3 ± 9.2, and 459.7 ± 13.8 mb at 13.5 ± 0.3, 14.1 ± 0.2, and 14.6 ± 0.3 MeV incident neutron energies, respectively, were obtained by interpolating the evaluated values in the report of Wagner *et al.* [4], and were selected as the monitor to measure the cross sections of the ^{122}Te(n,2n)^{121}Te^g and ^{128}Te(n,2n)^{127}Te^g reactions. The Te 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 Nb 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°, 90°, and 135° relative to the incident deuteron beam direction.

The γ-ray activities of ^{92}Nb^m, ^{121}Te^g, ^{121}Te^m, and ^{127}Te^g 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, D.C., 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 due to 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%.

The reactions and associated decay data of the activation products in the present investigation are summarized in Table I [5].

IV. RESULTS AND DISCUSSION

The cross sections are calculated using the equation proposed by Wang *et al.* [6]. The pure cross sections of the ^{122}Te(n,2n)^{121}Te^g and ^{128}Te(n,2n)^{127}Te^g reactions, which subtracted the effect of the excited state using the formulas deducted previously, are summarized in Table II, together with the affected data of the excited state for comparison.

Corrections are 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 the sample geometry. The major errors in our work result from the errors of

TABLE I. Reactions and associated decay data of activation products.

Reaction	Half-life	E_r (keV)	I_r (%)
^{122}Te(n,2n)^{121}Te^m	154 d	212.189	81.4
^{122}Te(n,2n)^{121}Te^g	16.78 d	507.59	17.666
^{128}Te(n,2n)^{127}Te^m	109 d		
^{128}Te(n,2n)^{127}Te^g	9.35 h	417.9	0.99
^{93}Nb(n,2n)^{92}Nb^m	10.15 d	934.44	99.07

TABLE II. Summary of the cross-section measurements.

Reaction	Pure cross sections		Affected cross sections		Relative error (%)
	E_n (MeV)	σ (mb)	E_n (MeV)	σ (mb)	
^{122}Te(n,2n)^{121}Te^g	13.5 ± 0.3	649 ± 32	13.5 ± 0.3	665 ± 33	2.5
	14.6 ± 0.3	694 ± 35	14.6 ± 0.3	709 ± 36	2.2
^{128}Te(n,2n)^{127}Te^g	14.1 ± 0.2	441 ± 21	14.1 ± 0.2	443 ± 21	0.5
	14.6 ± 0.3	481 ± 23	14.6 ± 0.3	485 ± 24	0.9

counting statistics, detector efficiency, monitor-reaction cross sections, the weight of samples, the self-absorption of γ rays, the coincidence summing effect of cascade γ rays, and the sample geometry.

It can be seen from Tables I and II that the excited state has an influence on the ground-state reaction cross-section measurement, but the effect of the excited state on the ground state is small, which can be ignored when the half-life $T_{m1/2}$ of the excited state is much longer than the half-life $T_{g1/2}$ of the ground state [the reactions of ^{122}Te(n,2n)^{121}Te^g and ^{128}Te(n,2n)^{127}Te^g are all of this case]. From the theoretical analysis, the effect of the excited state on the ground-state reaction cross-section measurement is large when the half-life $T_{m1/2}$ of Z^m and $T_{g1/2}$ of Z^g are not far apart and the branch ratio $X_{\rm it}$ of IT is big.

In summary, in this article the formulas used to subtract the effect of the excited state on the ground state in cross-section measurements are deduced, and the pure cross sections of the ^{122}Te(n,2n)^{121}Te^g and ^{128}Te(n,2n)^{127}Te^g reactions induced by neutrons around 14 MeV are measured by activation relative to the ^{93}Nb(n,2n)^{92}Nb^m reaction. It must be generally deduced that the effect of the excited state on the ground-state reaction cross-section measurement using the formulas deduced previously must be considered for measuring the pure ground-state reaction cross sections.

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