# Formation cross sections of nuclei with (n, 2n) reactions*

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**Abstract** Neutron activation technique is used to measure the formation cross sections on even-even target nuclei with 14.6 MeV (n, 2n) reactions. The absolute values are calculated by using an integrated pre-equilibrium statistical model. The result gives a general good fit to the experimental data and shows the existence of shell effect on the cross sections. Problems related to the effect are discussed.

**Keywords** Formation cross sections, (n, 2n) reactions, Pre-equilibrium model

## 1 Introduction

The formation cross sections of nuclei with (n, 2n) reactions play an important role in both fission and fusion reactors. The accurate cross section data for nuclei in the medium heavy mass region are particularly required [1], since they will be the structural materials in the reactors. In addition, Yuan *et al.*[2,3] recently used the 14 MeV neutron induced reaction successfully to produce the new isotopes of $^{185}$Hf and $^{237}$Th, so a fresh looking at the systematics between (n, 2n) cross sections and mass number, $A$, seemed highly desirable. Therefore, the neutron activation technique was used in the study to measure the formation cross sections of 14 even-even target nuclei of $A$ ranging from 46 to 110 with 14.6 MeV (n, 2n) reactions. The absolute values were calculated by using an integrated pre-equilibrium statistical model. The result gives a general good fit to the experimental data and shows an evidence of shell effect on the formation cross sections.

## 2 Experimental

The measurement of formation cross sections involves the measurement of radioactivity of the radionuclide produced by predetermining fluence of neutrons with specific energy. The reaction cross section is then obtained from these values and the related reaction parameters. The equation for the cross section is the following:

$$\sigma = \frac{N_\gamma \cdot R^2}{M \cdot \epsilon_\gamma \cdot f_s \cdot f_\alpha \cdot \frac{1}{1+\alpha} \cdot \sum_{i=1}^{l} \phi_i \left[1 - \exp(-\lambda T_i)\right] \exp(-\lambda t_i)} \tag{1}$$

where $N_\gamma$ is total energy peak counting rate of the characteristic gamma-ray for the product radionuclide, $R$ the distance between the neutron source and the sample, $M$ the number of isotopic nuclei involved in the reaction, $\epsilon_\gamma$ the total energy peak efficiency, $f_s$ the self-absorption correction factor for characteristic gamma-ray in the sample, $f_\alpha$ the branching ratio of characteristic gamma-ray, $\alpha$ the internal conversion factor, $\phi_i$ the neutron fluence in the time interval of the $i$-th irradiation period (n/(s·sr)), $\lambda$ the radioactivity decay constant, $l$ the number of irradiation intervals (depending on the steadiness of neutron fluence), $t_i$ the time interval of the $i$-th irradiation, $T_i$ the time interval from the end of the $i$-th irradiation to the starting of measurement or so-called the cooling time.

The samples were irradiated under the 14 MeV neutrons produced by T(d, n)$^4$He reaction

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on 400 KV neutron generator. The sample was placed at the position 5 cm from the tritium target and at an angle of 45° with respect to the deuteron direction (parallel to the target plane). The incident deuteron energy was 200 keV and the thickness of tritium target was $0.5 mg/cm^2$, the incident neutron energy was $14.6 \pm 0.2$ MeV, the strength of neutron sources was $5 \times 10^9$ n/s.

For the measurement of gamma-ray radioactivity, a coaxial $100 cm^3$ Ge(Li) detector and a $\phi 7.6 cm \times 7.6$ cm NaI(Tl) crystal were used. The detection efficiency for total energy peak of the spectrometer was calibrated by $4\pi\beta - \gamma$ coincidence method, in the whole energy region a relative error of 0.03 could be achieved. The stability of the detector efficiency was monitored with a standard $^{137}Cs$ source. The results indicated that in a long period the efficiency was not changed within error of 0.01. Corrections were made for the geometrical dependence of the detector efficiency and the variation of gamma-ray self-absorption in samples.

The associated particle method was used to measure neutron fluence. The detector for recording alpha particle is a gold surface barrier silicon detector placed at 90° with respect to the incident deuteron beam. Table 1 gives the sources of the errors in determination of the neutron fluence, where $\alpha_s$ results from the statistic deviation, $d$ the dead time correction, $b$ the background, $T_d$ the drift of beam spot, $S$ the solid angle uncertainty, $C_r$ the competing reaction, $A_i$ the anisotropy correction, $C_s$ the Coulomb scattering.

**Table 1** The errors in determination of the neutron fluence

| | $\alpha_s$ | $d$ | $b$ | $T_d$ | S | $C_r$ | $A_i$ | $C_s$ | Total |
|---|---|---|---|---|---|---|---|---|---|
| % | 0.1 | 0.3 | 0.2 | 0.6 | 0.1 | 0.4 | 0.3 | 0.5 | 1.0 |

## 3 Experimental results and error analysis

The activation technique has been used to determine the formation cross sections on even target nuclei with neutron number $N$ from 28 to 50. The error sources and the measured cross sections are shown in Table 2 and Table 3. In Table 2, $n$ results from neutron fluence rate, $\gamma$ the $\gamma$-ray detection efficiency for the total energy peak, $S_a$ the sample self absorption correction, $G_s$ the sample geometry correction for $\gamma$-ray efficiency, $M_s$ the sample weight, $D$ distance between target and sample, $S_c$ the count statistics, $T_{sa}$ the target scattering and absorption.

**Table 2** Sources of errors in absolute measurement

| | $n$ | $\gamma$ | $S_a$ | $G_s$ | $M_s$ | $D$ | $S_c$ | $T_{sa}$ | Total |
|---|---|---|---|---|---|---|---|---|---|
| % | 1.0 | 3.5 | 0.6 | 0.3 | <0.5 | 1.0 | 1.3 | 0.5 | 4.2 |

Table 3 (n, 2n) reaction cross sections for even proton target nuclide $10^{-31} m^2$

| Target | $^{46}Ti$ | $^{50}Cr$ | $^{54}Fe$ | $^{58}Ni$ | $^{64}Zn$ | $^{70}Ge$ | $^{76}Se$ | $^{80}Se$ | $^{86}Sr$ | $^{88}Sr$ | $^{96}Ru$ | $^{100}Mo$ | $^{102}Pd$ | $^{110}Pd$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mea. | 51 | 31 | 27 | 30 | 153 | 550 | 890 | 750 | 650 | 389 | 610 | 1229 | 1141 | 2510 |
| | ±2 | ±1 | ±1 | ±1 | ±6 | ±16 | ±27 | ±35 | ±21 | ±12 | ±20 | ±42 | ±50 | ±110 |
| Cal. | 26 | 6 | 0.2 | 190 | 248 | 605 | 743 | 833 | 851 | 442 | 965 | 1078 | 1081 | 1191 |

## 4 Theoretical calculation

In 1966 pre-equilibrium model was proposed by Griffin and some others. Their theory depicted that in addition to emission of particles from the compound nucleus after reaching equilibrium, there existed particle emission from the nucleus with non-equilibrium state. The reaction mechanism then lies between the direct interaction mechanism and the compound nucleus mechanism. Since the pre-equilibrium theory and the equilibrium state statistical theory are both capable of explaining the nuclear reaction in their applicable regions, by interlacing the above two theories, one may acquire theoretically calculated results in consistence with those of the experimental measurements. Calculation of (n, 2n) cross sections on 14 nuclides was undertaken under a frame work of A. Chattejee.[4]

### 4.1 Cross section calculation

The (n, 2n) cross section is expressed as a sum of a pre-equilibrium (PE) component and a statistical evaporation or equilibrium (EQ) component, i.e.

$$\sigma(\mathrm{n},2\mathrm{n}) = \sigma_{\mathrm{R}}\,[f_{\mathrm{PE}} + f_{\mathrm{EQ}}(1-\delta)]\cdot F_{\mathrm{n}} \tag{2}$$

where $\sigma_{\mathrm{R}}$ is the formatiom cross section of compound nucleus, $f_{\mathrm{PE}}$ and $f_{\mathrm{EQ}}$ are the pre-equilibrium and equilibrium fractions of emitting first neutron, $\delta$ the sum of all pre-equilibrium fractions for probable exit channels induced by incident neutrons, $F_{\mathrm{n}}$ the probability of emitting second neutron in (n, 2n) reactions. Here the only proton competing reaction is (n, np). At the second stage of the reactions the decay is assumed to be purely statistical.

### 4.2 Pre-equilibrium decay

The equation for pre-equilibrium fraction was given by Gadioli *et al*, originated from the exciton model of Griffin-William.

$$\frac{\mathrm{d}f_{\mathrm{PE}}}{\mathrm{d}\epsilon} = \frac{m\epsilon\sigma_{\mathrm{inv}}(\epsilon)}{2\pi^3\hbar^2|M|^2g^4E^3}\sum_{t=1,\Delta t=2}^{\bar{t}}(\frac{U}{E})^{t-2}(t+1)^2(t-1)(\frac{t+k}{t}) \tag{3}$$

where $m$ is the reduced mass of neutron, $\epsilon$ the kinetic energy of the outgoing nucleon, $\sigma_{\mathrm{inv}}$ the corresponding inverse reaction cross section, $E$ the excitation energy of compound nucleus, $U$ the excitation energy of the residual nucleus, $k$ constant 1 (or -1) for neutron (or proton) emission, $t$ and $\bar{t}$ the numbers of excitons in the precompound nucleus and equilibrium nucleus, respectively, $g$ the average single particle level density in the Fermi gas model, $|M|^2$ the average value of the squared matrix elements and can be expressed in simple equation[5]

$$|M|^2g^4 = \alpha A \tag{4}$$

where $\alpha$ is an adjustable parameter. In our work, $\alpha = 1.889\times10^{-4}\,\mathrm{MeV}^2$.

### 4.3 Equilibrium decay

After reaching excitation equilibrium state the nucleus will undergo equilibrium decay. This process can be represented by the following evaporation model:

$$f_{\mathrm{EQ}} = \frac{\int_0^{E_{\mathrm{n}}-S_{\mathrm{n}}} \epsilon\,\sigma_{\mathrm{inv}}^{(\mathrm{n})}(\epsilon)\,\rho^{(\mathrm{n})}\,(E_{\mathrm{n}}-\epsilon)\mathrm{d}\epsilon}{\int_0^{E_{\mathrm{n}}} \epsilon\,\sigma_{\mathrm{inv}}^{(\mathrm{n})}(\epsilon)\,\rho^{(\mathrm{n})}(E_{\mathrm{n}}-\epsilon)\mathrm{d}\epsilon + \int_0^{E_{\mathrm{n}}+Q_{(\mathrm{n,p})}} \epsilon\,\sigma_{\mathrm{inv}}^{(\mathrm{p})}(\epsilon)\,\rho^{(\mathrm{p})}(E_n+Q_{(\mathrm{n,p})}-\epsilon)\mathrm{d}\epsilon} \tag{5}$$

where $E_{\mathrm{n}}$ is the incident neutron energy, $S_{\mathrm{n}}$ the neutron binding energy in the target nucleus, $Q$ (n, p) the $Q$ value for (n, p) reaction, $\sigma_{\mathrm{inv}}^{(\mathrm{n})}(\epsilon)$ and $\sigma_{\mathrm{inv}}^{(\mathrm{p})}(\epsilon)$ the inverse reaction cross sections for (n, n') and (n, p) reactions respectively, $\rho^{(\mathrm{n})}$ and $\rho^{(\mathrm{p})}$ the corresponding residual nucleus level densities.

After emitting first neutron , the nucleus might remain at the excited state; therefore de-excitation by the second emission can occur. Because the excitation energy is rather low, only equilibrium state emission is considered in our calculation. In the second emission stage, $F_{\mathrm{n}}$ was calculated using the same formula and parameters as Chatterjee [4] .

## 5 Discussion

In our calculation, $\alpha$ value used was the same for different nuclei. The calculated reaction cross section for $^{58}$Ni is 6 times larger than the experimental result which needs further explanation. It is believed that although it belongs to light nuclei, due to the very special structure of this nuclide, its shape is distorted by use of distorted wave Born approximation. It was discovered that the direct reaction fraction of the (n, 2n) cross section is quite big. The result could be improved by correction of direct reaction and pre-equilibrium, reaching a value of $30\times10^{-31}\mathrm{m}^2$ [6] which is consistent with our experimental data.

The cross sections do exhibit a characteristic systematic behaviour. On the average, the values increase with increasing mass number $A$, but in more detail the cross sections vary with maximum and minima which are closely connected with the magic neutron numbers. For even-proton nuclei with neutron numbers around $N = 28(A \sim 54)$, there appears a minimum. The second minimum appears around neutron number $N = 50(A \sim 90)$.

The present results indicate the existence of shell effects in the cross section values for even-even closed neutron shell nuclei at 14.6 MeV neutron energy. Although the present measurements are in good agreement with valuces in recent literature,[6-10] more measurements are needed, as the lack of normalizing the experimental cross section data to the same excitation energy hinders an accurate systematic study of (n, 2n) reactions.

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