

# Study of Some Structural Fusion Materials for (n,2n) Reactions

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**Abstract** Studies of (n,2n) reaction are especially important for neutron multiplication. The (n,2n) cross section is neutron multiplier reaction in fusion reactor design.  $^{27}\text{Al}$ ,  $^{51}\text{V}$ ,  $^{52}\text{Cr}$ ,  $^{55}\text{Mn}$ ,  $^{56}\text{Fe}$  and  $^{58}\text{Ni}$  nuclei are the some structural fusion materials. Therefore, (n,2n) reactions of the selected blanket materials can play a key role for multiplying neutrons in reactor environment. In this study, for some structural fusion materials (n,2n) reactions such as  $^{27}\text{Al}(n,2n)^{26}\text{Al}$ ,  $^{51}\text{V}(n,2n)^{50}\text{V}$ ,  $^{52}\text{Cr}(n,2n)^{51}\text{Cr}$ ,  $^{55}\text{Mn}(n,2n)^{54}\text{Mn}$ ,  $^{56}\text{Fe}(n,2n)^{55}\text{Fe}$  and  $^{58}\text{Ni}(n,2n)^{57}\text{Ni}$  have been carried out up to 30 MeV incident neutron energy. In the calculations, the pre-equilibrium and equilibrium effects have been used. The calculated results have been compared with the experimental data as well as with evaluated data files.

**Keywords** (n,2n) cross-section · Excitation function · Nuclear reactions · TALYS-1.0 nuclear model code

## Introduction

Fusion power is the power generated by nuclear fusion processes. In nuclear fusion reactions two light atomic nuclei fuse together to form a heavier nucleus. Fusion is attractive as an energy source because of the virtually inexhaustible supply of fuel, the promise of minimal adverse environmental impact, and its inherent safety. Fusion will not produce  $\text{CO}_2$  or  $\text{SO}_2$  and thus will not contribute to global warming or acid rain. Furthermore, there are not radioactive nuclear waste problems in the fusion reactors.

Although there have been significant research and development studies on the inertial and magnetic fusion reactor technology, there is still a long way to go to penetrate commercial fusion reactors to the energy market [1–4].

The success of fusion power system is dependent on performance of the first wall, blanket or divertor systems. So, the performance of structural materials for fusion power systems, understanding nuclear properties systematic and working out of (n,2n) reaction cross sections are very important.

Nuclear data evaluation is generally carried out on the basis of experimental data and theoretical model calculations. It is both physically and economically impossible to measure necessary cross-sections for all the isotopes in the periodic table for a wide range of energies. Since the experimental data of charged particle induced reactions are scarce, self-consistent calculation and analyses using nuclear theoretical models are very important. The obtained experimentally and theoretically neutron cross sections data can be extensively used for the investigation of the structural materials of the fusion reactors, radiation damage of metals and alloys, tritium breeding ratio, neutron multiplication and nuclear heating in the components, neutron spectrum, and reaction rate in the blanket and neutron dosimetry [5–10]. In the present paper, by using equilibrium and pre-equilibrium reaction mechanisms, the (n,2n) reactions for some structural fusion materials were investigated up to 30 MeV.

## Reaction Cross Section Formulas and Calculation Methods

The nuclear reaction models are frequently needed to provide the estimation of the particle-induced reaction

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cross-sections, especially if the experimental data are not obtained or on which they are hopeless to measure the cross sections; due to the experimental difficulty. Such predictions can guide the design of the target/blanket configurations and can reduce engineering over design costs. Equilibrium and pre-equilibrium particle emissions during the decay process of a compound nucleus are very important for a better understanding of the nuclear reaction mechanism induced by medium energy particles.

The primary pre-equilibrium differential cross section for the emission of a particle  $k$  with emission energy  $E_k$  can then be expressed in terms of  $\tau$ , the composite-nucleus formation cross section  $\sigma^{CF}$ , and an emission rate  $W_k$ ,

$$\frac{d\sigma_k^{PE}}{dE_k} = \sigma^{CF} \sum_{p_\pi=p_\pi^0}^{p_\pi^{\max}} \sum_{p_\nu=p_\nu^0}^{p_\nu^{\max}} W_k(p_\pi, h_\pi, p_\nu, h_\nu, E_k) \tau(p_\pi, h_\pi, p_\nu, h_\nu) \times P(p_\pi, h_\pi, p_\nu, h_\nu) \tag{1}$$

where the factor  $P$  represents the part of the pre-equilibrium population that has survived emission from the previous states and now passes through the  $(p_\pi, h_\pi, p_\nu, h_\nu)$  configurations, averaged over time. The initial proton and neutron particle numbers are  $p_\pi^0 = Zp$ , and  $p_\nu^0 = Np$ , respectively with  $Zp$  ( $Np$ ) the proton (neutron) number of the projectile. For any exciton state in the reaction process,  $h_\pi^0 = h_\nu^0 = 0$  and  $h_\nu = p_\nu - p_\nu^0$ , so that for primary pre-equilibrium emission the initial hole numbers are  $h_\pi^0 = h_\nu^0 = 0$ . Particle emission only occurs from  $n = 3$  ( $2p1h$ ) and higher exciton states.

We use a hardwired value of  $p_\pi^{\max} = p_\nu^{\max} = 6$  as the upper limit of the summation. The maximum values  $p_\pi^{\max}$  and  $p_\nu^{\max}$  thus entail an automatic separation of the pre-equilibrium population and the compound nucleus population. The latter is then handled by the more adequate Hauser-Feshbach mechanism. The emission rate  $W_k$  for ejectile  $k$  with spin  $S_k$  is given by [11–19].

$$w_k(p_\pi, h_\pi, p_\nu, h_\nu, E_k) = \frac{2s_k + 1}{\pi^2 \hbar^3} \mu_k E_k \sigma_k \text{inv}(E_k) \times \frac{\omega(p_\pi - Z_k, h_\pi, p_\nu - N_k, h_\nu, E_x)}{\omega(p_\pi, h_\pi, p_\nu, h_\nu, E^{\text{tot}})}, \tag{2}$$

where  $\sigma_k$ ,  $\text{inv}(E_k)$  is the inverse reaction cross section as calculated from the optical model, and  $\omega$  is the two-component particle-hole state density. We here restrict ourselves to the formulas given above since they contain the model- and parameter-dependent quantities. The expression for  $S_{pre}$  contains the adjustable transition matrix element  $M_2$  for each possible transition between neutron-proton exciton configurations. A proton-neutron ratio of 1.6 for the squared internal transition matrix elements was adopted to give the best

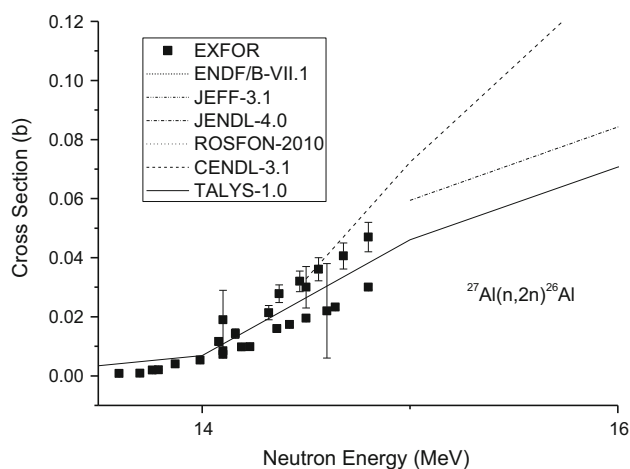
overall agreement with experiment, i.e.,  $M_{\pi\nu}^2 = M_{\nu\pi}^2 = 1.6M_{\nu\pi}^2 = 1.6M^2$ . Partial level density parameters  $g_\pi = Z/17$  and  $g_\nu = N/17$  were used in the equidistant spacing model for the partial level densities. Finally, an effective surface interaction well depth  $V = 12$  MeV was used [20–23]. In this study, for some structural fusion materials  $(n,2n)$  reactions such as  $^{27}\text{Al}(n,2n)^{26}\text{Al}$ ,  $^{51}\text{V}(n,2n)^{50}\text{V}$ ,  $^{52}\text{Cr}(n,2n)^{51}\text{Cr}$ ,  $^{55}\text{Mn}(n,2n)^{54}\text{Mn}$ ,  $^{56}\text{Fe}(n,2n)^{55}\text{Fe}$  and  $^{58}\text{Ni}(n,2n)^{57}\text{Ni}$  have been carried out up to 40 MeV incident neutron energy.

### Results and Discussions

In this study, for some structural fusion materials  $(n,2n)$  reactions such as  $^{27}\text{Al}(n,2n)^{26}\text{Al}$ ,  $^{51}\text{V}(n,2n)^{50}\text{V}$ ,  $^{52}\text{Cr}(n,2n)^{51}\text{Cr}$ ,  $^{55}\text{Mn}(n,2n)^{54}\text{Mn}$ ,  $^{56}\text{Fe}(n,2n)^{55}\text{Fe}$  and  $^{58}\text{Ni}(n,2n)^{57}\text{Ni}$  have been carried out up to 30 MeV incident neutron energy. The calculated results have been compared with the experimental data as well as with evaluated data files. A reasonable agreement with experimental and theoretical excitation functions was obtained. The results can be summarized and conclude as follows.

#### $^{27}\text{Al}(n,2n)^{26}\text{Al}$ Reaction

The excitation curve for  $^{27}\text{Al}(n,2n)^{26}\text{Al}$  is given in Fig. 1. The experimental data points are between 4 and 15 MeV. The theoretical study using TALYS-1.0 indicates that the emitted  $(2N)$  spectra, the lower energy part is dominated by compound nucleus contribution and the pre-equilibrium contribution appears only around 10–20 MeV. The equilibrium calculations with statistical model based on the



**Fig. 1** The comparison of calculated excitation function using TALYS-1.0 of  $^{27}\text{Al}(n,2n)^{26}\text{Al}$  reaction with available experimental values and evaluated nuclear data files ENDF/B-VII.1, JENDL-4.0 and JEFF-3.1, ROSFON-2010, CENDL-3.1. The values reported in Ref. [24]

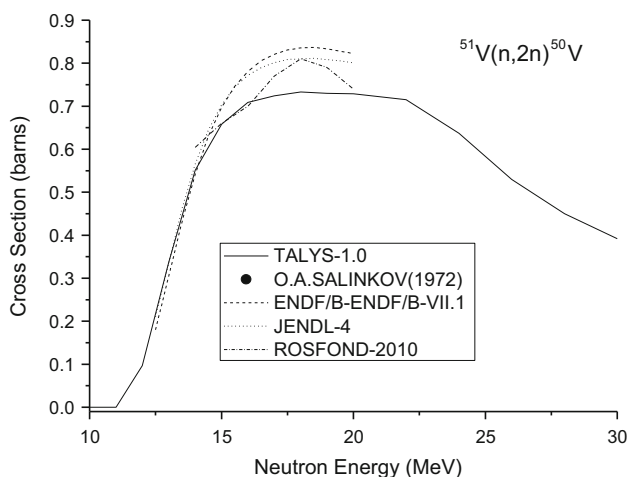
Hauser-Feshbach formalism give lower results than experimental data. The pre-equilibrium spectra calculations of emitted (2n) for  $^{27}\text{Al}$  nuclei are in good agreement between 13.8 and 14.5 MeV with experimental data. The evaluated nuclear data files ENDF/B-VII.1, JENDL-4.0, JEFF-3.1, ROSFON-2010 and CENDL-3.1 show important discrepancies in energy  $>14.4$  MeV. Our results would be useful to improve theoretical codes by adjusting the optimal parameters to provide reliable estimation of the cross-section.

#### $^{51}\text{V}(n,2n)^{50}\text{V}$ Reaction

The excitation curve for  $^{51}\text{V}(n,2n)^{50}\text{V}$  is given in Fig. 2. The experimental cross-section data are rather scarce for these reactions. When more experimental data for  $^{51}\text{V}(n,2n)^{50}\text{V}$  reaction more reliable results can be obtained. The theoretical study using TALYS-1.0 indicates that the emitted (2N) spectra, the lower energy part is dominated by compound nucleus contribution and the pre-equilibrium contribution appears only around 10–20 MeV. The evaluated nuclear data files ENDF/B-VII.1, JENDL-4.0 and ROSFON-2010 show important discrepancies in energy  $>14.8$  MeV and agree with each other in energy  $<14.8$ .

#### $^{52}\text{Cr}(n,2n)^{51}\text{Cr}$ Reaction

The excitation curve for  $^{52}\text{Cr}(n,2n)^{51}\text{Cr}$  is given in Fig. 3. The experimental data points are between 13 and 27 MeV. In Fig. 3 the bell like shape of the excitation curve is typical characteristics of compound nucleus which rises

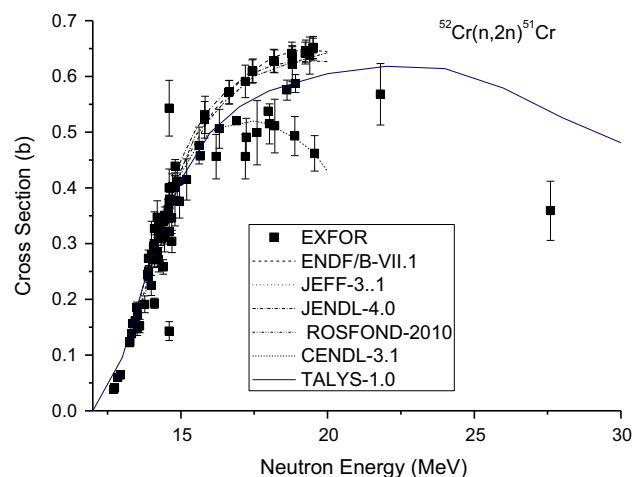


**Fig. 2** The comparison of calculated excitation function using TALYS-1.0 of  $^{51}\text{V}(n,2n)^{50}\text{V}$  reaction with available experimental values and evaluated nuclear data files ENDF/B-VII.1, JENDL-4.0 and JEFF-3.1, ROSFON-2010, CENDL-3.1. The values reported in Ref. [24]

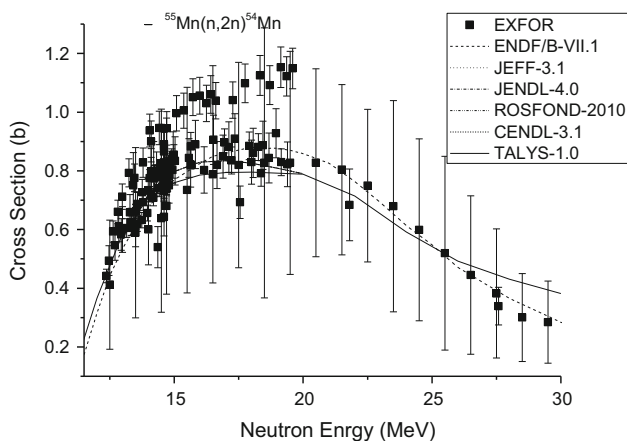
abruptly above the reaction and the increase of the pre-equilibrium contribution with neutron energy. The TALYS-1.0 calculations have similar shape to the experimental data. The theoretical study using TALYS-1.0 indicates that the emitted (2N) spectra, the lower energy part is dominated by compound nucleus contribution and the pre-equilibrium contribution appears only around 10–20 MeV. The pre-equilibrium spectra calculations of emitted (2n) for  $^{52}\text{Cr}$  nuclei are in good agreement between 13 and 17.5 MeV with experimental data. The evaluated nuclear data files ENDF/B-VII.1, JENDL-4.0, JEFF-3.1, ROSFON-2010 and CENDL-3.1 show important discrepancies in energy  $>15$  MeV. Our results would be useful to improve theoretical codes by adjusting the optimal parameters to provide reliable estimation of the cross-section.

#### $^{55}\text{Mn}(n,2n)^{54}\text{Mn}$ Reaction

The excitation curve for  $^{55}\text{Mn}(n,2n)^{54}\text{Mn}$  is given in Fig. 4. The experimental data points are between 12.5 and 30 MeV, and the data around  $14.8 < E < 20$  MeV shows very large discrepancies. The equilibrium spectra calculations of the emitted (2n) particles are approximately Maxwellian. The TALYS-1.0 calculations have similar shape to the experimental data. The theoretical study using TALYS-1.0 indicates that the emitted (2N) spectra, the lower energy part is dominated by compound nucleus contribution and the pre-equilibrium contribution appears only around 10–20 MeV. The pre-equilibrium spectra calculations of emitted (2n) for  $^{55}\text{Mn}$  nuclei are in good agreement between 12.5 and 20 MeV with experimental



**Fig. 3** The comparison of calculated excitation function using TALYS-1.0 of  $^{52}\text{Cr}(n,2n)^{51}\text{Cr}$  reaction with available experimental values and evaluated nuclear data files ENDF/B-VII.1, JENDL-4.0 and JEFF-3.1, ROSFON-2010, CENDL-3.1. The values reported in Ref. [24]



**Fig. 4** The comparison of calculated excitation function using TALYS-1.0 of  $^{55}\text{Mn}(n,2n)^{54}\text{Mn}$  reaction with available experimental values and evaluated nuclear data files ENDF/B-VII.1, JENDL-4.0 and JEFF-3.1, ROSFOND-2010, CENDL-3.1. The values reported in Ref. [24]

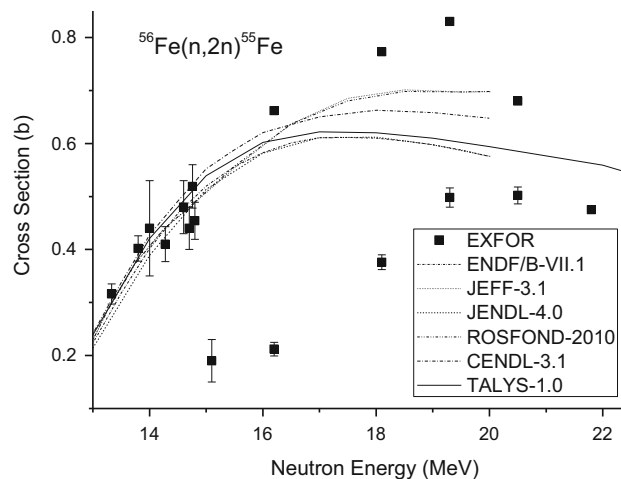
data and with the evaluated nuclear data files ENDF/B-VII.1, JENDL-4.0, JEFF-3.1, ROSFOND-2010 and CENDL-3.1. Our results would be useful to improve theoretical codes by adjusting the optimal parameters to provide reliable estimation of the cross-section.

#### $^{56}\text{Fe}(n,2n)^{55}\text{Fe}$ Reaction

The excitation curve for  $^{56}\text{Fe}(n,2n)^{55}\text{Fe}$  is given in Fig. 5. The experimental data points are between 13.5 and 22 MeV, and the data around  $15.3 < E < 22$  MeV shows very large discrepancies. The equilibrium spectra calculations of the emitted (2n) particles are approximately Maxwellian. The theoretical study using TALYS-1.0 indicates that the emitted (2N) spectra, the lower energy part is dominated by compound nucleus contribution and the pre-equilibrium contribution appears only around 10–20 MeV. The pre-equilibrium spectra calculations of emitted (2n) for  $^{56}\text{Fe}$  nuclei are in good agreement between 13.5–15 MeV with experimental data and with the evaluated nuclear data files ENDF/B-VII.1, JENDL-4.0, JEFF-3.1, ROSFOND-2010 and CENDL-3.1. Our results would be useful to improve theoretical codes by adjusting the optimal parameters to provide reliable estimation of the cross-section.

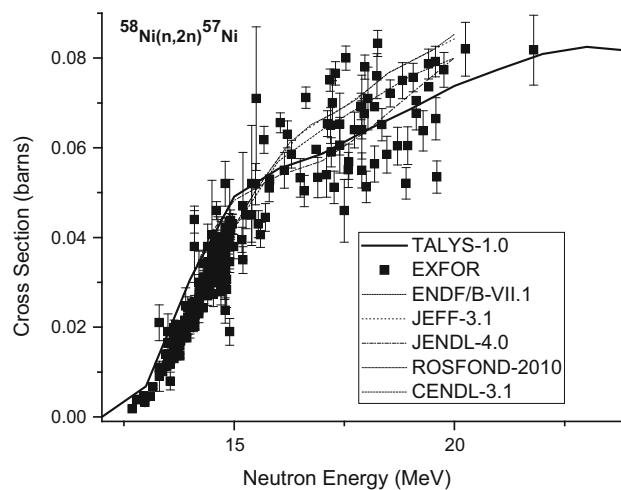
#### $^{58}\text{Ni}(n,2n)^{57}\text{Ni}$ Reaction

The excitation curve for  $^{58}\text{Ni}(n,2n)^{57}\text{Ni}$  is given in Fig. 6. The experimental data points are between 12.5 and 22 MeV. The TALYS-1.0 calculations have similar shape to the experimental data. The theoretical study using TALYS-1.0 indicates that the emitted (2N) spectra, the lower energy part is dominated by compound nucleus



**Fig. 5** The comparison of calculated excitation function using TALYS-1.0 of  $^{56}\text{Fe}(n,2n)^{55}\text{Fe}$  reaction with available experimental values and evaluated nuclear data files ENDF/B-VII.1, JENDL-4.0 and JEFF 3.1, ROSFOND-2010, CENDL-3.1. The values reported in Ref. [24]

contribution and the pre-equilibrium contribution appears only around 10–20 MeV. The pre-equilibrium spectra calculations of emitted (2n) for  $^{58}\text{Ni}$  nuclei are in good agreement between 12.5 and 19.8 MeV with experimental data and with the evaluated nuclear data files ENDF/B-VII.1, JENDL-4.0, JEFF-3.1, ROSFOND-2010 and CENDL-3.1. Our results would be useful to improve theoretical codes by adjusting the optimal parameters to provide reliable estimation of the cross-section.



**Fig. 6** The comparison of calculated excitation function using TALYS-1.0 of  $^{58}\text{Ni}(n,2n)^{57}\text{Ni}$  reaction with available experimental values and evaluated nuclear data files ENDF/B-VII.1, JENDL-4.0 and JEFF-3.1, ROSFOND-2010, CENDL-3.1. The values reported in Ref. [24]

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