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Excitation Functions of Neutron Induced Nuclear Reactions for ^{59}Co Nucleus using Different Level Density Models

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Cobalt alloys have been used in nuclear reactor design because these alloys have favourable mechanical properties at high temperatures. In this work, the nuclear cross section data of ^{59}Co(n,2n)^{58}Co, ^{59}Co(n,3n)^{57}Co, ^{59}Co(n,4n)^{56}Co, ^{59}Co(n,np)^{58}Fe, ^{59}Co(n,t)^{57}Fe, ^{59}Co(n,^{3}He)^{57}Mn and ^{59}Co(n,2nα)^{54}Mn reactions were obtained by using TALYS 1.8 and ALICE/ASH codes. Effects on the cross section data of nuclear level density models in the calculations were investigated. In addition, the obtained results of the cross section calculations are discussed and compared with the measured values from the literature.

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1. Introduction

The neutron cross sections are required in nuclear reactor, medical physics, dosimetry, spallation neutron sources, astrophysics and other nuclear physics applications [1–4]. Moreover, these data are useful for testing the nuclear reaction theory. Actually, from the viewpoint of the application in science and technology, the capability of some models is of great interest in obtaining the unknown cross sections [5].

Different models for pre-compound emission have been proposed for calculating the nuclear cross sections within the neutron-induced reaction processes. An accurate description of pre-compound models is important for understanding the nuclear reactions at projectile energies above 8–10 MeV. Moreover, different nuclear level density models in the pre-compound models are used to test the experimentally known cross section data. A nuclear level density model is therefore required in the excitation functions calculations.

Furthermore, the cross section data are important for the design, construction and evaluation of nuclear reactors. The selection of structural fusion materials is an indispensable component for nuclear reactor technology [6].

Because of the high strength and hardness properties, cobalt alloys are used as structural material of nuclear fusion reactors [6]. The activated cobalt materials in corrosion products have a significant role for determination of dose level during maintenance, after a coolant leak in a nuclear fusion device. The cobalt materials of the water cooling system are some of the principal parts of activated corrosion products [7]. The nuclear cross section calculations on ^{59}Co nucleus have been made by using different nuclear level density models in ALICE/ASH and TALYS 1.8 computer codes [8, 9].

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2. Nuclear cross section calculations

Nuclear reactions are processes that take place between the projectile and target nucleus, which may change the identity or characteristics of an atomic nucleus. Several models have been proposed to understand nuclear structure and nuclear reaction mechanisms. The nuclear reaction models are generally proposed for explaining various experimental nuclear reaction data. TALYS 1.8 [8] and ALICE/ASH [9] codes were developed to verify the reaction mechanisms and to analyze various products of nucleus decay [10]. The ALICE/ASH code applies the Weisskopf-Ewing model [11] for the statistical component, and Hybrid and Geometry Dependent Hybrid (GDH) models [12] for pre-compound emission of particles in reactions.

The pre-compound emission spectrum of nucleons in the GDH model is calculated as follows,

$$\frac{\mathrm{d}\sigma_v(\varepsilon)}{\mathrm{d}\varepsilon} = \pi^2 \sum_{l=0}^{\infty} (2l+1)\, T_l P_v(l,\varepsilon), \qquad (1)$$

where, term T_l denotes the transmission coefficient of the l-th partial wave. The quantity is the reduced de Broglie wavelength of the incoming particle. The term $P_v(l,\varepsilon)$ represents decay probability, at energy of exit reaction channel. For explanation of the effects of nuclear density distribution, the pre-compound GDH model is calculated according to incoming l orbital angular momentum [12].

The Fermi gas model (FGM) in TALYS 1.8 code assumes that single-particle states, which construct the excited nuclear levels of the nuclei are equally spaced, and that collective nuclear levels are absent. The total level density for back-shifted Fermi gas model [13] is calculated by:

$$\rho_F^{\mathrm{tot}}(E_x) = \frac{1}{\sqrt{2\pi}\sigma} \frac{\sqrt{\pi}}{12} \frac{\mathrm{e}^{2\sqrt{\alpha U}}}{\alpha^{\frac{1}{4}} U^{\frac{5}{4}}}, \qquad (2)$$

where the $\rho^{\mathrm{tot}}(E_x)$ total nuclear level density corresponds to the total number of nuclear levels per MeV around E_x. The U term is the effective excitation energy.

The term α corresponds to nuclear level density parameter. Term σ is nuclear cross section [8].

The level density within generalized superfluid model [14] is calculated by,

$$\rho(U) = \rho_{\mathrm{qp}}\left(U^{l}\right) K_{\mathrm{vib}}\left(U^{l}\right) K_{\mathrm{rot}}\left(U^{l}\right), \tag{3}$$

where the terms $K_{\mathrm{rot}}\left(U^{l}\right)$ and $K_{\mathrm{vib}}\left(U^{l}\right)$ represent rotational and vibrational enhancement factors at the U^{l} effective excitation energy, the term $\rho_{\mathrm{qp}}\left(U^{l}\right)$ represents the nuclear density for quasi-particle excitation [9].

3. Results and discussions

At energies from the reaction threshold to 50 MeV, the excitation functions of ^{59}Co(n,2n), ^{59}Co(n,3n), ^{59}Co(n,4n), ^{59}Co(n,np), ^{59}Co(n,t), ^{59}Co(n,^{3}He), ^{59}Co(n,2nα) nuclear reactions, for study of the the pre-compound emission, were calculated by using two-component exciton model [15], hybrid model and GDH model [12]. The level density formalisms such as back-shifted Fermi gas model (BSFGM) [13], generalized superfluid model (GSFM) [16], superfluid nuclear model (SFM) [14], Fermi gas model (FGM) and Kataria-Ramamurthy Fermi gas model (KRM) [17] in the pre-compound emissions were used for determining the accurate excitation functions. The experimental values of the neutron cross sections were taken from EXFOR libarary [18].

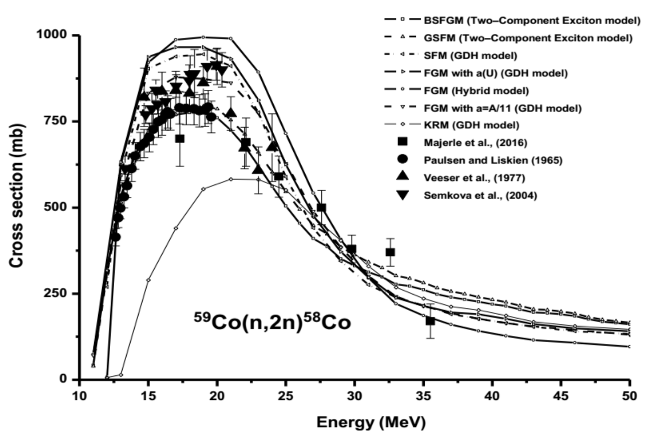

Fig. 1. Excitation functions of ^{59}Co(n,2n)^{58}Co reaction.

Figure 1 shows the calculated and the measured cross sections for ^{59}Co(n,2n)^{58}Co nuclear reaction up to energy of 50 Me. The measured data of Paulsen and Liskien (1965) [19] are in perfect harmony with BSFGM and GSFM predictions in the two-component exciton model. Additionally, BSFGM and GSFM cross section predictions are in an acceptable agreement with the experimental data of Majerle et al. (2016) [20]. On the other hand, FGM predictions with $a = A/11$ in GDH model have a very good fit with the experimental data reported by Semkova et al. (2004) [21] for the considered nuclear reaction. The experimental data of Veeser et al. (1977) [22] for energy range of 14.7–20 MeV give generally a good agreement with FGM calculation results with $a = A/11$ in GDH model. Moreover, the experimental data of Veeser et al. (1977) [22] for energy range of 21–24 MeV agree well with BSFGM and GSFM cross section predictions for this reaction.

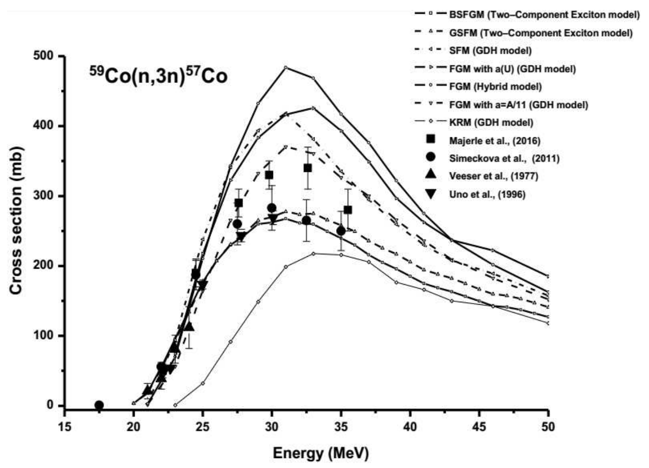

Fig. 2. Excitation functions of ^{59}Co(n,3n)^{57}Co reaction.

Figure 2 presents the excitation functions of ^{59}Co(n,3n)^{57}Co nuclear reaction. It can be said that the FGM calculations with $a = A/11$ in GDH model are in good agreement with the cross section results of Majerle et al. (2016) for ^{59}Co(n,3n)^{57}Co reaction. In the energy range of 22–35 MeV, there is in excellent agreement between the pre-compound model calculations with BSFGM and GSFM nuclear level densities, and the data of Simeckova et al. (2011) [23]. The cross sections of Uno et al. (1996) [24] at 22.66 MeV are in agreement with the hybrid model and GDH model calculation results, using FGM level density with $a = A/11$. The other three experimental data of Uno et al. (1996) for this reaction are also in excellent agreement with the predictions of two-component exciton model, including pre-compound process. In addition, the two-component exciton model predictions show a good match with experimental data of Veeser et al. (1977) [22] for the considered reaction.

The cross section results of ^{59}Co(n,4n)^{56}Co nuclear reaction are given in Fig. 3. It can be said that experimental results reported by Majerle et al. (2016) and Simeckova et al. (2011) are in harmony with each other for this nuclear reaction. At 32.5 to 32.6 MeV, the cross section values of these authors are in good agreement with results of GDH model, using FGM level density. On the other hand, KRM calculations at neutron energy of 35 to 35.5 MeV agree with the other data of these authors. The cross section data of Uno et al. (1996) at 38.3 MeV is in disagreement with the pre-compound calculation results.

Figure 4 shows the excitation curves for ^{59}Co(n,np)^{58}Fe nuclear reaction. The cross section

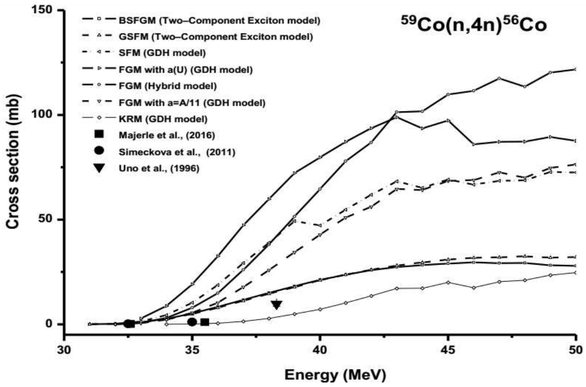

Fig. 3. Excitation functions of ^{59}Co(n,4n)^{56}Co reaction.

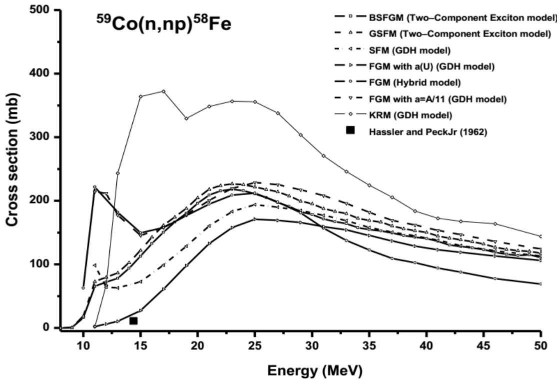

Fig. 4. Excitation functions of ^{59}Co(n,np)^{58}Fe reaction.

of 11 mb reported by Hassler and Peck Jr (1962) [25] at incident energy of 14.4 MeV agrees well with FGM predictions with $a(U)$ including the pre-compound GDH model. It seems that the cross section calculation results of the two-component exciton model, including BSFGM and GSFM nuclear level densities, are in harmony with each other for this reaction.

The cross section results of ^{59}Co(n,t)^{57}Fe nuclear reaction are given in Fig. 5. The agreement between the experimental data reported by Sudar and Csikai (1979) [26],

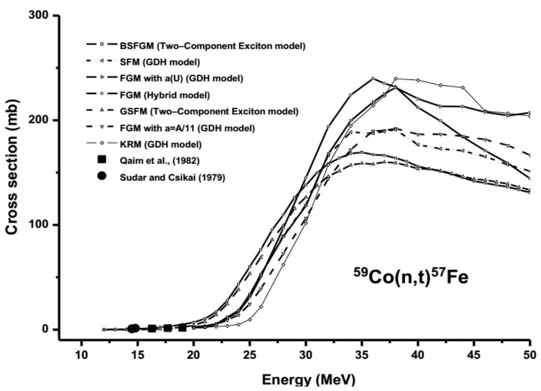

Fig. 5. Excitation functions of ^{59}Co(n,t)^{57}Fe reaction.

and BSFGM predictions is generally good for this reaction. On the other hand, the measured cross section data of Qaim et al. (1982) [27] have an acceptable fit with GSFM estimations via the two-component exciton model, calculated by TALYS code. The calculated excitation curves have maximum cross section values at projectile energy range of 33–43 MeV.

The nuclear excitation functions of ^{59}Co(n,^{3}He)^{57}Mn nuclear reaction are shown in Fig. 6. It appears that excitation function results of KRM level density, including GDH model, above the incident neutron energy of 35 MeV, have higher values than the other predictions. The obtained model-based calculations by using pre-compound approaches do not give the cross section values in the energy range of the experimental data, reported by Bahal and Pepelnik (1985) [28], Qaim (1974) [29] and Diksic et al. (1974) [30]. The structure of the obtained excitation functions by the GDH and the two-component exciton models are different from each other.

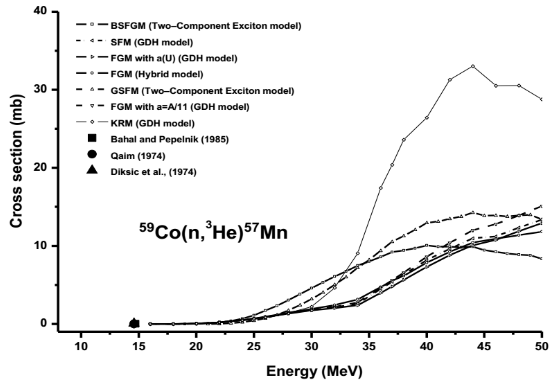

Fig. 6. Excitation functions of ^{59}Co(n,^{3}He)^{57}Mn reaction.

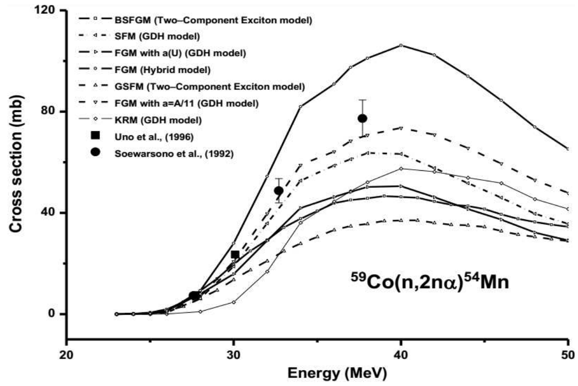

Fig. 7. Excitation functions of ^{59}Co(n,2nα)^{54}Mn reaction.

Figure 7 shows the excitation functions for ^{59}Co(n,2nα)^{54}Mn nuclear reaction. The experimental data of Uno et al. (1996) [24] and Soewarsono et al. (1992) [31] for the considered nuclear reactions are in good agreement with the cross section results of FGM calculations with $a = A/11$ in pre-compound GDH model. The maximum of the obtained excitation functions, calculated using two-component exciton model and GDH, is positioned in the energy range of 35–45 MeV.

Thereby, theoretical studies carried out in the present paper show that the cross sections are satisfactorily reproduced by the pre-compound model calculations. We hope that the obtained data can help in a better evaluation of the cross sections of these reactions of Co isotopes, in the future.

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