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Empirical formula on (n,^{3}He) reaction cross sections at 14.6 MeV neutrons

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HIGHLIGHTS

- The new empirical formula for the calculating of (n,^{3}He) cross sections at 14.6 MeV was obtained.
- The cross section formula was based on the *Q*-value of nuclear reaction.
- The obtained cross section results were compared with other cross sections.

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ABSTRACT

The systematic behavior of the cross sections of (n,^{3}He) nuclear reactions has been studied by various researches at neutron energy of 14.6 MeV. A new empirical formula based on the *Q*-value dependence of the cross sections of the investigated reaction has been proposed. The cross sections obtained from the new formula are compared with the other proposed formulae results and the experimental data. It seems that the present formula based on the *Q*-value dependence provides the good description for cross sections of neutron-induced (n,^{3}He) nuclear reactions at 14.6 MeV.

1. Introduction

The cross sections of (n,^{3}He) nuclear reactions produced by neutron particle are quite important for design of nuclear fission and fusion devices in terms of nuclear technology. The long-term goal of the fusion research programmers are to make available as early as possible, nuclear fusion power as a source to generate electricity (Fischer et al., 2011). Indeed, the charged particles emitted from nuclear reactions produced by neutrons will produce serious damage to the structure materials, particularly in nuclear reactor with high neutron flux (Lishan and Yuling, 1992). It is need to accumulate new data of nuclear reaction cross sections around the incident energy of 20 MeV (Tel et al., 2007). Thereby, more many experimental investigations have been carried out to obtain and detect the neutron particles at various energy ranges. For example, a technique known as time-of-flight (TOF) is widely used for the energy measurements by means of velocity determination. In addition the obtained data via the different techniques are essential to develop additional nuclear theoretical calculation models to explain the reaction mechanisms and the properties of the excited nuclear states at different energy ranges. On the other hand, the experimental neutron cross sections for the nuclear reactions at projectile energies around 14–15 MeV and the emission spectra of various particles have a profound importance for understanding the binding energy systematics, nuclear structure, the particle–nucleus interactions, and refined nuclear models (Tel et al., 2007). Many measurements of the excitation curves of the reactions induced by the fast neutrons on medium and heavy mass targets are quite difficult because of the low induced activities, such as the (n,2p), (n,^{2}H), (n,^{3}H), (n,^{3}He) cross sections, etc. (Atasoy and Dökmen, 1995). Particularly, the nuclear reactions such as (n,^{3}H) and (n,^{3}He) are also energetically possible but in the medium and heavy target nuclei are rather rare (Qaim et al., 1980). The (n,^{3}He) measurement cross sections reported by various authors have been measured about 90 data sets from various laboratories (Atasoy and Dökmen, 1995). The (n,^{3}He) nuclear reaction at neutron energy of 14 MeV is one of the weakest reactions (Yettou and Belgaid, 2014). Because the cross sections of this reactions are very small (around a few microbarn), in fact, the measurements are very difficult. Therefore, the cross section data measured are not often consistent and the discrepancies are very large. Indeed, theoretical calculations via the suggested nuclear models are

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necessary (Lishan and Yuling, 1992). On the other hand, if the measured data are scarce and calculated model results are unreliable, the use of systematics for the cross sections of the nuclear reactions is crucial (Broeders and Konobeyev, 2007). The applications of statistical and thermodynamical methods on the calculation of nuclear reactions in heavy nuclei go back to the investigation of Weisskopf (1937). Empirical and semi-empirical formulae on the nuclear reaction cross sections are applied for the creation of systematic studies. In fact, the empirical formulae use the evaporation model, and ignore an important role of the pre-equilibrium mechanisms of particle emission from medium and heavy target nuclei. On the other hand, the semi-empirical formulae are based on the analytical expressions for calculation of particle emission within the frame of the evaporation and pre-equilibrium exciton models (Aydın et al. 2008a). Moreover, numerous empirical and semi-empirical formulae with different parameters for various nuclear reactions have been proposed by several authors (Aydın et al., 2008a, 2008b; Yiğit and Tel, 2014a, 2014b; Belgaid et al., 2005; Goyal and Kishore, 2012; Konobeyev and Korovin, 1995; Challan and Fayez-Hassan, 2014). In this work a new empirical formula has been presented to describe the (n,^{3}He) reaction cross sections at 14.6 MeV energy. It has been noted that there is a correlation between the (n,^{3}He) nuclear cross sections and the reaction Q-value. Indeed the present formula proposed is actually different from previous cross section formulae for (n,^{3}He) nuclear reactions, because it based directly on the Q-value of nuclear reaction. Finally the present formula gives reasonably good agreement with the experimental reaction cross sections.

2. Cross section systematics of (n,^{3}He) nuclear reactions

In the present paper, the proposed empirical formula was obtained by using experimental cross section data for the (n,^{3}He) nuclear reactions at 14.6 MeV neutron energy and the target mass region $31 \leq A \leq 187$. This formula with dependence on the Q-value of nuclear reactions is based on the statistical model. The empirical approach of nuclear reaction cross sections produced by fast neutrons can be approximately expressed as below

$$\sigma(n, x) = C\sigma_{ne}e^{(as)} \tag{1}$$

where the term s corresponds to asymmetry parameter, σ_{ne} represents neutron non-elastic cross section, the coefficients a and C represent the fitting parameters obtained from least squares method, x denotes the produced particle of the nuclear reactions. The term e^{as} at Eq. (1) represents the escape of reaction products from compound nucleus. Eq. (1) indicates the product of two factors, each of which might be assigned to a stage of within the framework of statistical model of the reactions. This Equation represents the Levkovskii formula (Levkovskii, 1964) which are the most widely used and this formula also covers a broad range of mass number with expressions giving the (n,p) and (n,α) nuclear reaction cross sections. The Levkovskii's formula (Levkovskii, 1964) has been provided theoretical support by Pai and Andrews (1978). In this context, Pai and Andrews (1978) compared with statistical model calculations the (n,p) experimental cross sections on target nuclei with mass number $32 \leq A \leq 98$ at 14 MeV energy. Additionally, Pai and Andrews (1978) provided the good description between experiment and theory, by introducing an effective Q-value into the statistical model calculation.

In previous investigations on systematic behavior of the excitation functions the (n,^{3}He) nuclear reactions, several empirical and semi-empirical formulae have been proposed for example by Lishan and Yuling (1992), Atasoy and Dökmen (1995), Qaim et al. (1980), Yettou and Belgaid (2014), Broeders and Konobeyev (2007), Aydın et al. (2008b), and Bölükdemir et al., 2010. Qaim (1978) suggested an empirical formula for the nuclear excitation functions of the (n,^{3}He) reactions as given below

$$\sigma(\text{n, 3He}) = 0.08475\left(A^{1/3} + 1\right)^2 \exp\left[-1.6467\frac{N-Z}{A}\right] \tag{2}$$

This formula that depend on the asymmetry parameter describes the contribution of the equilibrium emission in the (n,^{3}He) nuclear reaction. According to calculations performed by Qaim, it can be obtained using only the simple evaporation model without considering the angular momentum Qaim (1978). On the other hand, Lishan and Yuling (1992) suggested the cross section systematic of the (n,^{3}He) reactions at 14.6 MeV energy could be expressed by means of the asymmetry parameters as given below

$$\sigma(\text{n, 3He}) = 0.918\left(A^{1/3} + 1\right)^2 \exp\left[-11.338\frac{N-Z}{A}\right] \tag{3}$$

An empirical expression by Atasoy and Dökmen (1995) was proposed to predict the (n,^{3}He) reaction cross sections. They investigated dependences of the (n,^{3}He) nuclear excitation functions on $(N-Z)$ and $(E_n - E_{th})$. Physically, the term $(N-Z)$ is the neutron excess of the target nucleus, and the terms E_n and E_{th} are the projectile neutron energy at 14–15 MeV and the (n,^{3}He) threshold energy in MeV, respectively. The cross section expression of Atasoy and Dökmen (1995) uses two fitting parameters. In their work, nuclear reaction cross sections can be given as below

$$\sigma(\text{n, 3He}) = ae^{-b(N-Z)}(E_n - E_{th}) \tag{4}$$

In above formula, the fitting parameters a and b are given in article of Atasoy and Dökmen (1995). Moreover, a semi-empirical formula for the evaluation of (n,^{3}He) nuclear cross sections within the frame of pre-equilibrium exciton model at the energies of 14.6 and 20 MeV was proposed by Broeders and Konobeyev (2007). According to calculations of Broeders et al. (2006) the pre-equilibrium emission gives the main contribution in the excitation curves of (n,^{3}He) nuclear reactions for target nuclei with $A > 40$ at the projectile neutron energy below 20 MeV. Therefore, their systematics of the (n,^{3}He) cross sections can be given as follows:

$$\sigma(\text{n, 3He}) = \pi r_0^2\left(A^{1/3} + 1\right)^2 A^{-2.3}\left(1.6534\frac{N-Z+1}{A} + 0.15257\right)^3 \tag{5}$$

where the quantity r_0 equals to 1.3 fm (Broeders and Konobeyev, 2007). The comparisons of previous nuclear cross section formulae on (n,^{3}He) reactions were given by Bölükdemir et al. (2010) at 14.6 MeV neutron energy. Bölükdemir et al. (2010) suggested a formula taking into accounting non-elastic cross sections by using optical model for (n,^{3}He) nuclear reactions of incident energy of 14–15 MeV and also they suggested that the semi-empirical cross sections of nuclear reactions can be approximately expressed as follows:

$$\sigma(\text{n, 3He}) = C'\sigma_{ne-opt}\exp\left[\frac{b}{s}\right] \tag{6}$$

In above formula, the coefficients C' and b correspond to the fitting parameters determined from the least-squares method. The term s denotes asymmetry parameter. The term σ_{ne-opt} represents the optical model neutron non-elastic cross section.

For the calculation of the (n,^{3}He) nuclear excitation functions at 14.6 MeV energy, Yettou and Belgaid (2014) obtained a new semi-empirical formula with three parameters based on the evaporation model. In their work, the Coulomb and Coulomb diffuseness effects are dominant than the asymmetry term. Their formula is given below