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Collective effects in deuteron induced reactions of aluminum

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ABSTRACT

Cross sections of ^{27}Al(d,x)^{22}Na, ^{27}Al(d,x)^{24}Na, and ^{27}Al(d,x)^{27}Mg reactions are calculated by using TALYS 1.6 computer code with different nuclear level density models, which are composite Gilbert–Cameron model, back-shifted Fermi gas model, generalized superfluid model, and recently proposed collective semi-classical Fermi gas model in the energy range of 3–180 MeV. The results are compared with the experimental data taken from EXFOR library. In these deuteron induced reactions, collective effects are investigated by means of nuclear level density models. Collective semi-classical Fermi gas model including the collective effects via the level density parameter represents the best agreement with the experimental data compared to the other level density models, especially in the low deuteron bombarding energies where the collective effects dominate.

1. Introduction

Charged particle (deuteron, proton, triton, alpha) induced nuclear reactions have been studied by many authors [1–4] and the cross sections of these reactions are extensively used in various fields ranging from medical to industrial applications of nuclear reactions. Among these particles, deuteron has a special importance because the cross sections of deuteron induced reactions on metal targets are required to produce medical radionuclides.

^{22}Na and ^{24}Na radioisotopes are long- (2.6 years) and short-lived (14.96 h) positron emitters, respectively, used as positron source in SPECT (single-photon emission computed tomography) and PET (positron emission tomography). The production of ^{24}Na from ^{27}Al(d,pα)^{24}Na was first measured by Batzel et al. [5] in the energy range from threshold to 190 MeV. With advancing technology, ^{24}Na radionuclide production experiments were performed by many groups of scientists at different bombarding deuteron energies [6–12]. Similarly, Ring and Litz measured the cross section of ^{27}Al(d,x)^{22}Na reaction in the energy range from 30 MeV to 190 MeV [13]. These data are suitable to be used for monitoring high energy deuteron beams. However, in some cases, such as radionuclide production for medical applications, estimation of neutron yield, and calculation of activity for radiation safety, etc. One usually needs the deuteron bombarding energy below 15 MeV. Until the early 2000s, very few measurements have been made in this energy region. Therefore, both experimental data obtained and theoretical analysis performed so far have been insufficient for the various nuclear applications mentioned above. Afterwards, the reaction cross sections were measured by activation method on stacks of thin metallic targets (Al, Ni, Fe, and Cu) with natural isotopic composition in the energy range below 20 MeV [14]. Another experiment measuring the production of ^{22,24}Na radioisotopes from threshold to 20 MeV deuteron bombarding energy was done by Hermanne et al. [15]. A similar experiment was done to measure the cross section of ^{24}Na at low deuteron bombarding energies from 1.7 MeV to 20 MeV [16] and the results were compared with the other experimental data as well as the theoretical analysis obtained by using some well-known codes. The production of another short-lived (9.46 min) radionuclide ^{27}Mg was also measured for proton and deuteron bombarding energies from threshold (2–10 MeV) to 45 MeV [7,11,12,17].

Radionuclides which are produced in nuclear reactions induced by deuterons or protons are widely used in nuclear medicine for diagnostic and therapeutic purposes [18–23]. Recently, these radinuclides are produced by neutron capture reactions in nuclear reactors. However, an alternative way to produce high specific activity final products is to use the charged particle induced nuclear reactions. Therefore, a strong demand has arisen for experimental data and their theoretical analysis. In most of these reactions, the stacked foil activation technique, which is the most used and trusted method, is employed to obtain the excitation functions. Cross section measurements for nuclear reactions induced by deuterons were performed by using this and other similar techniques in the IFMIF (International Fusion Materials Irradiation Facility) [24–26]. In the IFMIF, nuclear reactions are available with the accelerated deuterons up to 40 MeV.

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To analyze the cross section of nuclear reactions with the statistical Hauser-Feshbach theory [27] two important inputs, optical model potential, which defines the interaction between the target and projectile by using an effective potential, and nuclear level density, which is the number of the excited levels around an excitation energy, are required. For light ion induced reactions, many authors have developed reliable and advanced global optical potential parameter sets for a wide range of incident energy and target nucleus [28,29]. In contrast, the researchers studying the nuclear level density have been having some problems in deciding the correct method to include shell, pairing and collective effects, which are especially dominant in the low energy region below 20 MeV.

An exception to this general situation is deuteron induced reactions on ^{27}Al target, which are used to produce the radionuclides mentioned above, ^{22}Na, ^{24}Na, and ^{27}Mg. Since there does not exist any global optical potential parameter sets for these reactions [11], it is very important to determine the input parameters of the statistical model calculations, which can be performed by the well-known nuclear reaction codes such as TALYS [30], ALICE/ASH [31], and EMPIRE [32]. With this aim, some authors [33–36] have presented their analysis, which includes the comparison of the predictions obtained by using available nuclear level density models with each other and the experimental data. In this study, however, we present a first analysis of the cross section of deuteron induced reactions of ^{27}Al by using our recently proposed collective semi-classical Fermi gas model (CSCFGM) [37]. To calculate the cross sections, we include our model in TALYS 1.6 nuclear reaction code. This inclusion enables us to compare our results with other phenomenological nuclear level density models, which are employed in TALYS, on equal terms.

The main difference between our nuclear level density model and the other phenomenological models, such as back-shifted Fermi gas model (BSFGM), composite Gilbert–Cameron model (CGCM), and generalized superfluid model (GSM), is that we use a Laplace-like formula for the energy dependence of the nuclear level density parameter including the collective effects instead of the well-known formula proposed by Ignatyuk [38]. By including the collective effects into nuclear level density parameter, a much better agreement between the predictions and the experimental data of the nuclear structure observables, which are mean resonance spacings and the cumulative number of excited levels up to an excitation energy, is achieved [37]. Moreover, our new model provides a useful tool for the coupled channels calculations of inelastic scattering cross sections, by allowing to determine the deformation parameter of the low-lying excited levels of a nucleus [39]. Therefore, our aim in this study is to provide a better explanation of the cross section data of deuteron induced reactions of ^{27}Al, especially in the low-energy region below 20 MeV, by using this model.

This paper is organized as follows: In Section 2, we briefly outline the methods used in our calculations. In Section 3, we present our results and their implications. Finally in Section 4, we give some concluding remarks.

2. Materials and methods

2.1. Nuclear level density

Nuclear level density is the number of excited levels around an excitation energy. These levels are discrete at low excitation energies, but with the increasing excitation energy they appear to represent a continuum. A nuclear level density formula is therefore required in the continuum energy regime. However, an accurate and reliable definition of the nuclear level density should be able to describe the excited levels of a nucleus in both low and high excitation energy region. Therefore, the experimentally known discrete levels are used to test the success of a nuclear level density model. The agreement between the experimental discrete level scheme and the calculated cumulative number of excited levels can be tested by using

$$f_{\mathrm{lev}} = \frac{1}{N}\sum_{i=1}^{N}\sum_{k=N_L^i}^{N_U^i}\frac{\left[N_{\mathrm{cum}}^i(E_k)-k\right]^2}{k} \tag{1}$$

for N nuclei from a lower-level N_L with the excitation energy E_L to an upper- level N_U with the excitation energy E_U. The cumulative number of excited levels is calculated by taking the integral of the total nuclear level density from E_L to an excitation energy E,

$$N_{\mathrm{cum}}(E) = N_L + \int_{E_L}^{E}\rho^{\mathrm{tot}}(E)dE. \tag{2}$$

On the other hand, mean resonance spacings are also can be calculated by using the spin and parity dependent nuclear level density as

$$\frac{1}{D_0^{\mathrm{theo}}} = \sum_{J=\left|I-\frac{1}{2}\right|}^{J=I+\frac{1}{2}}\rho(S_n,J,\Pi) \tag{3}$$

where S_n is the neutron separation energy, I is the total angular momentum of the target nucleus. The comparison of calculated values of mean resonance spacings with the experimental data can be done by means of

$$f_{\mathrm{rms}} = \exp\left[\frac{1}{N}\sum_{i=1}^{N}\left(\ln\frac{D_{0,i}^{\mathrm{theo}}}{D_{0,i}^{\mathrm{exp}}}\right)^2\right]^{1/2} \tag{4}$$

for N nuclei. According to their definitions, the lower f_{rms} and f_{lev} values indicates the better agreement with the experimental data and the best agreement is achieved with $f_{\mathrm{rms}}=1$ and $f_{\mathrm{lev}}=0$. Table 1 represents the comparison of f_{rms} and f_{lev} values of the phenomenological nuclear level density models [37,40]. Effective model means that the model does not include any explicit enhancement factors to include the collective effects.

BSFGM is based on Fermi gas model, which was firstly proposed by Bethe [41]. This model assumes that the excited levels of nucleus are equally spaced and constructed from the single particle states. Therefore, nucleons don't interact with each other and the collective levels are absent. BSFGM also includes a back-shift, which corresponds to the energy required to break the nucleon pairs before they are individually excited, and it is usually considered as an adjustable parameter. BSFGM provides a reliable framework for high excitation energies, but has a divergence problem at low excitation energies in its original version. After this problem is solved [42,43], this model have become widely used in nuclear reaction calculations.

Table 1
The comparison of the predictive powers of phenomenological nuclear level density models.

Model	Type	f_{rms}	f_{lev}
CSCFGM [37]	Collective	1.53	1.32
BSFGM [40]	Effective	1.68	28.5
BSFGM [40]	Collective	1.71	35.3
CGCM [40]	Effective	1.76	24.2
CGCM [40]	Collective	1.77	47.8
GSM [40]	Effective	1.78	28.0
GSM [40]	Collective	1.94	47.4

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