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Analysis of charged particle induced reactions for beam monitor applications

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ABSTRACT

The reaction cross sections for different residual nuclides produced in the charged particle (p, d, ^{3}He and α) induced reactions were calculated and compared with the existing experimental data which are important for beam monitoring and medical diagnostic applications. A detailed literature compilation and comparison were made on the available data sets for the above reactions. These calculations were carried out using the statistical model code TALYS up to 100 MeV, which contains Kalbach's latest systematic for the emission of complex particles and complex particle-induced reactions. All optical model calculations were performed by ECIS-03, which is built into TALYS. The level density, optical model potential parameters were adjusted to get the better description of experimental data. Various pre-equilibrium models were used in the present calculations with default parameters.

1. Introduction

Reliable evaluated nuclear structure and decay data are of vital importance in a large number of nuclear applications such as medical diagnostics, power generation, design and optimization of radionuclide production routes, the monitoring of beam energies and intensities, dosimetry as well as basic nuclear physics and astrophysics. The importance of different emission channel production cross sections induced by charged particles like protons, deuterons and alphas are increasingly recognized by nuclear data community. Efforts are underway to improve the database by experimental measurements as well as by theoretical calculations. Since model based calculations offer cost effective and broader applicability, the present work is motivated to use TALYS. The objective of the present work is, first to study the charged particle induced reactions, by applying suitable theoretical approaches. Since for these reactions, fairly complete and internally consistent experimental data are available for different emission channels, it is intended to analyze them with the new statistical model code TALYS [1], in order to learn more about the predictive power of this model. Secondly, to make an inter-comparison between the investigated reactions. Precise measurement of charged particle induced reactions in high energy domain will serve the purpose of testing and recommending the input parameters. These parameters are required in model-based evaluations of cross-sections at high energies that are essential to support advanced nuclear energy systems. The TALYS code has opened up options for calculating cross sections for various nuclear reaction channels including complex particle emission. All optical model calculations are performed by ECIS-03 [2], which is a part of TALYS code. In this model, the optical model potentials for local and global parameterisation are given by Koning and Delaroche [3].

The selection of reliable data is still difficult even after the analysis of published data. This is due to the fact that, in some cases, they show unacceptable deviations in the values of cross sections and in the energy scale as well. Therefore, one cannot depend on the existing data for monitoring of bombarding beams without proper evaluation. Keeping this in view, the above reactions were considered for a detailed study in the low and medium energy region. Most of the experimental cross-section values have been taken from the original publications. In case where the original sources are not available, the data were taken from earlier compilations [4]. As there were no calculations for the above reactions, we have tried to reproduce the cross-sections with the new statistical model code TALYS. There is however difference between the calculated and experimental results in some cases, but it would require further evaluations of model parameters to find the reason for the individual deviations."

2. Model code TALYS

In the present study new version of model code TALYS was used to calculate the cross sections. TALYS is a computer code system for the prediction and analysis of nuclear reactions. This code simulates reactions that involve neutrons, photons, protons, deuterons, tritons, helions and alpha particles, in the energy range from 1 keV to 200 MeV and for target nuclides $A \geqslant 12$. To achieve

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this, different nuclear reaction models are incorporated into a single code system. The calculations described in this paper are based on a theoretical analysis that utilizes the optical model, compound nucleus statistical theory and pre-equilibrium processes. The theoretical calculations have been performed within the frame work of Hauser–Feshbach statistical model theory [5], with pre equilibrium cross-sections by exciton model [6]. Both classical [6] and quantum mechanical [7] approach in pre-equilibrium analysis were introduced and gave better cross section calculations. Reactions with complex particles in the entrance and/or exit channels, mechanisms like stripping, pick-up and knock-out play an important role and these reactions are not covered by the exciton model. Therefore, for the emission of complex particles and complex particle-induced reactions, Kalbach's [8] latest systematic was introduced. The pre-equilibrium cross section contribution in these reactions was reproduced by the sum of the exciton model calculations, including nucleon transfer and knock-out contributions. All optical model calculations are performed by ECIS-03 [2]. The TALYS code uses several level densities, which range from phenomenological analytical expressions to tabulated level densities derived from microscopic models [9]. Energy dependent level density parameter proposed by Ignatyuk et al. [10] was used.

The present model calculations were similar to the recently constructed optical model potentials of Ref. [3]. Generally, there are two different ways to use TALYS:

1. A very detailed calculation with various adjusted parameters and choices for nuclear models, so that specific experimental data are reproduced.
2. Large scale, default calculations for many nuclides, in which case adjustment to experimental data is not practical. These two approaches are strongly linked. Since nuclear model calculations and fits to experiments generally require many adjustable parameters, it is important that these parameters remain within physically acceptable boundaries.

The measured data was not simply reproduced with default parameters. To get the best experimental fit within the limits given in the TALYS code, few parameters have been changed as mentioned below. Starting from the default parameters, a few parameters were adjusted to obtain the best possible result. In the present work, adjustments were made in the multipliers **r_v adjust, v_1 adjust** and **a_v adjust** to get the acceptable optical model parameters (OMP). The adjusted value in the input multiplies the standard value given in the TALYS database. Similarly, **alphald** and **betald**, the constants for the global expression for the asymptotic level density parameter were also adjusted to obtain the best fitting of the experimental results. Table 1 shows the values of these parameters adjusted for a few reactions of the present work. The table also shows those reactions where default values were used. In the case of ^{3}He induced reactions only the default values of the above mentioned parameters were used. For pre-equilibrium model calculations, different models were used rather than using default one, without changing any parameters. The required inputs like nuclear masses, discrete energy levels and level densities of the nuclides involved in the calculations had been taken care of in a proper way in the calculations. The changes in the above mentioned parameters have been done to fit those experimental data, where it was not possible to reproduce the data with the default values in the TALYS.

Table 1
Parameters adjusted/taken default to reproduce experimental results.

Parameter	p + ^{27}Al	p + ^{nat}Cu	p + ^{nat}Ti	p + ^{nat}Ni
Optical model parameters				
r_v adjust p	0.7	0.8	default	default
a_v adjust p	1.25	default		
v_1 adjust p	0.85	0.78		
	d + ^{27}Al	d + ^{nat}Ti	d + ^{nat}Fe	d + ^{nat}Ni
r_v adjust d	1.05	default	1.1	default
v_1 adjust d	1.06	0.85	1.1	
a_v adjust d	1.01	default	default	
Level density parameters				
Alphald	0.06	default	default	0.047
Betald	0.21			0.18
Ldmodel	3	2		3
	d + ^{27}Al	d + ^{nat}Ti	d + ^{nat}Fe	d + ^{nat}Ni
Alphald	0.057	default	0.06	default
Betald	0.2		0.21	
Ldmodel	3		5	5
	α + ^{27}Al	α + ^{nat}Ti	α + ^{nat}Cu	
Alphald	Default	0.07	Default	
Betald		0.3		
Ldmodel	2	Default		
Preequilibrium	Model			
Preeqmode	3	Default		

3. Model calculations

3.1. Optical model

The optical model plays an important role in nuclear reaction calculations. The origin of the optical model potential (OMP) is the interaction between nucleons in the projectile with those in the target nucleus. The aim of the optical model is to find a potential to describe smooth variations of the scattering cross sections as a function of energy and target nucleon number. The main assumption underlying the optical model is that the interaction between an incident particle and a nucleus can be represented by a complex mean field potential, which divides the reaction into two categories: (i) elastic scattering in which only the direction of the wave propagation is changed and (ii) inelastic scattering in which the particle is scattered into an exit channel different from the incident one. Solving the Schrödinger equation with this complex potential yields among others the reaction and total reaction cross sections, the elastic scattering angular distribution, the transmission coefficients that enter the statistical model of compound nucleus reactions, and the distorted wave functions that were used for the description of direct inelastic scattering to discrete states. In TALYS, all optical model calculations were performed by ECIS-03, which is incorporated as a subroutine. The present model calculations are based on recently constructed optical model potentials of [3].

3.2. Pre-equilibrium reactions

It is known that at higher incident energies around 10 MeV, pre-equilibrium emission contributes significantly in the reaction cross section. These emissions take place after the first stage of the reaction but long before the compound nucleus attains statistical equilibrium. It is imagined that the incident particle slowly creates more complex states in the compound system and gradually loses its memory how it was formed. Two-component exciton model is used in the TALYS code as a default pre-equilibrium model [6] which has been tested against basically all available experimental nucleon spectra for A > 24.

For pre-equilibrium reactions involving deuterons, tritons, ^{3}He and alpha particles, a contribution from the exciton model is automatically calculated using the default two-component exciton model. In the present work, we have dealt with all these charged particles as projectiles and as well as ejectiles. It is well known that for nuclear reactions involving projectiles and ejec-