Production of long-lived $^{26}$Al and $^{24}$Na from neutron interaction in Al target

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The excitation functions of (n, 2n) and (n, $^3$He$^3$) reactions for the production of long-lived radio nuclides $^{26}$Al and $^{24}$Na from $^{27}$Al have been calculated for 1-20 MeV neutrons. The excitation functions of these reactions are calculated using the codes ALICE-91, EMPIRE-2.19 and TALYS-1.0. The codes account for the major nuclear reaction mechanisms, including direct, pre-equilibrium and compound nuclear ones. The excitation functions of these isotopes have been compared graphically with the evaluated nuclear data file and available experimental data. The results are more or less agreeing up to which energy the experimental data are available whereas ALICE code largely under predicts the data in the energy range 1-20 MeV.

Keywords: Pre-equilibrium emission, Exciton model, Geometry dependent hybrid model, Evaporation model, Hauser-Feshbach theory.

1 Introduction

Precise estimate of radionuclide production in neutron induced reaction is important in the latest state-of-the-art nuclear technology of Accelerator Driven Sub-critical Systems (ADSS). Demand of efficient running, optimized output and ensuring personnel safety in an ADSS has boosted the study of high energy neutron induced nuclide production, while target design and other logistic studies have revived interest in the study of same system at lower energies. In the present paper, the production cross-section and yield of radio nuclides formed in thick aluminium target by neutron induced reactions up to 20 MeV projectile energy, have been reported. $^{27}$Al is a common element found in accelerator facility and this study provides data for induced activity generation for any accidental condition in low energy studies related to structural stability and parameters of an ADSS facility. We have calculated the source term for production of nuclides in $^{27}$Al (n, 2n) $^{26}$Al and $^{27}$Al (n, $^3$He$^3$) $^{24}$Na reactions in the framework of nuclear reaction model codes ALICE, EMPIRE and TALYS and estimated the total yield. Our calculated results are compared with experimental data wherever available.

2 Nuclear Reaction Model Calculations

2.1 ALICE-91

The cross-section values were estimated using the computer code ALICE-91 given by Blann$^1$. This code accounts$^4$ for pre-compound emission in the general framework of hybrid/geometry-dependent hybrid model (GDHM) and compound/statistical reactions using Weisskopf-Ewing evaporation model. In this work, excitation function of the residual nuclides is calculated using GDHM. According to this model, the nucleus has a density distribution which can affect pre-equilibrium (PEQ) decay in two ways. First, the nucleon mean free path is expected to be longer (on average about a factor of two) in the diffuse nuclear surface. Secondly, in a local density approximation, there is a limit to the hole depth. These two changes were incorporated into the geometry-dependent hybrid model. In the present work, we have used optical model inverse cross-section and Fermi gas level density options. The level density parameter $a = A/9$ where $A$ is the mass number of the residual nuclide. The parameters have been chosen such as to select an evaporation calculation without fission. For pre-compound decay, the initial exciton number is $n = 3$. The binding energies and $Q$-values used in the present work were all based on the experimental masses$^5$.

2.2 EMPIRE-2.19

The EMPIRE-2.19 code$^6$ accounts for compound, direct and pre-equilibrium nuclear reactions. The secondary compound nuclei (CN) are formed due to subsequent particle emission. The only difference is that although the first CN is initially excited to the
unique (incident channel compatible) energy, the secondary CNs are created with excitation energies that spread over the available energy interval. The transmission coefficients are estimated from the optical model subroutine SCAT2 code\(^7\). Binding energies are determined using masses recommended by Audi and Wapstra\(^8\) whenever available, otherwise the theoretical predictions of Moller and Nix\(^9\) are used. The code uses the statistical Hauser–Feshbach theory\(^10\) to describe the compound nuclear emissions and several models to calculate PEQ mechanisms like multistep direct (MSD), multistep compound (MSC) and Hybrid Monte-Carlo Simulation (HMS) approach to the emission of nucleons. In this work, we have used different PEQ models along with different level density formalisms for EQ reactions and in the figures these are mentioned as follows:

1. **EMPIRE 1**: MSD+MSC PEQ, with EMPIRE specific level densities (BCS + Fermi gas with deformation dependent collective effects, adjusted to experimental “a” values and to discrete levels)
2. **EMPIRE 2**: HMS PEQ with EMPIRE specific level densities
3. **EMPIRE 3**: MSD+MSC PEQ, with Fermi gas level density including deformation dependent collective effects and “a” parameters derived from the shell model
4. **EMPIRE 4**: HMS PEQ, with Fermi gas level density as mentioned in item 3 above

### 2.3 TALYS-1.2

Excitation functions of \(^{26}\)Al and \(^{24}\)Na from neutron induced reaction on \(^{27}\)Al were also estimated using the TALYS-1.2 code. In TALYS code\(^11\) direct reactions are calculated using any one of spherical optical model, DWBA, rotational or vibrational coupled channel analysis and giant resonances. Two component exciton model estimates the PEQ particle emission and the angular distribution of these PEQ particles is determined using Kalbach systematics. Compound nuclear emission is calculated in the framework of Hauser-Feshbach formalism in competition to fission. Here we have used different PEQ models along with different pairing options viz:

1. **TALYS1**: PREEQMODE=2, Exciton model, numerical transition rates with energy dependent matrix element; PAIRMODEL=1, Fu’s pairing energy correction
2. **TALYS2**: PREEQMODE=3, Exciton model, numerical transition rates with optical model for collision probability; PAIRMODEL=2, Compound nucleus pairing energy correction

### 3 Results and Discussion

In this study, the production cross-sections of \(^{26}\)Al and \(^{24}\)Na were calculated using the nuclear reaction model codes ALICE-91, EMPIRE-2.19 and TALYS-1.2 and for incident neutron energies in the range 1-20 MeV.

The excitation functions of \(^{26}\)Al and \(^{24}\)Na from n + \(^{27}\)Al reaction are shown in Figs 1-4 along with the available experimental data\(^{12-23}\). The comparison of calculated results with Evaluated Nuclear Data Files\(^{24,25}\) (ENDF) and with available experimental data.
data have been shown separately. The reaction channel $^{27}\text{Al} \ (n, 2n) \ ^{26}\text{Al}$ opens at about 13 MeV and the experimental data are available for the neutron energy range of $\sim$13-18.5 MeV. In the case of $^{27}\text{Al} \ (n, \alpha) \ ^{24}\text{Na}$ reaction, the reaction channel opens at about 5 MeV and experimental data are available up to about 39 MeV neutron energy.

Our analysis (Fig. 2) shows that the shape of the excitation function curve of the long-lived $^{26}\text{Al}$ isotope, is reproduced by EMPIRE and TALYS calculations but the measured production cross-sections are over predicted at neutron energies above 15 MeV. ALICE largely under predicts the data in the energy range 13-15 MeV. From the trend of the ALICE calculated excitation function, it is observed that at higher energies the experimental data are over predicted by ALICE. The experimental data given by Ikeda et al.\textsuperscript{14} and Iwasaki et al.\textsuperscript{16} for $^{27}\text{Al} \ (n, 2n) \ ^{26}\text{Al}$ excitation function show excellent agreement with the calculations of EMPIRE and TALYS codes, while the results of Filatenkov et al.\textsuperscript{13} are also within good accuracy. In both the cases (EMPIRE and TALYS), the transition rates are calculated using optical model subroutines and the compound nuclear emission is calculated using Hauser-Feshbach formalism while in ALICE Weisskopf-Ewing formalism is used. For (n, $\alpha$) reaction the results of TALYS code show fairly good agreement while EMPIRE with HMS PEQ and LD=0 calculations have a 10%-20% over prediction. Results from EMPIRE with HMS PEQ and LD=1 agree with the experimental data except for the energy interval 10-14 MeV where it shows under prediction. Other calculations with EMPIRE under predict the cross-sections. ALICE calculations also under predict the excitation function below 16 MeV.

From the plots, it is observed that for (n, $\alpha$) reaction the results of TALYS2 calculations are agreeing better throughout the energy range, but for (n, 2n) reaction TALYS1 calculations are closer to the experimental data. Our analysis of EMPIRE results showed that the level density option plays a more important part in predicting the excitation function of $^{26}\text{Al}$ while the choice of PEQ model is crucial for $^{24}\text{Na}$. This observation suggests that evaporation is predominant mechanism in the former case while PEQ emission has significant contribution for the latter.

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**References**
