

Excitation Functions of Proton-Induced Reactions on ^{209}Bi up to 200 Mev

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Abstract The excitation functions of $^{209}\text{Bi}(p,n)^{209}\text{Po}$ and $^{209}\text{Bi}(p,2n)^{208}\text{Po}$ reactions for the production of radio nuclides $^{208,209}\text{Po}$ were evaluated by nuclear model calculations in the 1-200 MeV energy range. The nuclear model codes used for these reactions are ALICE-91, EMPIRE-3.1 and TALYS-1.8. The codes deal with three major nuclear reaction mechanisms including, direct, pre-equilibrium and compound reaction mechanism. The computed excitation functions of these reactions have been compared graphically with available experimental data and the evaluated nuclear data files.

Keywords: Pre-equilibrium emission; hybrid Model; evaporation model; Hauser Feshbach theory; Cluster emission.

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1. Introduction

Nuclear model calculations play a significant role for the evaluation of the cross-sections and excitation functions related to nuclear reactions even when experimental data are available. Proton induced excitation functions are important for medical radio isotope production, spallation neutron source, shield design for nuclear facilities, technology development of an

accelerator driven system and for transmutation of nuclear waste. Nucleon induced reactions are also studied to test and verify different nuclear reaction model codes¹⁻³.

In the present work we have calculated the excitation functions of $^{209}\text{Bi}(p,n)^{209}\text{Po}$ and $^{209}\text{Bi}(p,2n)^{208}\text{Po}$ reactions for 1-200 MeV energy using the nuclear reaction model codes like EMPIRE-3.1, ALICE-91 and TALYS 1.8. The computed excitation functions with these codes have been compared with the experimental data wherever available and evaluated nuclear data (ENDF) files⁴ to validate the computational models and algorithms.

2. Calculations Using Nuclear Reaction Model Codes

We have used the codes ALICE-91, EMPIRE-3.1 and TALYS-1.8 with various input options related to different level densities and reaction mechanisms for the present study to evaluate the suitability of different level density options and reaction mechanism to be incorporated.

ALICE-91: The ALICE-91 code⁵⁻⁷ calculates pre-equilibrium (PEQ) cross-sections using geometry dependent hybrid (GDH) model and evaporation through Weisskopf–Ewing (WE) formalism. The geometry dependent hybrid model is the modified version to include the effect of diffuse nuclear surface. In the ALICE code we have used Fermi gas level density and optical model inverse cross-section. The following input parameters used in the code:

- (a) ALICE1: LEVEL DENSITY OPTION LDOPT=0, MP=0 i.e., Using Fermi Gas level density along with no pairing term in masses.
- (b) ALICE2: LEVEL DENSITY OPTION LDOPT=0, MP=1 i.e., Using Fermi Gas level density along with invoking pairing term in masses applied back shifted, here level density ground state calculated from Myers Swiatecki Lysekil (msl) mass formula.
- (c) ALICE3: LEVEL DENSITY OPTION LDOPT=0, MP=2 i.e., Using Fermi Gas level density along with invoking pairing term in masses applied back shifted, here level density ground state calculated from Myers Swiatecki Lysekil (msl) mass formula with shell correction included.
- (d) ALICE4: LEVEL DENSITY OPTION LDOPT=0, MP=3 i.e., Using Fermi Gas level density along with normal pairing shift in masses.
- (e) ALICE5: LEVEL DENSITY OPTION LDOPT=1, MP=0 i.e., Using Kataria Ramamurthy formula for level density with shell correction due

to difference of experimental mass and liquid drop correction along with no pairing term in masses.

EMPIRE3.1: The EMPIRE-3.1⁸ is a nuclear reaction code which includes major nuclear reaction mechanisms, direct, pre-equilibrium (PEQ) and compound nuclear reactions. The secondary compound nuclei (CN) are formed due to subsequent particle emission. Binding energies are computed using masses recommended by Audi and Wapstra⁹, whenever available, otherwise theoretical value given by Moller and Nix¹⁰ are used. The code uses several PEQ models like PCROSS, Hybrid Monte-Carlo Simulation (HMS), multistep direct (MSD) and multistep compound (MSC) to the emission of nucleons and the statistical Hauser–Feshbach theory to describe the EQ (compound nuclear) emissions along with different level density options. We have used the following input options of the code:

- (a) EMPIRE1 (LEVDEN=0 HMS=0 PCROSS=1.5 and MSC+MSD=0): Empire specific level densities (EGSM) have been used using PCROSS Pre-equilibrium model.
- (b) EMPIRE2 (LEVDEN=0 HMS=1 PCROSS=1.5 and MSC+MSD=0): Empire specific level densities (EGSM) have been used along with HMS and PCROSS Pre-equilibrium models.
- (c) EMPIRE3 (LEVDEN=0 HMS=0 PCROSS=0 and MSC+MSD=1): Empire specific level densities (EGSM) have been used along with MSC and MSD Pre-equilibrium models.
- (d) EMPIRE4 (LEVDEN=1 HMS=0 PCROSS=1.5 and MSC+MSD=0): Generalized super fluid Model level densities (GSM) have been used using PCROSS Pre-equilibrium model.
- (e) EMPIRE5 (LEVDEN=1 HMS=1 PCROSS=1.5 and MSC+MSD=0): Generalized super fluid Model level densities (GSM) have been used along with HMS and PCROSS Pre-equilibrium models.
- (f) EMPIRE6 (LEVDEN=1 HMS=0 PCROSS=0 and MSC+MSD=1): Generalized super fluid Model level densities (GSM) have been used along with HMS and PCROSS Pre-equilibrium models.

TALYS1.8: TALYS¹¹ is a computer code system which simulates reactions for gamma rays, neutrons, deuterons, protons, tritons, alpha particles and helions as projectiles for the energy range 1 keV to 200 MeV. Pre-equilibrium reaction mechanism is simulated in the framework of two-component exciton model for particle emission. PEQ particle-cluster emission and PEQ gamma emission are also considered. Compound nuclear emission is calculated in the framework of the statistical theory. Direct

reactions are calculated using spherical optical model, DWBA, rotational or vibrational coupled in competition to fission yield. The optical model plays a central role to simulate nuclear reaction calculations. We have used following option of the code:

TALYS: Pre-Eqmode =2, Exciton model, numerical transition rates with energy dependent matrix element: Pairmodel =1, Fu's pairing energy correction.

3. Results and Discussions

The computed excitation functions of $^{209}\text{Bi}(p, n)^{209}\text{Po}$ and $^{209}\text{Bi}(p, 2n)^{208}\text{Po}$ reactions have been shown in Figs. 1-4 along with the available measured data¹²⁻¹⁷ and (ENDF) files. In the reaction $^{209}\text{Bi}(p, n)^{209}\text{Po}$, two sets of measured excitation function vary by a factor of 2-3 above 20 MeV proton energy. Upto 18 MeV projectile energy TALYS and EMPIRE calculations reproduce the measured data well but at higher energies the measurements of Miyano & Nakahara (1973) agree well with EMPIRE2, EMPIRE5 and TALYS calculations. (Reduced χ^2 - test also shows goodness of fit). Though we are investigating (p, n) reaction here, but competition from PEQ cluster emission channel has significantly influenced the cross section of (p, n) reaction channel. The other sets of calculations (EMPIRE1, 3, 4, 6) have under predicted both sets of experimental data. While EMPRE1 and 4 do not consider any PEQ neutron emission, EMPIRE3 and 6 with PEQ contributions from (MSD+MSC) somewhat under predict experimental data.

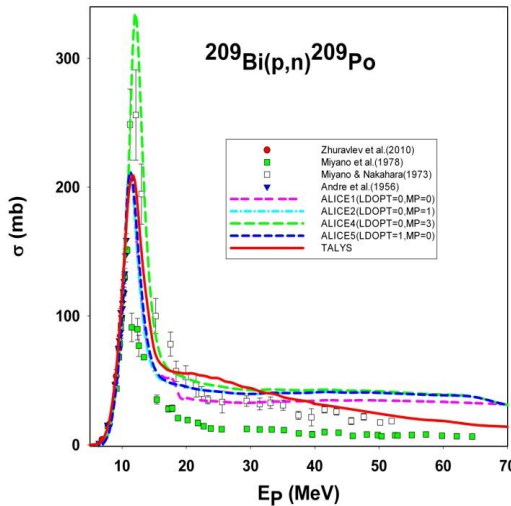


Figure 1: Excitation Functions of ^{209}Po

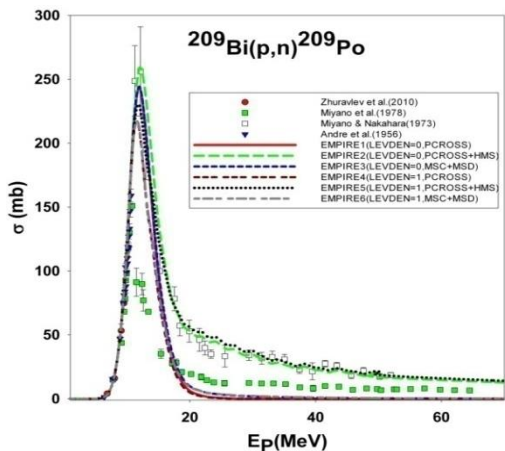


Figure 2: Excitation Functions of ^{209}Bi from p + reaction using ALICE and ^{209}Po from p + ^{209}Bi reaction using TALYS codes

EMPIRE code: All the calculated results using the ALICE code (figure1) reproduce available experimental data well up to about 10 MeV but over predict both sets of measured data above 40 MeV incident energy and also give a larger value of the excitation function peak at 16 MeV.

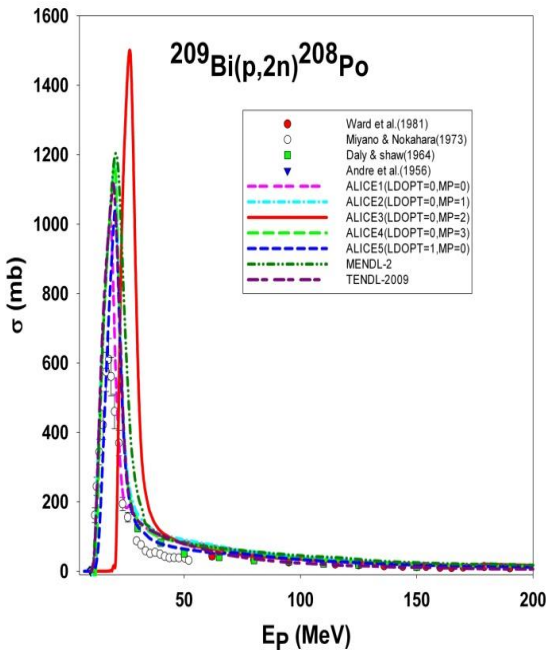


Figure 3: Excitation Functions of ^{208}Po

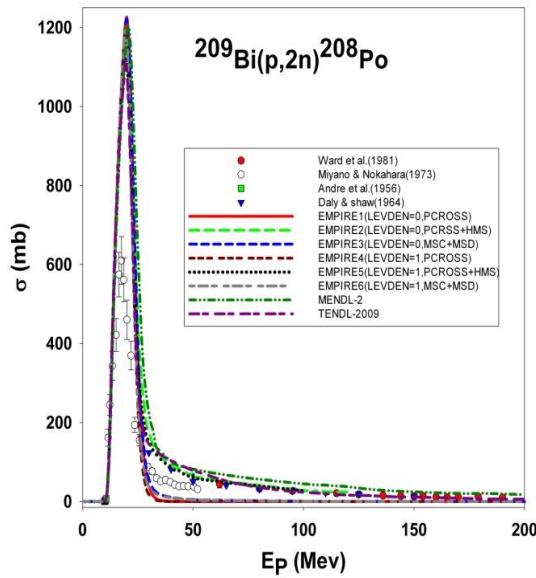


Figure 4: Excitation Functions of ^{208}Po from $p + ^{209}\text{Bi}$ reaction using ALICE code.
 $p + ^{209}\text{Bi}$ reaction using EMPIRE code.

For the production of ^{208}Po from $p + ^{209}\text{Bi}$ results are shown in Figures 3 and 4. Measured cross section by Miyano & Nakahara (1973) is reproduced by all the EMPIRE calculations and TENDL-2009 cross sections. But at higher energies this set of experimental data is over predicted by MENDL-II, TENDL-2009, EMPIRE 2 & 5 calculations, while the other set of measured data by Daly and Shaw (1964) agrees well with these calculations and evaluated data set. EMPIRE 2 & 5 upto 115 MeV energy range are in good agreement with available experimental data. In Fig.4 it is observed that the ALICE 3 fails to produce any agreement with the formation cross section of ^{208}Po upto 50 MeV. Other ALICE calculations agree with the measured data of Miyano & Nakahara (1973) upto 15 MeV and that of Daly and Shaw (1964) above 25 MeV. ALICE results also show agreement with Ward et al. (1981) and Andre et al. (1956).

4. Summary and Conclusions

The cross sections of $^{209}\text{Bi}(p, n)^{209}\text{Po}$ and $^{209}\text{Bi}(p, 2n)^{208}\text{Po}$ reactions have been calculated for 1-200 MeV energy. The computed excitation functions with EMPIRE, ALICE and TALYS show agreement with measured data in lower energy range which validates Hauser Feshback and Weisskoff Ewing formalism.

At high energies above 20 MeV pre equilibrium model HMS along with PCROSS which gives cluster emission shows good agreement due to pre equilibrium effect dominate in this region for ^{209}Bi in proton induce reactions, whereas ALICE results produce agreement with the formation cross section of ^{208}Po only for energy range above 50 MeV, from which it can be concluded that PEQ models have significant contributions and therefore are important to be included in the nuclear reaction model calculations .

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