EPJ Web of Conferences **100**, 01003 (2015)
DOI: 10.1051/epjconf/201510001003

Fission cross section calculations for ^{209}Bi target nucleus based on fission reaction models in high energy regions

Abdullah Kaplan[1,a], Veli Capali[1] and Hasan Ozdogan[1,2]

[1]*Süleyman Demirel University, Faculty of Arts and Sciences, Department of Physics, 32260 Isparta, Turkey*
[2]*Akdeniz University, Faculty of Medicine, Department of Biophysics, 07058 Antalya, Turkey*

Abstract. Implementation of projects of new generation nuclear power plants requires the solving of material science and technological issues in developing of reactor materials. Melts of heavy metals (Pb, Bi and Pb-Bi) due to their nuclear and thermophysical properties, are the candidate coolants for fast reactors and accelerator-driven systems (ADS). In this study, α, γ, p, n and ^{3}He induced fission cross section calculations for ^{209}Bi target nucleus at high-energy regions for (α,f), (γ,f), (p,f), (n,f) and (^{3}He,f) reactions have been investigated using different fission reaction models. Mamdouh Table, Sierk, Rotating Liquid Drop and Fission Path models of theoretical fission barriers of TALYS 1.6 code have been used for the fission cross section calculations. The calculated results have been compared with the experimental data taken from the EXFOR database. TALYS 1.6 Sierk model calculations exhibit generally good agreement with the experimental measurements for all reactions used in this study.

1 Introduction

Melts of heavy metals (Pb, Bi and Pb−Bi), due to their nuclear and thermophysical properties, are candidate coolants for fast reactors and accelerator-driven systems (ADS) [1]. A design methodology for the lead-bismuth eutectic spallation target has been developed and applied for the accelerator-driven test facility target. This methodology includes the target interface with the subcritical multiplier of the ADS and the different engineering aspects of the target design, physics, heat-transfer, hydraulics, structural, radiological, and safety analyses. Several design constrains were defined and utilized for the target design process to satisfy different engineering requirements and to minimize the time and the cost of the design development. Interface requirements with the subcritical multiplier were defined based on target performance parameters and material damage issues to enhance the lifetime of the target structure [2].

Nucleon-induced fission cross-section data are important for the nuclear reactors. Firstly, fission reactions may have a significant effect on spallation target performance. In particular, fission may contribute notably to the production of radioactive materials in the target. On the other hand, the predictive power of available nuclear reaction models and codes with respect to the description of the fission process should be developed.

Fission can be induced not only by neutrons, but also by protons, light and heavy ions, photons, electrons, π-mesons etc. In this study, α, γ, p, n and ^{3}He induced fission cross section calculations for ^{209}Bi target nucleus at high energy regions for (α,f), (γ,f), (p,f), (n,f) and (^{3}He,f) reactions have been investigated using four fission reaction models. TALYS 1.6 Theoretical fission barriers; Mamdouh Table, Sierk, Rotating Liquid Drop and Fission Path models have been used for the fission reactions. The calculated results have been compared with the experimental data taken from the EXFOR [3] database.

2 Methods

TALYS [4, 5] is a nuclear reaction simulation code for the estimation and analysis of nuclear reactions that include protons, neutrons, photons, tritons, deuterons, ^{3}He and alpha particles in the energy range of 1 keV–1 GeV. For this, TALYS integrates the optical model, direct, pre–equilibrium, fission and statistical nuclear reaction models in one calculation scheme and thereby gives a prediction for all the open reaction channels. In TALYS, several options are included for the choice of different parameters such as γ-strength functions, nuclear level densities and nuclear model parameters.

The probability that a nucleus fissions can be estimated by TALYS on both phenomenological and microscopic grounds. Cross sections for (multi-chance) fission can be calculated. For this, various nuclear quantities are required. A fission model has been developed by Schmidt-Jurado [6]. It is based on the statistical population of states in the fission valleys at the moment of dynamical freeze-out, which is specific to each collective degree of freedom. Three fission channels are considered. The separability principle governs the interplay of macroscopic and microscopic effects.

---

[a] Corresponding author: abdullahkaplan@sdu.edu.tr

In the Sierk fission barrier model, fission barrier heights are estimated in MeV with Sierk's method using the rotating finite range model. It is dependent upon calculations using exact Coulomb diffuseness corrections, diffuse-matter moments of inertia, and Yukawa-plus-exponential double folded nuclear energy [7]. Additional details on the model parameters and options of TALYS codes can be found in Refs. [5].

Sierk approximates the partial widths Γ_j for the emission of a particle j ($j \equiv n, p, d, t, {}^3He$) and Γ_f for fission by the expression

$$\Gamma_j = \frac{\left(2s_j+1\right)m_j}{\pi^2\rho_c\left(U_c\right)} \int_{V_j}^{U_j-B_j} \sigma_{inv}^j\left(E\right)\rho_j\left(U_j-B_j-E\right)EdE \qquad (1)$$

$$\Gamma_f = \frac{1}{\pi^2\rho_c\left(U_c\right)} \int_0^{U_j-B_j} \rho_j\left(U_j-B_j-E\right)EdE \qquad (2)$$

where ρ_c, ρ_j, and ρ_f are the level densities of the compound nucleus, the residual nucleus produced after the emission of the j-th particle, and of the fissioning nucleus at the fission saddle point, respectively; m_j, s_j and B_j are the mass, spin and the binding energy of the j-th particle, respectively, and B_f is the fission-barrier height. $\sigma_{inv}(E)$ is the inverse cross section for absorption of the j-th particle with kinetic energy E by the residual nucleus. The "thermal" energies U_c are defined by

$$\begin{aligned} U_c &= E^* - E_R^C - \Delta_J \\ U_j &= E^* - E_R^j - \Delta_j \\ U_f &= E^* - E_R^{sp} - \Delta_J \end{aligned} \qquad (3)$$

where E^* is the total excitation energy of the compound nucleus. For the fission cross sections, the approximations proposed by Sierk [8] are

$$\sigma_{inv}^j\left(E\right) = \sigma_{geom}^j\alpha_j\left(1+\frac{B_j}{E}\right) \qquad (4)$$

where

$$\sigma_{geom}^j = \pi R_j^2; \quad R_j = \tilde{r}_0 A_{fj}^{1/3}; \quad \tilde{r}_0 = 1,5\, fm \qquad (5)$$

and

$$\sigma_f = \frac{\sigma_{in}}{N_{in}}\sum_{i=1}^{N_{in}}\left(W_f\right)_i \qquad (6)$$

where σ_f is the total fission cross section.

3 Results

In the present study, fission reaction cross sections of ^{209}Bi(α,f), ^{209}Bi(γ,f), ^{209}Bi(^{3}He,f) ^{209}Bi(n,f) and ^{209}Bi(p,f) reactions have been calculated for the energy range of 1 MeV to 1 GeV incident energy using different fission reactions models of TALYS 1.6 computer codes. The fission reaction cross sections exhibited by (*,f) reactions for ^{209}Bi target nuclei have been plotted as a function of different incident particle energy in Figs. 1-5. All the experimental values used in this study have been taken from the EXFOR library.

The calculated cross sections of ^{209}Bi target nucleus for (α,f) reaction have been compared with the experimental values in Fig. 1. All model calculations are harmony with the experimental data but they are lower than the experimental values. The TALYS 1.6 Sierk model calculations lower than the experimental data of Penionzkevich *et al.* [9].

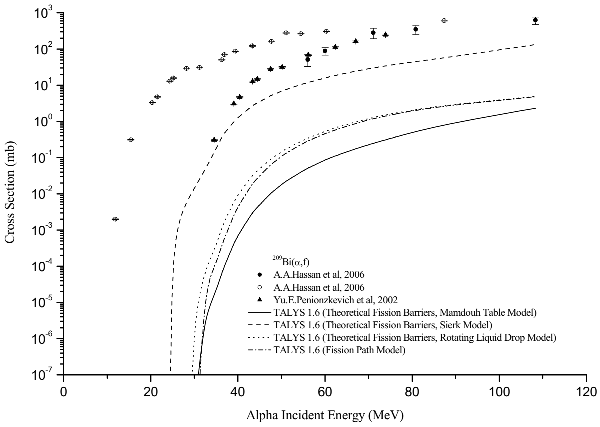

Figure 1. The comparison of calculated alpha-fission cross sections of ^{209}Bi(α,f) reaction with the experimental values taken from the EXFOR.

The ^{209}Bi(γ,f) photo-fission reaction cross section calculations have been compared with the experimental data in Fig. 2. The experimental values are higher than the all model calculations. The TALYS 1.6 Sierk model calculations are in good agreement with the experimental data in the gamma energy range of 30 – 175 MeV.

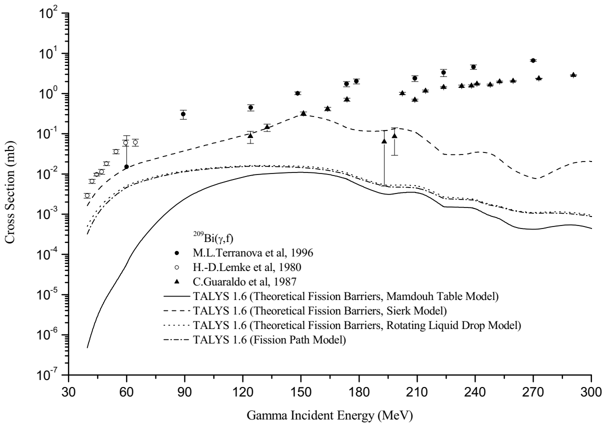

Figure 2. The comparison of calculated photo-fission cross sections of ^{209}Bi(γ,f) reaction with the experimental values taken from the EXFOR.

The ^{209}Bi(^{3}He,f) reaction calculations have been compared with the experimental data in Fig. 3. All the calculations show a similar structure with the experimental values but they are lower than the experimental results.

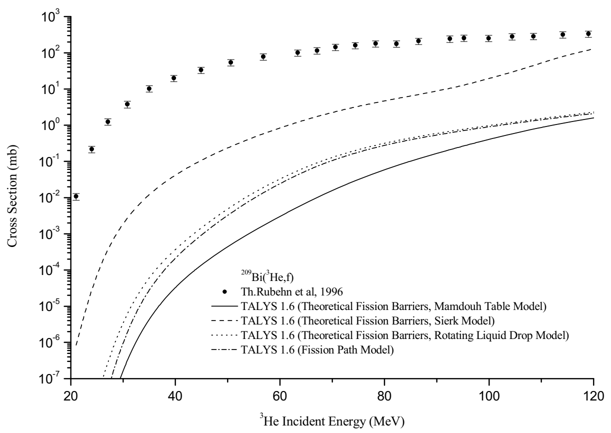

Figure 3. The comparison of calculated helium3-fission cross sections of ^{209}Bi(^{3}He,f) reaction with the experimental values taken from the EXFOR.

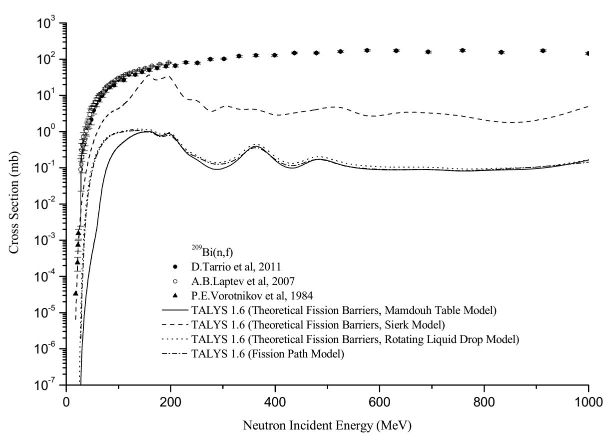

Figure 4. The comparison of calculated neutron-fission cross sections of ^{209}Bi(n,f) reaction with the experimental values taken from the EXFOR.

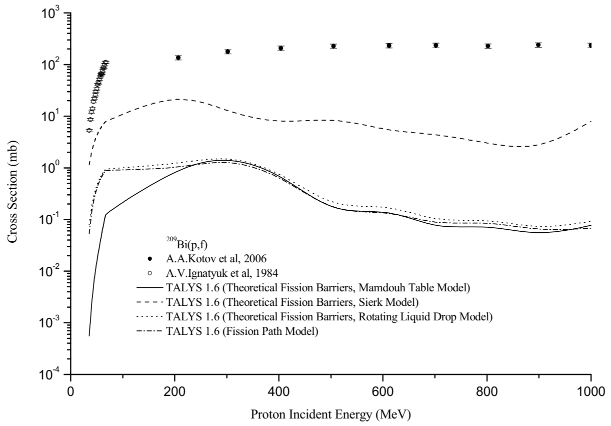

Figure 5. The comparison of calculated proton-fission cross sections of ^{209}Bi(p,f) reaction with the experimental values taken from the EXFOR.

The calculated cross sections of ^{209}Bi target nucleus for (n,f) and (p,f) reactions in the neutron incident energy range of 1 MeV to 1 GeV have been compared with the experimental values in Figs. 5 and 6. All model calculations give similar geometry with the EXFOR data but they are lower than the experimental results.

In general all figures show the fission models give the same geometry with the experimental data but they give lower results than EXFOR data. It can be possible to obtain the better agreement with experimental cross section data using several different adjustments of the available parameters. The obtained ^{209}Bi cross section results for the projectile charged particles can be used in several applications such as fission reactor design and cooling.

References

1. Comparative assesstment of thermophysical and thermohydraulic characteristics of lead, lead-bismuth and sodium coolants for fast reactors / IAEA-TECDOC-1289. Vienna, p. 72 (2002)

2. Y. Gohar, et al., Argonne National Laboratory Report, ANL/TD/02-01 (2002)

3. Brookhaven National Laboratory, National Nuclear Data Center, EXFOR/CSISRS (Experimental Nuclear Reaction Data File). Database Version of February 05, 2015 (2015), (http://www.nndc.bnl.gov/exfor/).

4. A. Koning, S. Hilaire, S. Goriely, TALYS-1.6 A Nuclear Reaction Program, User Manual (NRG, The Netherlands), First Edition: December 23, 2013 (2013)

5. A.J. Koning, S. Hilaire, M.C. Duijvestijn, TALYS: Comprehensive Nuclear Reaction Modeling. In: R. C. Haight, M. B. Chadwick, T. Kawano, P. Talou (eds), Proceedings of the International Conference on Nuclear Data for Science and Technology-ND 2004, AIP vol 769. Santa Fe, USA, 1154 (2005)

6. K.H. Schmidt and B. Jurado, Phys. Rev. C **82** (2011)

7. A.J. Sierk, Phys. Rev. C **33**, 2039 (1986)

8. A.J. Sierk and S.G. Mashnik, Fourth Workshop on Simulating Accelerator Radiation Environments, 9812070v1, (1998)

9. Yu.E., et al., Eur. Phys. J. A **13**, 123 (2002)