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Analysis of Double Differential Cross Section for Neutron Induced and Neutron Emission Reaction of ^{209}Bi Isotope

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Abstract

The double-differential cross sections (DDX) of neutron induced and neutron emission reaction of ^{209}Bi isotope are calculated and analysed at neutron emission energies below 7 MeV at 3 laboratory angles between 20^0 and 150^0 . In the calculations, the latest version of Talys 1.96 is utilized to calculate the total, direct, pre-equilibrium and compound cross sections, which are obtained using the same parameters. The contributions of direct, pre-equilibrium and compound processes to the total cross section are separately investigated. It is presented that the compound part has the greatest contribution. The calculation results are compared with the existing experimental data taken from EXFOR library.
Keywords: ^{209}Bi , DDX, neutron emission reaction, neutron induced reaction, Talys 1.96

^{209}Bi İzotopunun Nötron ile İndüklenmiş ve Nötron Emisyon Reaksiyonu için Çift Diferansiyel Tesir Kesiti Analizi

Özet

^{209}Bi izotopunun nötron ile indüklenen ve nötron yayınlayan reaksiyonuna ait çift diferansiyel tesir kesiti değerleri (DDX) hesaplanmıştır ve 7 MeV altında nötron yayma enerjilerinde 20^0 ve 150^0 arasındaki 3 laboratuvar açısında analiz edilmiştir.Hesaplamalarda, aynı parametreler kullanılarak elde edilen toplam, direkt, denge-öncesi ve bileşik tesir kesitleri Talys 1.96 son versiyonukullanılarak elde edilmiştir. Direkt, denge-öncesi ve bileşik süreçlerin toplam tesir kesitine katkıları ayrı ayrı incelenmiştir. Bileşik kısmın en büyük katkıya sahip olduğu sunulmuştur. Hesaplama sonuçları EXFOR kütüphanesinden alınan deneysel veriler ile karşılaştırılmıştır.

Anahtar Kelimeler: ^{209}Bi , DDX, nötron ile indüklenen reaksiyon, nötron yayma reaksiyonu, Talys 1.96

INTRODUCTION

There are many ways to describe the interplay between incident particles and target nuclei. The three major mechanisms of a nuclear reaction are preequilibrium, direct, and compound processes. The compound process dominates the emission of particles induced such as proton, neutron, triton, alpha etc. up to 8 MeV, direct and pre-equilibrium processes are dominant at higher particle emission energies. The compound is also created through the pre-equilibrium and direct processes. All mechanisms can contribute to the capture of a light charged particle. Therefore, the total DDX is generally taken account as the sum of these contributions (Demir et al.,2015; Sarpün et al.,2016; Rajput et al.,2018).

To understand these contributions in detail, light charged particles induced reactions can be analysed. The DDX have been studied by many groups both experimentally (Lalremruata et al.,2009; Kondo et al.,2007; Marcinkowski et al.,1991) and theoretically (Han, 2006; Zhang et al.,2010). Especially, neutron induced nuclear reactions can be selected to characterize the reaction mechanisms and analyze the nuclear structure with constraints on nuclear models. The nuclear data and their analysis for neutron induced reactions are required in many fields of nuclear technology, industry, medicine etc.

In this study, for ^{209}Bi(n,2n)^{208}Bi reaction, total, direct, compound, pre-equilibrium DDX are calculated at three laboratory angles and compared with the experimental data (Schröder et al.,1978)studied with two time-of flight detectors.A neutron detector responds depend on the energy of neutron.The experimental definition of detector

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response functions is determined at facilities which are produced monoenergetic neutrons. These neutrons are obtained in the energy range from 120 keV to 20 MeV for widely used nuclear reactions.^{209}Bi is a single quasi stable isotope of bismuth, an alpha emitter with a half-life of $1.9x10^{19}$ years (De Marcillac et al.,2003) and the heaviest of all radioactively stable isotopes. It is near magical in terms of the number of protons (Z=83) and magical in terms of the number of neutrons (N=126). It is the end point of the s process path and its abundance is known as sprocess component in the He-shell (Travaglio et al.,2001).Bismuth is also used with lead (Fazio et al.,2008) in the neutron activation studies for the advanced nuclear reactors (Semkova et al.,2009;Toshinsky et al.,2012).Therefore, ^{209}Bi is used as a target material. Talys 1.96 computer code is used for the calculations. It is chosen because of its success and usefulness in the simulation of nuclear reactions. TheKalbach-Mann systematics (Kalbach and Mann, 1981; Kalbach, 1982) arepreferred for DDX calculations in the code because of play an important role in the pre-equilibrium reaction studies.For compound and direct processes, Hauser-Feshbach,exciton model, and optical model parameters are used (Hauser and Feshbach, 1952;Koning and Delaroche, 2003). There are many theoretical studies (Yiğit, 2021; Özdoğan et al., 2021a; Sadeghi et al., 2010; Kara et al., 2021; Şekerci et al., 2020; Kaplan et al., 2015; Kaplan et al., 2013; Özdoğan, 2021; Küçüksucu et al., 2022; Özdoğan et al., 2021b; Canbula, 2021; Canbula, 2017; Canbula, 2020) using Talys computer code for neutron induced or neutron emission nuclear reactions in the literature.

The rest of this paper is arranged as follows: In section Material and Methods, we give ourcalculation method. In section Results and Discussion, we represent our results and their discussions. Finally in section Conclusions, we present some concluding remarks.

MATERIAL AND METHODS

The calculations are performed with Talys computer code (Koning et al.,2021).It is a program using the simulation of nuclear reactions. It enables us todescribe all reaction channels and takes into account all types of reaction mechanisms to determine the total cross section probability. One of the major purpose of Talys is to determine all of answers for all open channels of a nuclear reaction,and associated with the cross sections.

A powerful phenomenological approach Kalbach formula (Kalbach, 1988) is preferred to calculate the DDX for light charged particle based on a systematical work on a wide range of data. This approach is only based on experimental knowledge and a pre-equilibrium process consists of a multistep compound and multistep direct parts. The DDX for a projectile a and an ejectile b is given below

$$\frac{d^2\sigma_{a,xb}}{dE_b\, d\Omega} = \frac{1}{4\pi}\left[\frac{d\sigma^{PE}}{dE_b} + \frac{d\sigma^{comp}}{dE_b}\right]\frac{a}{\sinh(a)}\left[\cosh(a\cos\theta) + f_{MSD}(E_b)\sinh(a\cos\theta)\right] \quad (1)$$

where $\frac{d\sigma^{PE}}{dE_b}$is the angle integrated preequilibrium, and $\frac{d\sigma^{comp}}{dE_b}$is compound spectra. θ is the emission angle in the center of mass frame. f_{MSD} is named multistep direct or preequilibrium ratio and given as

$$f_{MSD}(E_b) = \frac{d\sigma^{PE}}{dE_b} / \left[\frac{d\sigma^{PE}}{dE_b} + \frac{d\sigma^{comp}}{dE_b}\right] \quad (2)$$

which increases from 0 at low emission energy to 1 at the highest energies. E_b is the outgoing energy. The DDX preequilibrium can be defined as

$$\frac{d^2\sigma^{PE}_{a,xb}}{dE_b\, d\Omega} = \frac{1}{4\pi}\frac{d\sigma^{PE}}{dE_b}\frac{a}{\sinh(a)}\exp(a\cos\theta) \quad (3)$$

The compound cross section σ^{comp} which is the basic feeding term for preequilibrium, is given by

$$\sigma^{comp} = \sigma_{tot} - \sigma_{direct} \quad (4)$$

where σ_{tot} is the total cross section and directly provided from the optical model. The direct reaction cross section σ_{direct} is the sum of the cross sections to discrete states $\sigma_{disc,direct}$ defines as

$$\sigma^{disc,direct} = \sum_i \sum_{k=p,n,t,d,\alpha,h} \sigma^{i,direct}_{n,k} \quad (5)$$

where p,n,t,d,α,h(proton, neutron, triton, deuteron, alpha, helium) are light ions.

RESULTS AND DISCUSSION

In this study, DDX of ^{209}Bi(n,2n)^{208}Bi reaction is calculated by using Talys computer code below 7MeV neutron energy at laboratory angles 20^0, 90^0, and 150^0. Since the cross section results are very close to each other at the intermediate angles, the results at low, medium and high angles are studied. The predicted results at these angles are compared with

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the existing experimental data (Schröder et al.,1978) taken from Exfor (EXFOR) library in Figs. 1-3.

The comparison of predictions and experimental data at 20^0 laboratory angle are shown in Figure 1. The compound cross section makes the biggest contribution to the total cross section. Although, direct and pre-equilibrium cross sections increases when compound cross section decreases at increasing energies. The preequilibrium cross section becomes more dominant than compound cross section at the emission energy range between 5-7 MeV. The calculated total DDX is in agreement with the experimental data at 20^0 laboratory angle. Figure 2 shows the comparison of obtained DDXs with the experimental data at 90^0 laboratory angle.

The neutron particles up to the most probable energies are dominantly emitted through the compound process whereas the higher energy neutron particles are mostly emitted through the preequilibrium and direct processes. The predicted total cross section deviates a little from the experimental data at increasing energies.

In Figure 3, calculations of DDXs are performed at 150^0 laboratory angle and are compared with the data. The dominant effect of the compound process is clearly seen in this reaction as well. The total DDX is in good agreement at all energy region, especially after 3 MeV compared to the other Figures.

CONCLUSION

In summary, we aim to calculate and analyze the DDX of ^{209}Bi(n,2n)^{208}Bi reaction at several laboratory angles. The following concluding remarks can be written from this work:

- The predictions provide reasonable distributions of double-differential cross section with neutron emission energies for selected laboratory angles.
- For all laboratory angles, compound contribution is the most dominant from the other contributions (preequilibrium and direct).
- The calculated total differential cross section reproduce the experimental data quite well after 3 MeV neutron emission energy for 20^0 and 150^0 laboratory angles.
- The direct double differential cross section shows the least contribution to the total up to around 6 MeV neutron emission energy at all laboratory angles.
- It is observed from the figures that, direct reaction cross sections have two peaks, however compound reaction cross sections have a smooth behavior at all laboratory angles.
- The direct process contribution has sharper and higher peaksat increasing laboratory angles.

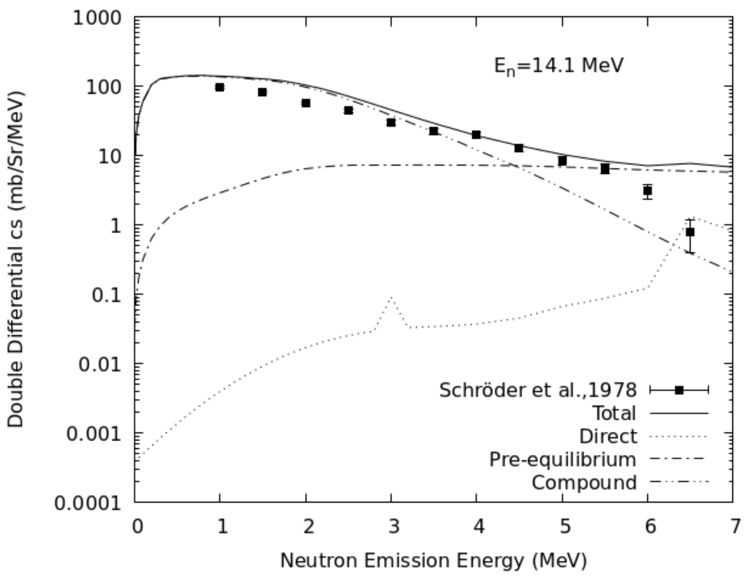

Figure 1. The comparison of DDX of ^{209}Bi (n,2n) ^{208}Bi reaction with the experimental data at 20^0 laboratory angle

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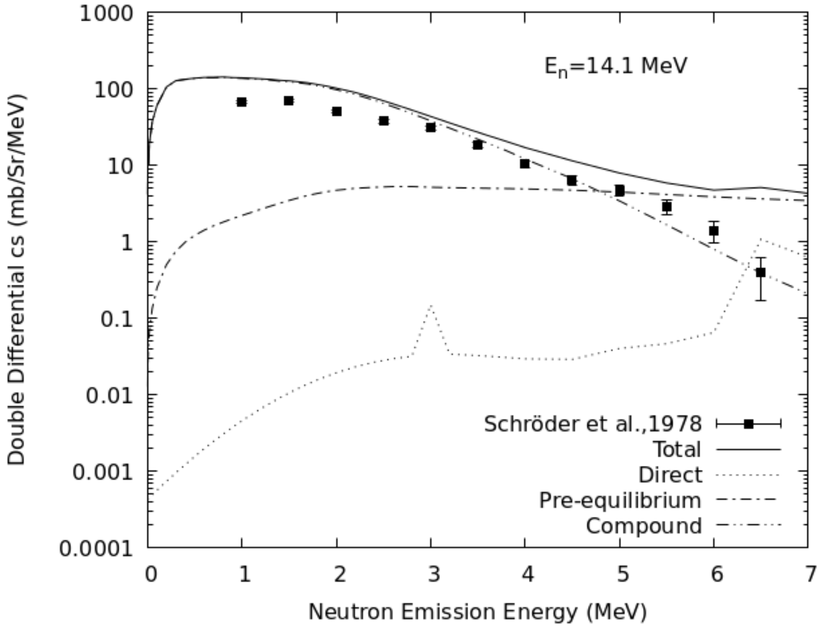

Figure 2. The comparison of DDX of ^{209}Bi (n,2n) ^{208}Bi reaction with the experimental data at 90^0 laboratory angle

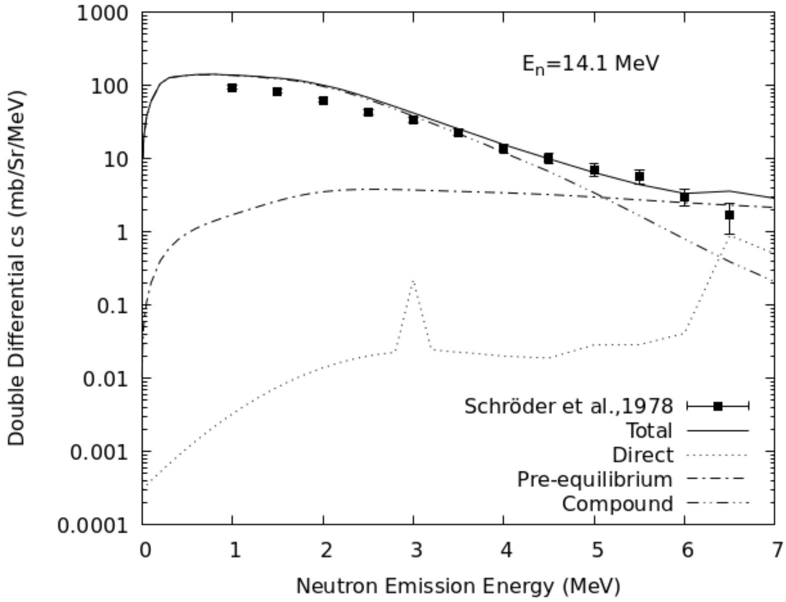

Figure 3. The comparison of DDX of ^{209}Bi (n,2n) ^{208}Bi reaction with the experimental data at 150^0 laboratory angle

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

RESEARCH AND PUBLICATION ETHICS STATEMENT

The author declares that this study complies with research and publication ethics.

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