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RESEARCH ARTICLE

A STUDY ON THE CALCULATIONS OF CROSS–SECTIONS FOR ^{66,67}Ga AND ^{75}Se RADIONUCLIDES PRODUCTION REACTIONS VIA ^{3}He PARTICLES

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ABSTRACT

The intend of this paper is to study on different production routes of medical ^{66,67}Ga and ^{75}Se radionuclides used in cancer diagnostic. Both ^{66,67}Ga and ^{75}Se are the most well-known radionuclides used in diagnostics of malignant and benign tumors also brain studies and scintigraphy scanning. For this purpose, production cross–section calculations of medical ^{66,67}Ga and ^{75}Se radionuclides have been calculated for ^{64}Zn(^{3}He,p)^{66}Ga, ^{65}Cu(^{3}He,2n)^{66}Ga, ^{65}Cu(^{3}He,n)^{67}Ga, ^{66}Zn(^{3}He,n+p)^{67}Ga, ^{69}Ga(^{3}He,n+α)^{67}Ga, ^{76}Se(^{3}He,α)^{75}Se, ^{77}Se(^{3}He,n+α)^{75}Se reactions. In the calculations, TALYS 1.8 and ALICE/ASH computer codes have been used. The models which have been employed within the calculations are Two Component Exciton and Equilibrium of TALYS 1.8 and Hybrid and Geometry Dependent Hybrid of ALICE/ASH. The results obtained from the calculations for each reaction have been compared with other calculation results and previously recorded experimental values collected from the Experimental Nuclear Reaction Data (EXFOR) library.

Keywords: ^{3}He induced reaction; ALICE/ASH code; radionuclide production; TALYS 1.8 code

1. INTRODUCTION

According to one of the reports published by World Health Organization (WHO), 8.2 million people around the world die from cancer. The number of deaths is predicted to increase from 8.2 million annually to 13 million per year. The number of 8.2 million could be specified as the following cancer types and rates; lung 19 %, liver 0.09 %, stomach 0.088 %, colorectal 0.085 %, breast 0.064 % and esophageal 0.049 % [1]. Scientists have developed various methods for cancer therapy and diagnostics. Some methods employed in cancer therapy could be given as chemotherapy, immunotherapy, radiation therapy and photodynamic therapy while magnetic resonance imaging, computerized axial tomography, positron emission tomography and radiography could be given as the examples of employed methods in diagnostic studies. ^{66,67}Ga and ^{75}Se are some of the most well-known radionuclides used in cancer diagnostics.

^{67}Ga, which has 78 hours of half-life and mostly produced via cyclotrons, used for tumour imaging and locating inflammatory lesions also for osteomyelitis detection, evaluation of sarcoidosis and other granulomatous diseases particularly in lungs and mediastinum by employing either a gamma camera or a Single Photon Emission Computerized Tomography (SPECT) camera. In addition, it is possible to use a hybrid machine known as SPECT/CT (computerized tomography) [2, 3]. On the other hand, ^{75}Se has been using as radiotracer in brain studies and scintigraphy scanning. Also, for some situations it may preferred due to its long half-life advantage, which is 120 days [2, 4].

The term reaction cross–section can basically be explained as the possibility of a nuclear reaction. The investigation of this quantity has critical importance on many topics such as, to avoid from unexpected

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nuclear reaction outcomes, to keep material development process and to evaluate radioisotope production routes. Experimental difficulties or lack of the experimental data can lead to the emergence of the theoretical calculations for many occurrences. For such similar situations, experts have developed various computer softwares in where different theoretical nuclear reaction models have been included to be able to obtain different quantities such as nuclear reaction cross–section, spectrum of out-going particles and dose calculations [5-11].

This paper focused on the calculations of production cross–sections for the ^{66,67}Ga and ^{75}Se radionuclides via ^{3}He induced nuclear reactions. TALYS 1.8 [12] code's Two-Component Exciton (TCE) [13] and Equilibrium [14] models have been used while ALICE/ASH [15] code's Hybrid [16] and Geometry Dependent Hybrid (GDH) [17] models have been utilized between the energy range from 8.1 to 69.4 MeV. Values obtained as a result of calculations for each reaction have been compared with each other and previously recorded experimental values collected from the Experimental Nuclear Reaction Data (EXFOR) library [18].

2. MATERIAL and METHODS

The TALYS computation code, which serves in the energy interval from 1 keV to 1 GeV, is widely used for computation and analysis of γ, n, p, t, d, ^{3}He and α particle induced reactions. Differently, computation code ALICE/ASH serves up to 300 MeV energy. Likewise, TALYS, ALICE/ASH is also able to investigate n, p, t, d, ^{3}He and α induced nuclear reactions except γ.

Nuclear reactions can be classified into three categories according to the time scale of their occurrence, such as direct, pre–equilibrium and compound reactions. Incoming particles in direct reactions interact with the surface of the target nucleus firstly. After, there may occur an angular momentum transfer.

The compound reactions occur in two steps, which follow each other. In the first step, target and projectile particles combine and form compound nucleus. In the second step, decay of compound nucleus forms the product nucleus and particle [19]. The mechanism of compound reaction is given in Eq. 1 and C^* is known as the compound nucleus.

$$a + X \rightarrow C^* \rightarrow Y + b \tag{1}$$

For the projectile energies above 10 MeV, before the statistical equilibrium has been reached, particle emission after the direct reaction process may occur. This type of reaction is admitted as pre–equilibrium (PEQ) reaction. PEQs have been characterized by exciton number that is the sum of particle and hole numbers.

In this particular study, the estimations of the cross–section values for the ^{64}Zn(^{3}He,p)^{66}Ga, ^{65}Cu(^{3}He,2n)^{66}Ga, ^{65}Cu(^{3}He,n)^{67}Ga, ^{66}Zn(^{3}He,n+p)^{67}Ga, ^{69}Ga(^{3}He,n+α)^{67}Ga, ^{76}Se(^{3}He,α)^{75}Se, ^{77}Se(^{3}He,n+α)^{75}Se reactions have been obtained by employing the Equilibrium and the PEQ nuclear reaction models. For PEQ, TALYS 1.8 TCE model, ALICE/ASH Hybrid and GDH models have been used whereas Equilibrium model of TALYS 1.8 has been used to analyse compound process.

TCE model is the altered adaptation of Griffin Exciton model that explains pre–equilibrium reaction [19]. In exciton model, exciton and hole numbers do not distinguished as protons or neutrons. However, TCE model takes into account of particle and hole numbers separately for protons and neutrons.

Pre–equilibrium emission spectra used in TCE model has been given in Eq. 2. In this equation, p_π, h_π terms are used to identify the particle and hole numbers for protons while p_v, h_v are used to identify the particle and hole numbers for neutrons. Detailed explanation is available in Ref. [12].

$$\frac{d\sigma_k^{PE}}{dE_k} = \sigma^{CF} \sum_{p_\pi = p_\pi^0}^{p_\pi^{max}} \sum_{p_v = p_v^0}^{p_v^{max}} W_k(p_\pi, h_\pi, p_v, h_v, E_k)\tau(p_\pi, h_\pi, p_v, h_v)P(p_\pi, h_\pi, p_v, h_v) \quad (2)$$

The hybrid model emerged by interpreting the basic definitions of the Fermi–Gas and Griffin Exciton models together. As with the Griffin model, the Hybrid model treats single particle states as an equal distance distribution. The hybrid model gives the probability of emission of a particle, which could be either a proton or a neutron, with ε_v channel energy and v type form an $n = p + h$ exciton structured compound nucleus whose energy is E.

GDH model is the modified version of Hybrid model. Mathematical equations of this model have been given by Blann and Vonach [17]. GDH model has high mean free path parameter due to low density and Fermi Energy level.

3. RESULT and DISCUSSIONS

Although there are many different reaction routes for the production of ^{66,67}Ga and ^{75}Se radionuclides, which are mostly used in the diagnosis and scanning of different types of cancer, ^{64}Zn(^{3}He,p)^{66}Ga, ^{65}Cu(^{3}He,2n)^{66}Ga, ^{65}Cu(^{3}He,n)^{67}Ga, ^{66}Zn(^{3}He,n+p)^{67}Ga, ^{69}Ga(^{3}He,n+α)^{67}Ga, ^{76}Se(^{3}He,α)^{75}Se, ^{77}Se(^{3}He,n+α)^{75}Se reactions have been studied in this work by utilizing the TALYS 1.8 and the ALICE/ASH computer codes. Eventually, obtained calculation results and the experimental data have been compared visually in Figures 1-7.

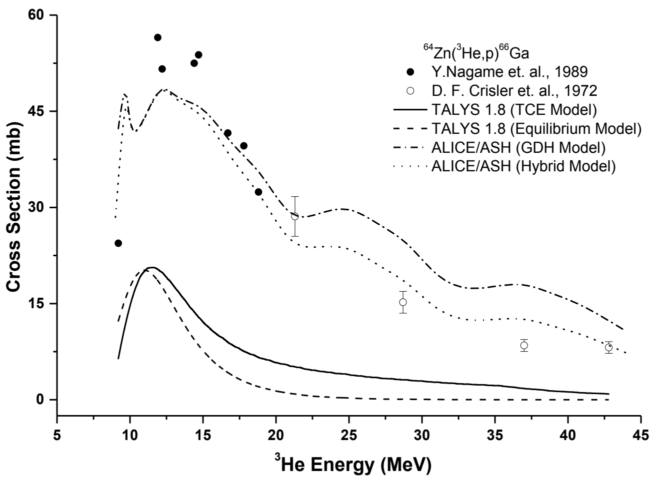

Figure 1. Comparisons of the calculated cross–sections of ^{64}Zn(^{3}He,p)^{66}Ga reaction with the experimental values

The outcomes from the calculations for the ^{64}Zn(^{3}He,p)^{66}Ga reaction have been analyzed with the experimental values in the Figure 1. Calculation results obtained via utilizing ALICE/ASH Hybrid model are in accordance with the previously recorded experimental values in the energy range of 14.4-42.8 MeV incident ^{3}He energy. Moreover, the calculation results from the TALYS 1.8 code are obtained as in agreement with each other but following the experimental results from the below. The calculations of GDH model are in accordance with the results of Hybrid model yet they obtained above than the the experimental measurements after 23.1 MeV.

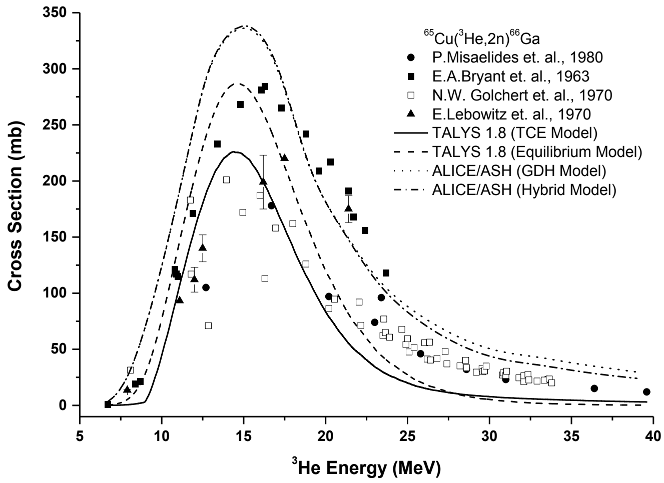

Figure 2. Comparisons of the calculated cross–sections of $^{65}Cu(^{3}He,2n)^{66}Ga$ reaction with the experimental values

The comparison of the calculation results of the $^{65}Cu(^{3}He,2n)^{66}Ga$ reaction, another reaction in which the ^{66}Ga production cross-section calculations are analyzed within this study, and the experimental values are given in Figure 2. As it can be seen, obtained different model based calculation results displayed similar structures with the previously recorded experimental data within the overall investigated incident ^{3}He energy range.

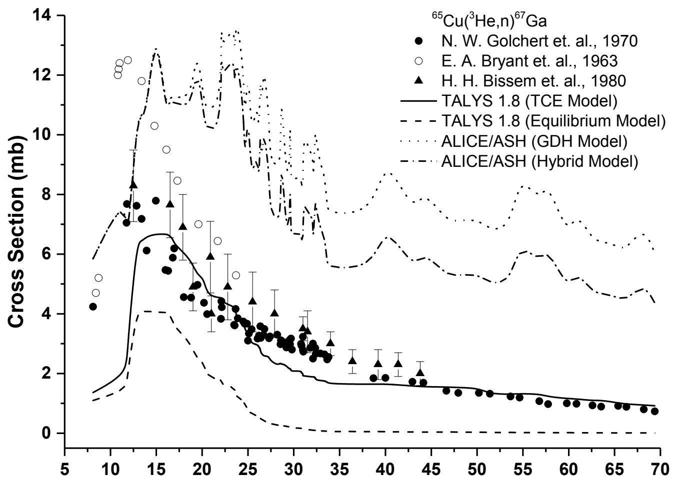

Figure 3. Comparisons of the calculated cross–sections of $^{65}Cu(^{3}He,n)^{67}Ga$ reaction with the experimental values

$^{65}Cu(^{3}He,n)^{67}Ga$ reaction cross–section calculations have been represented in the Figure 3. Both of the TALYS 1.8 models show almost the same geometry with experimental data. TALYS 1.8 TCE model is in good accordance with the experimental values in the energy ranges of 12.5-25 MeV and 40-70 MeV except the experimental results of Bryant *et al.,* [20]. On the other hand, ALICE/ASH model results are not in consensus with the experimental measurements and also track them from the above.

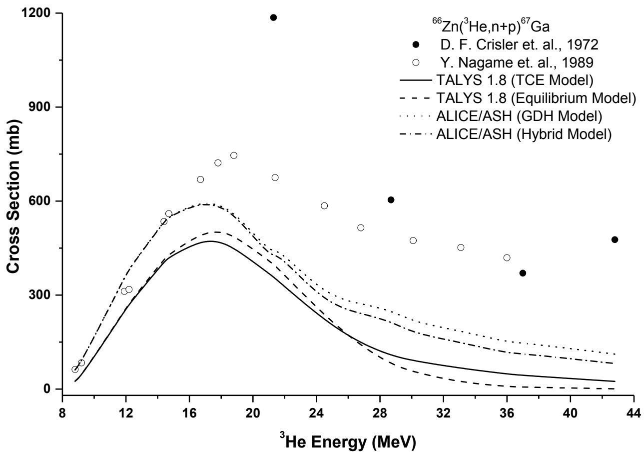

Figure 4. Comparisons of the calculated cross–sections of $^{66}Zn(^{3}He,n+p)^{67}Ga$ reaction with the experimental values

In the Figure 4, the cross–section results of $^{66}Zn(^{3}He,n+p)^{67}Ga$ have been given. All models have almost the same geometry with each other and the experimental data but follow them from the below. GDH and Hybrid models are in good accordance with the experimental measurements of Nagame *et. al.*, [21] up to approximately 14 MeV.

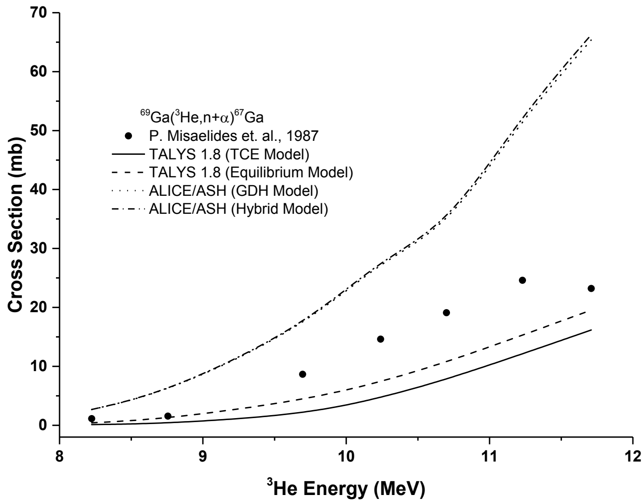

Figure 5. Comparisons of the calculated cross–sections of $^{69}Ga(^{3}He,n+\alpha)^{67}Ga$ reaction with the experimental values

The comparison of the experimental and the theoretical results of $^{69}Ga(^{3}He,n+\alpha)^{67}Ga$ reaction has been given in the Figure 5. For this reaction, TALYS 1.8 model results follow the experimental values from the above whereas ALICE/ASH model calculations follow them from the below.

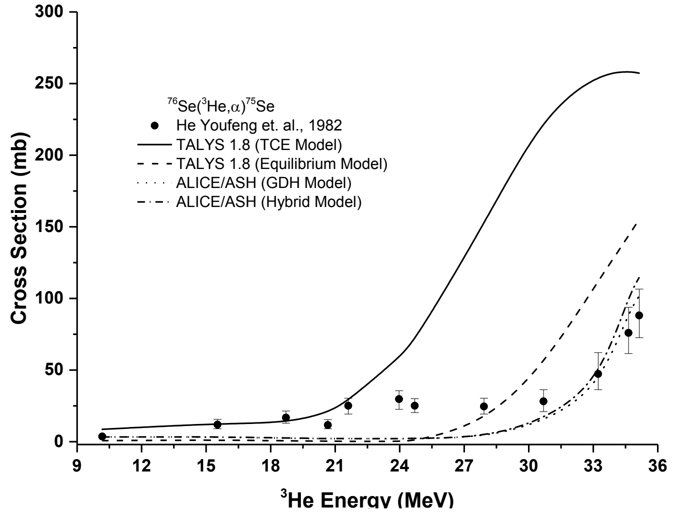

Figure 6. Comparisons of the calculated cross–sections of $^{76}Se(^3He,\alpha)^{75}Se$ reaction with the experimental values

The TALYS 1.8 TCE model calculations are in agreement with the experimental results for the $^{76}Se(^3He,\alpha)^{75}Se$ reaction up to 20 MeV as it can be seen in the Figure 6. In addition, both ALICE/ASH model calculations are in agreement with the experimental measurements in the 33.2-35 MeV ^{3}He energy region.

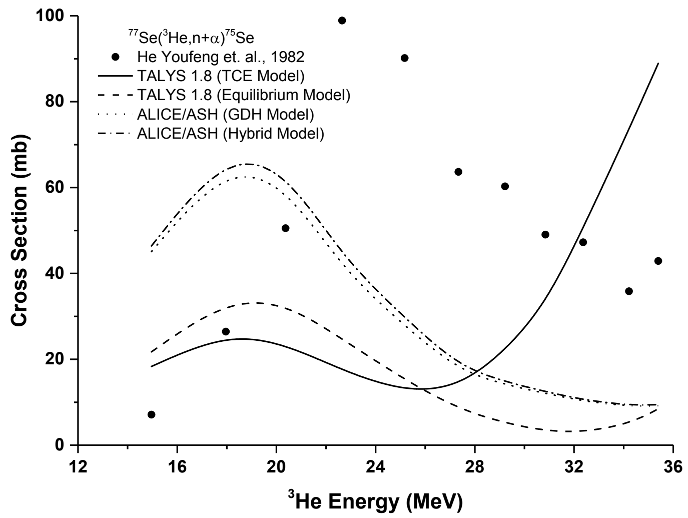

Figure 7. Comparisons of the calculated cross–sections of $^{77}Se(^3He,n+\alpha)^{75}Se$ reaction with the experimental values

The experimental and the theoretical results on the production cross–sections of ^{75}Se radionuclide via $^{77}Se(^3He,n+\alpha)^{75}Se$ reaction have been given in the Figure 7. As can be seen from this figure, the calculation results obtained with different models of the ALICE/ASH code are compatible with each other, but are incompatible with the experimental data. TCE and Equilibrium models of the TALYS 1.8 computer code results are also in disagreement with the each other and experimental values.

4. CONCLUSION

Although there are some disagreements between the calculated results and the experimental data, in generally, the ALICE/ASH Hybrid model calculations are close to the experimental results except for the $^{65}Cu(^3He,n)^{67}Ga$, $^{69}Ga(^3He,n+\alpha)^{67}Ga$ and $^{77}Se(^3He,n+\alpha)^{75}Se$ reactions. This model can be used in case lack of experimental data or experimental difficulties.

The different production routes for $^{66,67}Ga$ and ^{75}Se have been discussed in this paper. The results obtained from the Figures 1-7 have been given in Table 1. In addition to the optimum energy ranges of the radioisotopes studied in each reaction, comments can also be made on the cross-section values for these reactions. In this context, it is noted that the cross-sections are about 50-60 mb for $^{64}Zn(^{3}He,p)^{66}Ga$ reaction, about 200-250 mb for $^{65}Cu(^{3}He,2n)^{66}Ga$ reaction, about 8-12 mb for $^{65}Cu(^{3}He,n)^{67}Ga$ reaction, about 600-900 mb for $^{66}Zn(^{3}He,n+p)^{67}Ga$ reaction, about 15-25 mb for $^{69}Ga(^{3}He,n+\alpha)^{67}Ga$ reaction, about 50-100 mb for $^{76}Se(^{3}He,\alpha)^{75}Se$ reaction and about 80-100 mb for $^{77}Se(^{3}He,n+\alpha)^{75}Se$ reaction. As can be seen, different energy ranges and cross-section values are obtained for the studied reactions. There are multiple possible reasons for this situation. Some of these reasons can be shown as the structure of the target, the energy of the incoming particle, and the fact that these two factors can reveal different physical processes in the interaction between the target and the incoming particle. Various theoretical models have been proposed and developed in order to explain these physical processes. The different calculation steps in which these theoretical models are constructed can be shown as another reason for the different results obtained. Therefore, it is important to discuss the results of calculations made with different models for the same route and it is obvious that these kinds of works will contribute to the literature. Also, considering certain conditions such as existing facilities and capabilities, the most reasonable route to produce one of the radioisotopes studied in this work can be determined by taking into account of these obtained optimum energy ranges and cross-section data.

Table 1. Optimum energy ranges of $^{66,67}Ga$ and ^{75}Se radionuclides production by ^{3}He induced reactions.

Reaction	Produced Radionuclide	Optimum Energy Range of Production (MeV)
$^{64}Zn(^{3}He,p)^{66}Ga$	^{66}Ga	15 → 10
$^{65}Cu(^{3}He,2n)^{66}Ga$	^{66}Ga	17,5 → 12,5
$^{65}Cu(^{3}He,n)^{67}Ga$	^{67}Ga	15 → 10
$^{66}Zn(^{3}He,n+p)^{67}Ga$	^{67}Ga	25 → 15
$^{69}Ga(^{3}He,n+\alpha)^{67}Ga$	^{67}Ga	12 → 11
$^{76}Se(^{3}He,\alpha)^{75}Se$	^{75}Se	36 → 33
$^{77}Se(^{3}He,n+\alpha)^{75}Se$	^{75}Se	27 → 20

As it can be seen from the Table 1., approximately 40 MeV ^{3}He beam is enough for producing the studied $^{66,67}Ga$ and ^{75}Se radioisotopes.

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